Applications of FBG sensors for airship structural health monitoring

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***Abstract*—The application of structural health monitoring (SHM) based on fiber Bragg grating (FBG) for airships is investigated. In order to verify the validity of the FBG-based SHM in the field of airships, a qualitative strain monitoring experiment for ZHIYUAN-1 airship nosecone has been carried out. A commercial FBG interrogation system (Micron Optics sm130) is used in this experiment to measure the strain. Moreover, a finite element (FE) analysis is proceeded to confirm the result of the experiment. Results indicate the effectiveness of the FBG-based SHM system for the strain monitoring in the airship field. Finally, some proposals for future researches are provided.**

Keywords-fiber Bragg grating (FBG); structural health monitoring (SHM); airship; composite materials

I. INTRODUCTION

Airship is a lighter-than-air aircraft that can be steered and propelled through the air by rudders and propellers or other thrust mechanisms (see Fig.1). It has attracted much attention in the past years due to the fact that it can be widely used in regional disaster prevention, environmental monitoring, urban security, missile defense, regional communications, and so on. The airship structures have the following characteristics when in use:

1) Large flexible structure and easy deformation of the envelope.
2) Complex service environment and easy to cause damage.
3) Long working hours.

The safety of the airship structure is a prerequisite to ensure the normal operation of its system, including the inflatable structure part and other boat loading equipments, which makes SHM necessary. Among optical fiber sensors (OFSs) for SHM, FBG sensors have become a reliable monitoring tool during two decades' development. What earlier researches on FBG sensors focus on is the fundamentals of the reliability [1]. These researches have revealed approving results for the potential use of FBG sensors in various fields for SHM, such as advanced aircraft and space vehicles [2], marine [3] and medical science [4]. Nowadays, FBG sensors have enormous application potential where quasi-distributed measurements are demanded, such as temperature, strain, vibration, pressure, ultrasound and high magnetic field [5].

Figure 1. ZHIYUAN-1 airship.

However, up to date and to the best knowledge of the authors, the application of FBG-based SHM for airships has never been reported in the literature and this will be the goal of this paper. A strain monitoring experiment of ZHIYUAN-1 airship nosecone using FBG sensors is brought out in this paper. Experiment results demonstrated the validity of FBG-based SHM in the field of airships qualitatively. Furthermore, some technical proposals for future researches are presented.

II. FBG SENSING TECHNIQUE

In 1978, Ken Hill, using a visible laser propagating along the fiber core, successfully synthesized the first in-fiber Bragg grating. In 1989, Gerald Meltz et al. demonstrated the more pliable transverse holographic technique. In 1993, a progressive FBG production technique was reported [6], which made the use of an optical phase mask to generate interference fringes.

The fundamental principle behind the operation of a FBG is Fresnel reflection. The reflected wavelength λ_B , called the Bragg wavelength, is defined as

$$\lambda_B = 2 n_{eff} \Lambda \tag{1}$$

Where λ_B is the center wavelength of fiber grating, n_{eff} is the actual refractive exponent of center fiber, and Λ is the grating period. n_{eff} and Λ both depend on strain and temperature, so the Bragg wavelength is sensitive to both strain and temperature. The shift in the Bragg wavelength in response to strain and temperature is defined by

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$$\frac{\Delta\lambda_B}{\lambda_B} = (1-\rho_\varepsilon)\Delta\varepsilon + (\alpha+\xi)\Delta T \qquad (2)$$

Where ρ_ε , α and ξ are the strain optical sensitivity coefficient, the thermal expansion coefficient and the thermo-optic coefficient respectively. For static and quasi–static measures of the deformations, measuring results are often influenced by variations of the exterior temperature. Consequently, temperature compensation should be carried out. The most efficient way is to use a reference FBG sensor, free from eventual exterior solicitations that can bring deformations in it, dedicated to the temperature measurement.

Due to their quasi-point sensing and multiplexing capability, FBGs have many notable advantages over other OFSs. The unique property that FBGs have is that the measurand is encoded in terms of the wavelength directly. The wavelength is an absolute parameter that is immune to the disturbances along the light paths [7], and can be monitored easily since every reflected signal has a unique wavelength. A classified comparison of FBG and several other successful OFSs for SHM at the present stage is shown in Table.1. In recent years, FBG sensors are becoming one of the most promising sensing techniques and will remain its primary leading position among OFSs.

TABLE I. COMPARISON OF FBG AND SEVERAL OTHER OFSS FOR SHM

Sensing technique	**Operating bandwidth**	**Sensing distance**	**Measuring time**	**Stress measurement accuracy**	**Temperature measurement accuracy**	**Spatial resolution**	**Signal Processing**
FBG	Wide	Long	Short	High	High	High	Simple
BOTDR	Wide	Long	Medium	High	High	High	Simple
ROTDR	Wide	Long	Medium	——	High	High	Simple
SOFO	Wide	Short	Short	High	——	High	Complex

Note: "——" indicates no this parameter.

III. EXPERIMENTAL PROCESS AND RESULTS

In order to realize a qualitative demonstration of airship SHM, a strain monitoring experiment for ZHIYUAN-1 airship nosecone has been carried out.

A. Experimental Setup

The experimental setup is shown in Fig.2. A commercial FBG interrogation system (Micron Optics sm130) is the main part of the SHM system with a resolution of 1pm and repeatability of 0.2 pm. Experimental results are stored into a PC. A FBG is assumed to have a uniform strain along its working length. Thus, the shift in the Bragg wavelength is proportional to the change in length of the grating. The Micron Optics instrument uses this principle to measure the strain.

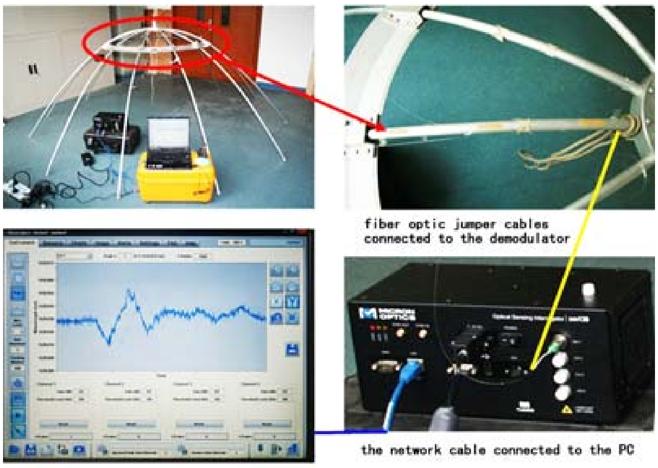

Figure 2. Experimental setup.

Three FBGs, fiber optic jumper cables and the network cable are respectively connected to the upper part of the nosecone, the demodulator and the PC. The lower end of the nosecone is fixed, and at the same time a concentrated force is applied on the top of it. During the experiment, the strain in the FBG sensor is changed and then the reflected signal of the FBG is transmitted back to the demodulator. And finally, the information of the modulated signal is shown on the PC.

After the experiment, a FE analysis is carried out, using Pro/Engineer and Ansys Workbench, as a confirmation of the results of the experiment.

B. Results and Analysis

The waveform graph from the demodulator and the strain contour chart from the FE analysis are shown in Fig.2 and Fig.3 respectively. Then, a comparison of the results of FBG sensors and FE model is displayed in Fig.4.

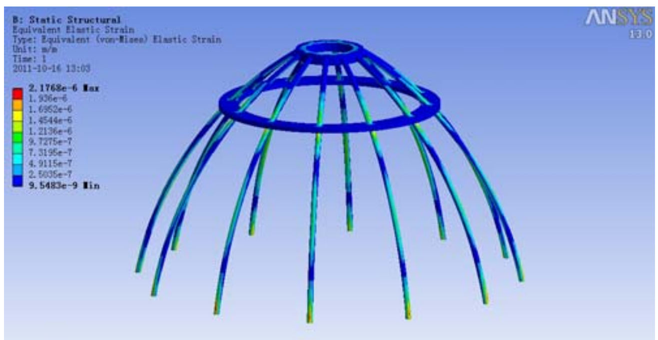

Figure 3. Result of the FE analysis.

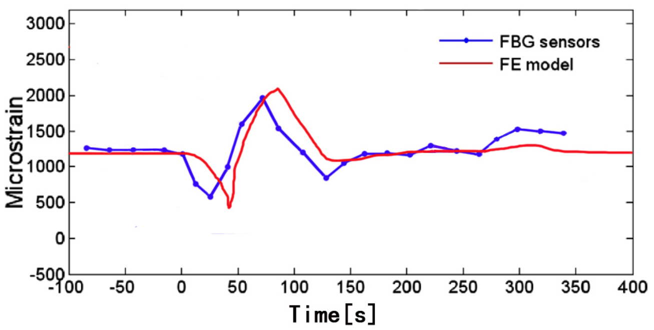

Figure 4. Comparison of the results of FBG sensors and FE models.

As can been seen from the above, the result of the FE model can approximately reflect the reliability of the result of FBG sensors. Therefore, the validity of FBG-based airship SHM is verified through this experiment.

However, there are still some problems in this experiment that may affect the accuracy of the results:

1) The boundary conditions and the load exist some diffrences with the real situation.

2) The cross-sensitivity problem that FBGs are sensitive to both stress and temperature has not taken into consideration.

3) Optimal placement of sensor is another major factor to affect the accuracy of the results in the experiment.

IV. Proposals for Future Researches

FBG-based airship SHM is a new concept in the SHM field, which have a comprehensive application potential in the near future. In order to achieve its optimum function, several technical proposals of FBG-based airship SHM are put forward as follows:

1) Because of the sensitivity of FBGs to both strain and temperature, it is very necessary to measure strain and temperature simultaneously so as to correct the thermally induced strain for static strain measurement. Therefore, the temperature should be compensated in practice.

2) Low-cost and practical problems of FBG sensors, which is mainly related to the manufacturing method, sensor package and distributed measurement, should be solved.

3) High-performance composite materials have been widely used in various industries and are extremely promising candidates for stratospheric airships. Therefore, techniques of FBGs for composite SHM, including composite cure monitoring, are the research direction of the future. In composites materials, simultaneous measurement of multi-axis strain and temperature remains as a main challenge for FBG sensors community because of the complexity.

4) Although the current FBG instruments can meet most practical demand, including composite SHM, for some special applications of higher strain sensitivity and measurement bandwidth, further improvement is still necessary. Techniques of non-standard FBG sensors, e.g. FBG-based fiber laser sensors [8,9] and phase-shifted FBGs [10,11], are proposed to address these applications. However, due to their complexity in fabrication and signal processing, the application range of the non-standard FBG sensors is limited. At the present stage, standard FBG sensor systems are likely to continue to play a leading role in FBG sensors.

5) Monitoring for the flexible large deformation envelope materials, such as the corrugated-form and honeycomb core flexible composites is a new issue for futher aiships.

6) Various optimal sensor placement methods for airship SHM with the aim of acquisiting all-sided data information is another challenge.

V. Summary

In this paper, a new application idea of SHM in the airship field using FBG sensors is presented. In order to verify the validity of this idea, a qualitative strain monitoring experiment of the ZHIYUAN-1 airship nosecone using FBG sensors has been carried out. Afterwards, a FE analysis by Pro/Engineer and Ansys Workbench has been proceeded to confirm the results of the experiment. Results have demonstrated the validity of FBG-based SHM in the field of airships. In the end, some technical proposals are put forward, which lay a foundation for further researches.

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