Real Time Load Monitoring Technology of Wing Structure Based on Fiber Bragg Grating

Xiaobei Liang¹, Weifang Zhang², Wei Dai²*, Jin Bo¹, Jinyong Yao² and Yanrong Wang¹

1 School of Energy and Power Engineering, Beihang University, Haidian Dist., Beijing 100191, China; liangxiaobei@163.com; by1504121@buaa.edu.cn; yrwang@buaa.edu.cn
2 School of Reliability and Systems Engineering, Beihang University, Haidian Dist., Beijing 100191, China; 08590@buaa.edu.cn; dw@buaa.edu.cn; jinyongyao@buaa.edu.cn
* Correspondence: dw@buaa.edu.cn; Tel.: +86-138-1058-4286

Abstract

A fiber Bragg grating strain transducer network was designed to implement the real-time load monitoring of the aircraft wing structure. A fiber grating sensor network was reasonably applied on spar of wing structure to achieve load monitor. The experimental investigation was performed on spar of wing structure with fiber grating monitoring structural strain. Four loading modes were designed to investigate the relationship model between strain and loading of I-beam spar. According to the superposition principle of structural mechanics, the relationship matrix between the strain and the loading on the wing structure spar were established.

Keywords: load monitoring; FBG sensor; I-beam spar; relationship matrix

1. Introduction

Since the emergence of structural health monitoring technology for nearly 30 years, its application in the field of aeronautics and astronautics has drawn extensive attention[1]. The plane is a type of complex mechanical electronic equipment that require high manufacturing costs, complex maintenance, high reliability and safety[2]. The integration of structural health monitoring technology into aircraft design and manufacturing to improve the reliability and safety of aircraft and to effectively understand aircraft lifetime information has also been the focus of the aviation industry. Aircraft structure strain, stress and load monitoring are the basis of aircraft structure durability/damage tolerance design, analysis and test. Since aircraft experience different flight environments and flight states while in service, which makes each aircraft experience different loads, it is crucial to obtain the true load of the aircraft[3]. The whole load history of aircraft during its service is one of the basic parameters for predicting aircraft fatigue damage and predicting its life. Therefore, real-time monitoring of aircraft load is one of the important directions in structural health monitoring technology research[4].

Fiber Bragg grating sensor has the characteristics of small size, easy integration and strong ability to resist electromagnetic interference[5-7]. Since its appearance, it has become the star of the sensing field[8-10]. The load history that the aircraft experienced in the past is a rough estimate based on the flight status of the aircraft. The method has a large error. The emergence of fiber grating sensors provides possibility for monitoring
the real load history of single aircraft, which will greatly improve accuracy of aircraft fatigue damage and structural life prediction, and meet the development requirements of high reliability and long life of aircraft. Integrating advanced sensors into the material structure, combined with advanced data acquisition equipment, enables online real-time access to a wide range of parameters that affect the health of the structure\[^{11}\]. Use mathematical modeling to determine the state of the structural material and automatically predict and assess the structural health status. It not only can reduce the cost of structural maintenance, improve structural safety, but also extend the service life of the structure and obtain greater economic benefits\[^{12}\].

### 2. Research method

#### 2.1 Test platform

Spar of wing structure test platform comprises I-beam spar, strain signal acquisition and analysis system, loading monitor system, support and loading structure (see Fig.1). Design the wing girder according to the actual structure of the aircraft. Signal acquisition and analysis system includes fiber Bragg grating sensor, FBG sensor demodulator, strain display system, which function is collecting stress in the key position of wing structure. The function of loading monitor system is implementing real-time monitoring loading imposed on spar. Support and loading structure is applied to fix spar and exert force on wing girder.

![Figure 1. Spar of wing structure test platform](image)

According to force analysis of wing structure, four loading modes were simulated, which contain pure bending mode, pure torsion mode, bending shear combination mode, bending shear torsion combination mode. There are 6 load points on the spar (see Fig.2) represented respectively form A to F. The pure bending moment is imposed on wing spar through A and B. The pure torsion is exerted on wing spar through E and F. Obtained by mechanical analysis, the bending shear combination mode can be imposed on the spar through C. The bending shear torsion combination mode can be applied on the wing girder by C and D.
The wing spar’s section is I-beam, which dimension is revealed by Fig.3. Eight group of FBG sensors were pasted on the I-beam spar. 24 FBG sensors were used to measure the strain on the wing structure surface. On the upper surface of wing spar, four group of FBG sensors were pasted as shown in Fig.4. The layout of four group of FBG sensor on the lateral surface of the wing spar is indicated in Fig.5.

**2.2 Strain-load relationship model**

According to the superposition principle of structural mechanics, the relationship between the strain and the load at one point is expressed by Formula (1).

$$\varepsilon = aQ + bM + cT$$

The layout of a group of eight FBG sensors is shown in Fig.6. It assumes that the strain measured by FBG1 is $\varepsilon_1$ which direction is parallel to long axis of the I-beam, the strain measured by FBG2 is $\varepsilon_2$ which direction is 45 degree with long axis of the I-beam, the strain measured by FBG3 is $\varepsilon_3$ which direction is perpendicular to long axis of the I-beam.
The strain values in three directions of a single measuring point can be represented by bending moment $M$, shearing force $Q$, and torque $T$ received by the I-beam as follows:

$$
\varepsilon_1 = a_{11}M + a_{12}Q + a_{13}T \\
\varepsilon_2 = a_{21}M + a_{22}Q + a_{23}T \\
\varepsilon_3 = a_{31}M + a_{32}Q + a_{33}T
$$

(2)

The equation (2) is expressed in a matrix form as expressed in equation (3).

$$
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3
\end{bmatrix} =
\begin{bmatrix}
a_{11} & a_{12} & a_{13} \\
a_{21} & a_{22} & a_{23} \\
a_{31} & a_{32} & a_{33}
\end{bmatrix}
\begin{bmatrix}
M \\
Q \\
T
\end{bmatrix}
$$

(3)

The coefficient matrix in the formula is represented by $A$. In practical engineering problems, matrix $A$ is reversible, So formula X can expressed as:

$$
\begin{bmatrix}
M \\
Q \\
T
\end{bmatrix} =
\begin{bmatrix}
b_{11} & b_{12} & b_{13} \\
b_{21} & b_{22} & b_{23} \\
b_{31} & b_{32} & b_{33}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3
\end{bmatrix}
$$

(4)

Equation (4) is the strain load relationship matrix, strain load coefficient matrix is represented by $B$.

3. Load test and results analysis

3.1 Pure bending mode

According to Fig.2, The pure bending moment was imposed on wing spar through A and B. It fixed support at both ends at the I-beam spar. The external loads of the same magnitude and direction were applied at the symmetric position at both side of spar. At the pure bending loading state, the bending moment and shear state of the I-beam structure are shown in Fig.7.
According to Fig.7, both bending moment and shear force exist in the AB and CD segment of the spar. While in the BC segment of the beam, the shear force is zero and the bending moment is an invariant constant. Under such circumstances, the BC segment of the beam is in a pure bending state. Taking a set of sensors on the upper surface of the second section as an example, it reveals the measured strain values changing with pure bending load in Fig.8. It applied least squares method to fit the trend of strain change with loads.

![Figure 7. Force distribution of I-beam under pure bending moment](image)

3.2 Pure torsion mode
According to Fig.2, The pure torsion was imposed on wing spar through E and F. It fixed support at one side of the I-beam spar. The external force of same magnitude but different direction were exerted at the E and F of the Spar of wing structure test platform. At the pure torsion loading state, the torsion state of the I-beam structure are shown in Fig.9. The torsion is equally distributed along the long axis of the I-beam spar. Taking a set of sensors on the upper surface of the second section as an example, it reveals the measured strain values changing with pure torsion loads in Fig.10. It applied least squares method to fit the trend of strain change with loads.

![Figure 8. Strain varies with pure bending loads](image)
3.3 Bending shear combination model

The bending shear combination load was exerted on I-beam spar through C according to Fig.2. At the bending shear combination loading state, the bending and shear force state of the I-beam structure are shown in Fig.11. The shear force is constant at all parts of the beam. The bending moment reaches the maximum at the position near the support, and gradually decreases with a constant slop. In Fig.12, it reveals the measured strain values changing with bending shear combination loads on the upper surface of the second section.
3.4 Bending shear torsion combination model

The bending shear torsion combination load was applied on I-beam spar through C and D according to Fig.2. At the bending shear torsion combination loading state, the bending, shear and torsion force state of the I-beam structure are shown in Fig.13. The shear force and torsion moment are constant at all parts of the beam. The bending moment reaches the maximum at the position near the support, and gradually decreases with a constant slop. In Fig.14, it reveals the measured strain values changing with bending shear torsion combination loads on the upper surface of the second section.

Figure 12. Strain varies with bending shear combination loads

Figure 13. Force distribution of I-beam under bending shear torsion combination

Figure 14. Strain varies with bending shear torsion combination loads

3.5 Establishment of strain-load relationship model
From the above test data processing and analysis, only the FBG2 in 45 degree direction has a good linear relationship with loads when the pure torsion was imposed on the spar. When the bending shear combination was loaded on the I-beam, only the FBG1 has a good linear relationship with loads. When the spar was applied pure bending load, the signal of FBG1 in 0 degree direction has a good linearity with the loads. Therefore there is an independent relationship between stain signal of FBG sensors in different directions with bending shear torsion loads. According to the experimental data and equation (4), the strain and load relationship matrix is as follow:

\[
\begin{bmatrix}
M \\
Q \\
T
\end{bmatrix} =
\begin{bmatrix}
-418.0428 & 200.0677 & -141.4036 \\
-491.815 & 235.3738 & -166.352 \\
-147.5445 & 70.6121 & -49.9072
\end{bmatrix}
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3
\end{bmatrix}
\] (5)

Equation (5) is the strain and load relationship matrix is derived from the FBG sensors of upper surface on the second section. Using the same method, it can obtain the other seven load relationship matrix. The real-time monitoring of the structural load of I-beam spar can be achieved through the eight sets of strain load relationship matrix.

4. Conclusions

With the development of structural health monitoring technology in recent years, FBG sensors are increasingly used in the field of structural condition monitoring due to the numerous advantages of FBG sensors. In this article, on account of fiber-based wing spar load monitoring theoretical research and experimental verification, it provides an important basis for fiber-based aircraft load real-time monitoring technology. The structural stress distribution was monitored by placing FBG sensors on the wing I-beam structure. Based on the superposition principle of structural mechanics, the strain load relationship matrix was established, which can achieve the real-time monitoring of the structural loading.

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References and footnotes

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