Statistic model for calculating the Hole-Edge crack length using Fiber Bragg grating sensors

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Abstract
Fiber Bragg grating has been reported to be a potential tool in structural health monitoring (SHM). However, the application of this technology mainly focus on the composite health monitoring, seldom fatigue crack propagation researches on the aluminum material. This paper presents a new crack length quantification method based on fiber Bragg grating sensors (FBGs). The damage sensitive features were collected by characteristics algorithm. In this paper, the primary wavelength of the reflection intensity spectra and full width at half width (FWHM) were analyzed versus the crack length. The relationship between the crack length and damage sensitive characteristics was analyzed by the BP neural network, and 15 hidden layers were used in this model. The results of BP neural network were validated using coupon test data with fatigue crack propagation.

Keywords: SHM, optical fiber Bragg grating, crack propagation

1. Introduction
Fatigue crack of the hole edge is common dangerous defects in the aircraft industries [1]. The fatigue crack propagates due to the stress concentration around the hole, under cyclic fatigue loading condition. Thus, to ensure the functionality of the structure is necessary.

Fiber Bragg Grating (FBG) sensors have shown great potential in non-destructive evaluations (NDE) and structural health monitoring (SHM) systems. It has been used in composite and shown high sensitivity to many damage pattern (such as delamination, cracks, corrosive, etc.). And a considerable number of researches have been reported damage identification using Fiber Bragg Grating [2]. The significant damage characteristics are primary wavelength and full width at half width (FWHM). McGugan [3] proposed that primary wavelength variation of the reflected spectrum, which is caused by the strain distribution of the crack tip, and the damage characteristics are
independent of the geometry and loading type. Meanwhile, Jin [4] present that with multiple peaks appeared and the spectrum width variation with the crack propagation. Accordingly, the spectrum bandwidth broadened with the multiple peaks appeared. Full width at half maximum was first proposed by Mizutani [5] as a damage index for composite lamination. Yuan [6] extract the crack initiation factor (CIF) for the damage initiation, and the crack propagation factor (CPF) for the damage propagation. Jin [7] proposed that the grating can sense the plastic zone ahead of the crack tip, and the spectrum changes as a function of strain distribution along the length of grating. And the FBG spectra characteristics changes caused by the damage is investigated in this paper.

However, there is no appropriate model to describe the relationship between the crack length and the damage characteristics. In this paper, the change regulation of two damage sensitive characteristics are analysed during the fatigue crack propagation. Then, the crack length quantity model using the proposed three damage sensitive features was implemented to evaluate the crack size.

2. Experiment

To analyse the correlation of sensitive damage characteristics against crack length, the fatigue crack propagation is designed and developed. With the effect of elasto-optical properties, the grating of FBG is sensitivity to the external strain. In this paper, the fibre Bragg grating sensors are adhered as a fibre-bridging, distributed along the crack propagation orientation, with the axial of the grating is parallel to the external loading.

2.1 specimen

In this study, the healthy and damage reflectivity spectrum of six specimens are analysed for the damage characteristics. The specimens for the target system are made of 2024-T3 aluminum alloy. The detail geometry of the specimen is shown in Figure 1. The specimen is a plate with dimensions of 300mm × 100 mm × 2 mm, a 10mm hole is in the centre of it. A 3mm through-thickness pre-crack is introduced with 2mm width in the middle of the plate to promote fatigue crack propagation. The FBG sensors are extended terminal of the crack tip for sensing the variation of axial strain profile with the crack propagation.
2.2 Experiment setup

This study building a fatigue hole-edge crack damage detection experiment platform, the FBG sensor is adhered on the aluminium plate to extract the damage features. The experiment platform contains three major segments as a fatigue crack measurement system, an optical sensing system (SM125), and a fatigue load-cycling system, which is shown in Figure 2. A charge coupled device (CCD) camera was used for monitoring the crack length, and the FBG spectra were collected under the different crack length various from 1-30 mm, with a 1 mm accuracy. And the constant maximum amplitude is set at 80MPa.

3. Quantitative calculation method of crack length

3.1 Damage characteristic extraction

It is well known that the FBG spectrum is sensitive to the strain distribution of the grating, and the relationship between the plastic zone with the FBG spectrum has been discussed in our previous research [7]. At the initial stage, the spectrum performs as a very narrow symmetric Gaussian wave shape. When the crack propagates 1.2mm close to FBG, with the complexity strain filed is changing over a section of the grating, the subordinate peak appeared, and the full width at half maximum (FWHM) became broaden. The reason is that the grating is sensitive with the non-homogeneous strain fields, with the change in the grating pitch Λ (due to the elastic elongation) and the reflection index (due to the photo elasticity induced). And the effective descending height which could make efforts for the crack length is called FWHM.

Thus, the primary wavelength and FWHM could be used as an indicator for real-time health monitoring of aluminium. And the damage characteristic algorithms are investigated in this section.

In this paper, the damage sensitive characteristics extraction algorithm is employed, for extract the sensitive damage characteristics with the fatigue crack propagation. The peak seeking algorithm is applied for calculation the wavelength shift. The peak seeking
algorithm for the wavelength shift calculation is considered as the search of maximum value [8]. And the FWHM value seeking is obtained by cyclic counting method [9], and in this paper, the full width at half maximum is set to the 3dB band width. The spectrum bandwidth detection algorithm of FBG by a threshold method as the spectrum identity diminishing to only half of the maximum spectrum intensity. The full width at half maximum (FWHM) is set to the -3dB band width, and its detection algorithm is resemblance to the spectrum bandwidth detection algorithm.

![Diagram](image)

Figure 3. The schematic diagram of damage characteristics extraction algorithm

3.2 Damage characteristics various

It is well known that the FBG spectrum is sensitive to the strain distribution of the grating. In this paper, two damage sensitive characteristics, namely the primary wavelength and full-width at half maximum (FWHM), extracted from the full spectral response of FBG sensors, were as the input of statistical model.

3.2.1 the primary wavelength

Generally, when the uniform strain is sensed by the FBG, the wavelength shift simply forwards or backwards. And the reflected spectrum shift to the lower wavelength due to compressional strain, while tensile strain distributed along the grating, the reflected spectrum will shift to a higher wavelength [10]. The principle of wavelength variety as shown in Figure 4. At the crack propagation initial period, The Bragg grating performs as a very narrow symmetric Gaussian wave shape.
Figure 4. Principle of wavelength variety

With the crack propagated close to the FBG, the plastic zone of crack tip located at the head of the crack tip, the primary wavelength shifting to the higher wavelength with the grating sensing the non-homogeneous strain. With the crack propagate close to FBG 1.2mm, the subordinate peak initially appeared at the lower wavelength. When the crack propagating across the FBG, the non-homogeneous strain loaded to the grating increase, and the primary wavelength present a tendency to higher wavelength. With the crack propagation, the wavelength shift increases stabilized with the crack increment, but then keep significantly, as shown in Figure 5.

Figure 5. The primary wavelength various vs the crack length

3.2.2 the full width at half width

It is known to us that the bandwidth of FBG spectrum is a threshold value which is often defined relative to the difference between the maximum value and the minimum value of reflection spectrum, that is the point where the spectral density is half its spectral amplitude. The minimum value considered to be upper than -50dB to prevent the noise effectively, and the maximum value of reflection spectra could be acquired by primary peak detection algorithms. The bandwidth of FBG reflection spectra are closely related to the strain gradients induced by measured fields. When FBG sensor is imposed at a point far away from the crack, the original spectrum reflection present a prefect Gaussian envelop, and it has a narrow-bandwidth since the FBG sensor capture the plane elastic stress. With the crack propagating closely to the FBG, here comes the inhomogeneous deformation of the plane, and the grating senses the plastic zone ahead of the crack tip which is the plasticity plane cubic strain differ to the former plane quadratic strain. As a result, the bandwidth of FBG spectrum broadened as shown in the following Figure 6.
According to the damage characteristics discussion above, in this section, a three-layer structured BP neural network method is applied for the crack size quantitative model, which denotes the relationship between the wavelength shift and FWHM with the damage characteristics. The BP neural network structure as shown in Figure 7. A crack damage status can be expressed as

\[ g = g(w, f) \]

where \( g \) is the crack lengths, \( f \) presents FWHM and \( w \) is the main wavelength shift.

BP neural network provide a general, non-linear parameterized mapping between a set of inputs and outputs. And Bayesian regulation algorithm was applied here for the training algorithm. The quantitative model in this paper was more superior to the traditional linear regression methods. And it does not need to describe the function between the input and the output.

In the quantitative calculation, A 25 groups data including different crack lengths from the experiment have been taken into consideration as the training samples. The results shown that the predictions of the current network are in good consistence with the 6 groups real crack length, the robustness testing demonstrates that the current neural network has its feasible to be utilized in practical engineering applications. The error calculation results as shown in Figure 8.
4. Conclusions

In this paper, the capability of FBG adhered on the aluminium material to detect the crack length. The damage characteristics detection algorithm was applied for the crack detection. And the result shows that the primary wavelength and the FWHM increased with the crack propagation. The BP neural network was applied for the further correlation of damage characteristics with the crack length.
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References and footnotes


