Research on Applicability of Fiber Bragg Grating Sensor for Ship Structure Monitoring System

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Abstract. A complete application research of Fiber Bragg Grating sensing technology in ship structure stress monitoring and evaluation system is studied in this paper. The working principles of Fiber Bragg Grating strain sensor in monitoring system are briefly introduced. And a kind of new differential FBG strain sensor for ship structure stress monitoring is applied and verified by a series of calibration and force measurement test systematically. Through finite element calculation and test towards ship structure, some defects of monitoring sensor used in bending deformation are found. Then, a three-dimensional strain sensor arrangement for stress monitoring of hull structure is designed and developed. The satisfactory test results are obtained by this sensor arrangement. Finally, the accuracy and reliability of hull structure monitoring system is improved further through this research results.

1. Introduction
Hull structural strength is one of the main factors affecting ship navigation safety. In order to ensure that ship has enough hull strength to resist the destructive effect caused by the environmental loads, various rules and maintenance plans have been taken in the process of ship design and construction[1-2]. However, for ship navigation in the complex environment, the external wave impact often shows some strong randomness. And these random factors cannot be predicted accurately in the ship design and construction process. Thus, the structural stress monitoring and evaluation system for ship is needed to ensure the safety of ship operation. The ship structure safety monitoring system is a kind of engineering intelligent system with sensors embedded in the hull structure, which endows similar life characteristics of structural health using self-diagnosis function[3]. Ship structural safety monitoring technology is also an interdisciplinary and comprehensive technology. It includes dynamics, material science, sensing technology, communication technology and database technology. Herein, the sensing technology is basic and critical. In the late 1970s, Lindemann[4] took some exploratory researches. Due to the limitation of computer technology and sensor technology at that time, the research did not obtain ideal results. With the development of related technology, the hull structure monitoring becomes an achievable goal gradually. Relevant ship companies, which are in the United States, Britain and France, have developed their own structural monitoring software[5-10]. And the monitoring sensor used in ship structure has gradually changed from strain gauge to optical fiber sensor[11-14]. Fiber optic sensors have incomparable advantages over strain gauges, so they are widely used in ships with complex structures. But the reliability and layout of fiber optic sensors to monitor various complex deformations in ship still have some difficulty. In this paper, the principle of...
optical fiber sensor are introduced. And a new differential sensor monitoring method is presented. Through experiments, the error reason and distribution characteristics of sensor are analysed. In addition, three-directional strain sensor arrangement is given in paper to monitor the vertical bending deformation. Through the finite element calculation and experiment, the design of sensor frame is modified, which further improves the accuracy of optical fiber sensor on hull structure monitoring.

2. Fiber Bragg Grating Sensing Principle

Fiber Bragg Grating (FBG) is a kind of core made by fiber materials. Using its photosensitive properties, the core can make the optical waveguide change periodically or aperiodically. And it also has the function of wavelength selectivity. Because the grating fiber has the advantages of small size and low fusion loss, it has been widely used in the field of optical fiber communication and sensing. With the wide application of FBG, the types of FBG are varied. According to the distribution of refractive index along the grating axis, the ultraviolet-written FBG can be divided into uniform FBG and non-uniform FBG. Uniform fiber Bragg Grating is a kind of FBG whose amplitude and period of refractive index remain unchanged along the fiber axis. And, the amplitude and period of refractive index in Non-uniform Fiber Bragg Grating is varied. In hull structure monitoring, the designed Bragg Grating core belongs to uniform FBG. It only reflects the light about the central wavelength \( \lambda_c \) and transmits the light of other wavelengths. In fact, its basic optical properties are just like a reflective optical filter, and the optical equation is as follows.

\[
\lambda_c = 2r_T \varepsilon
\]  

(1)

Where, \( r_e \) is the effective refractive index, and \( T_g \) is the grating period. Because the refractive index and grating period is sensitive to dynamic strain, the centre wavelength \( \lambda_c \) will be offset when the environmental physical field like strain changes. Through measuring the offset of wavelength in fiber core, the dynamic waves of external field can be obtained, and the FBG sensing can be realized[15].

Herein, the reflection bandwidth is in the order of magnitude about \( 10^4 \) nm, and the reflectivity can reach 95%~100%.

2.1. Effect Of Strain on Central Wavelength

In ship structure monitoring, the sensors are mainly used to monitor the structural strain change at its location. Therefore, the establishment on relationship between the measured value of sensor and the structural strain is very important. In fiber sensors, the variation of central wavelength caused by strain is calculated based on Equation (2).

\[
\Delta \lambda_c = 2 \left[ \varepsilon T_r + \varepsilon T_e \frac{r_e^3}{2} [(1 - \nu) P_{12} - \nu P_{11}] \right]
\]  

(2)

Herein, \( P_{12} \) and \( P_{11} \) are the elasto-optic coefficients, \( \nu \) is the Poisson ratio of core material, and \( \varepsilon \) is strain variation. Then, the effective elasto-optic coefficient is defined as Equation (3).

\[
p_e = \frac{r_e^3}{2} \left[ P_{12} - \nu (P_{11} + P_{12}) \right]
\]  

(3)

Finally, the relationship between the measured value of sensor and the structural strain is as follows.

\[
\Delta \lambda_c = (1 - p_e) \varepsilon \lambda_c
\]  

(4)

In fact, in addition to strain, the temperature change around the sensor will also cause the change of central wavelength. Similar method is used, and the relationship between the measured fluctuation of sensor and the temperature variation is also as follows.

\[
\Delta \lambda_c = (\alpha + \zeta) \Delta W_T \lambda_c
\]  

(5)

Where \( \alpha \) is the coefficient of thermal expansion, \( \zeta \) is the thermo optic coefficient, and \( \Delta W_T \) is temperature variation around the sensor. It is assumed that the effects of strain and temperature on the central wavelength of grating are independent at each other. Thus, it is derived from equation (4) and (5) that, when the strain and temperature change simultaneously, the relative change of central
wavelength on the grating can be expressed as follows.

\[ \frac{\Delta \lambda_{cw}}{\lambda_{cw}} = (1 - p_w)e + (\alpha + \zeta)\Delta W_r \] 

(6)

In summary, Equation (6) is the basic principle formula of Fiber Bragg Grating sensing technology.

3. Fiber Bragg grating strain sensor

3.1. Sensor Structure and Working Principle

In section 2.1, it is found that both fluctuation of structure strain and temperature can affect the central wavelength of fiber bragg grating. Therefore, strain sensors using fiber bragg grating needs to consider the interference of temperature on structure strain measurement. A simple and common solution is to equip these strain sensors with some temperature compensation sensors. The strain sensor measurements is corrected by temperature-induced changes in the central wavelength of FBG measured by temperature sensors, then the influence of temperature on strain measurement can be eliminated. Because the different temperature changes at each compartment, a large number of temperature sensors are arranged at these monitoring positions. These temperature sensors greatly increase the burden of the monitoring system. And temperature data also occupy a large amount of system computing space[16]. In order to improve the efficiency of monitoring system, another advanced processing method is adopted using the FBG sensor, namely differential Fiber Bragg Grating strain sensor. The sensor uses two fiber bragg gratings encapsulated in the shield to eliminate the influence of temperature on the central wavelength by the differential method. Thus, the temperature compensation sensor is omitted. The structure of FBG sensor is shown in Figure 1(a).

![Figure 1. Differential Fiber Bragg Grating sensor: (a) Structure of differential fiber bragg grating sensor; (b) Deformation of sensor under tension stress.](image)

When the sensor on the hull structure suffers tension stress, the frame of Fiber Bragg Grating sensor produces mid-hog deformation. Because the two fiber gratings are attached to the upper and lower surfaces of frame beam, the upper grating is pulled and the lower grating is compressed, as shown in Figure 1(b). The central wavelength of upper and lower grating appears deviation by strain and temperature. Because the position of grating at upper and lower surfaces is close to each other, the temperature change is considered as the same value. Thus, when the differential method is used, the effect of temperature fluctuation is offset. And the influence caused by strain is enlarged due to the two deformations in opposite directions. Similarly, when the sensor on the hull structure is subjected to compressive stress, the frame structure produces mid-sag deformation. In the frame beam, the upper grating is compressed and the lower grating is pulled. This design improves the sensitivity of sensor towards strain, so that it can obtain larger range and higher accuracy.

3.2. Sensor calibration test

The linearity of monitoring sensor was taken in a calibration test. In order to simulate tensile deformation in sensors, the ends of the monitoring sensor frame were fixed on two supports of
calibrator. Then, the sliding support of calibrator was driven to produce relative displacement and another support kept fixed. Strain was also calculated and compared with the measured value by differential FBG sensor.

\[ \varepsilon = A \Delta \lambda + B \]

where \( A = 0.0008 \) and \( B = 8.1322 \).

Figure 2. Calibration test: (a) Relation between central wavelength difference and tensile deformation; (b) Distribution of relative error about differential FBG sensor.

In the calibration test, it is found that the central wavelength difference of FBG sensor is linear with the tensile deformation. And the strain measured formula is obtained by the least square method from the results of calibration experiment, as shown in Figure 2(a). The error between the theoretical strain and the measured value from the differential FBG sensor is also calculated. The maximum of absolute error is 7.795 \( \mu \varepsilon \), which account for 2.72% of whole structural strain. Figure 2(b) shows the distribution of relative error about the differential FBG sensor. It observed that the relative error is remarkable when the structural strain approaches zero, and gradually reduces to both ends. In fact, when the structural strain is close to zero, the accuracy requirement of measurement system is higher. Thus, the error of differential FBG sensor is relatively large. For the actual ship structure monitoring, the structural stress, which is caused by waves and lead to the damage of hull structure, is often remarkable. The range of structural strain is more than 2000 \( \mu \varepsilon \). Therefore, the differential FBG sensor always has small relative error in actual environmental structure response. The measurement by differential FBG sensors can meet the application requirements on hull structure monitoring.

3.3. One-directional sensor monitoring test

In practical engineering application, the differential FBG sensors need to be installed on column and crossbeam of hull structure, so the monitoring performance of sensors should be tested in detail through the one-directional sensor monitoring test.

Figure 3. One-directional sensor monitoring test: (a) Design of one-directional sensor monitoring test.; (b) Error analysis on the differential FBG sensor and strain gauge.
The hydraulic testing machine was used to simulate the structural response caused by wave load in the mechanical test, as shown in Figure 3. And the steel specimen is adopted to simulate the hull structure. During the mechanical test, the specimen was fixed on the testing machine firstly. Then, the FBG strain sensor was installed on the specimen, and the strain gauge was also pasted on the specimen under the frame of differential FBG sensor to observe the measurement difference between the FBG strain sensor and strain gauge. When the designed force using the hydraulic testing machine was applied on the specimen, the structural strain was monitored by two kinds of monitoring sensors. Through observation on the results of one-directional sensor monitoring test, it is found that the monitoring by two kinds of sensors have good linearity. But they have different errors compared with the theoretical value. Figure 3(b) show the relative error using FBG strain sensor and strain gauge. Obviously, the relative error of FBG sensor is smaller than that of strain gauge at the high and low pressure conditions. Especially in the violent strain, the one-directional sensor monitoring using the FBG sensors is more reliable.

3.4. Three-directional sensor monitoring test
Fiber Bragg Grating sensor can obtain high reliability data when measuring unidirectional tension and compression. In fact, the hull structure not only suffers tension and compression deformation, but also some bending deformation. In the stress monitoring of hull structures with complicated wave loads, the three-dimensional strain sensor arrangement is often used to obtain the composite stress[17]. And the corresponding strength theory is also applied to evaluate the hull structure strength. Thus, the three-directional sensor monitoring test was taken, as shown in Figure 4(a).

![Figure 4. Three-directional sensor monitoring analysis: (a) Design of the three-directional sensor monitoring test; (b) Finite element calculation on steel plate.](image)

In order to compare the test results with the theoretical values, the finite element model about rigid steel plate was established, and the surface pressure was used to load this steel plate. Figure 4(b) show the stress distribution of steel plate under designed pressure. Obviously, the stress concentration occurs near the applied point of pressure. The stress decreases gradually as it expands around. Figure 5(a) shows the relationship between the measured and theoretical values of Mises stress with the different external load. It is found that the measured values deviate from the theoretical values gradually with the external pressure increasing. In fact, when the hull structure is suffering bending deformation, the bottom of differential FBG sensor frame will rotate inward. And the bracket of FBG sensor frame also incline inward under the influence of bending moment. Thus, the extrusion force at cross-beam increases, as shown in Figure 5(b). With the external load increasing, the inclination angle becomes more obvious, and the measured values deviate from the theoretical values more remarkable. It is suggested that some monitoring errors of differential FBG sensor rise with the large pressure loading. Through analysis on the reason caused monitoring error, the differential FBG sensor is revised. The height of sensor bracket is modified and reduced by a third in the improved plan I. Also, the height of sensor bracket is reduce by half in the improved plan II. The same sensor experiments are
repeated. Figure 6(a) shows the relationship between the measured and theoretical values of the improved sensor with different external load. It is found that the coincidence between the measured and theoretical values of improved sensor is much higher with the sensor bracket height decreasing. Figure 6(b) also shows the distribution of measurement errors before and after this improvement. Obviously, with the implementation of improved plan, the relative error of differential FBG sensor decreases gradually. The relative error is reduced by 3.24% in the large pressure case. It is indicated that the improvement for differential FBG sensor can increase monitoring accuracy effectively. The max relative error of revised sensor is less than 2.50%, which also meets the requirements of structural monitoring.

Figure 5. Results and analysis of three-directional sensor monitoring: (a) Results of three-directional sensor monitoring test; (b) Differential FBG sensor under bending deformation.

Figure 6. Results and error distribution of three-directional sensor monitoring after improvement: (a) Results of three-directional sensor monitoring revised test; (b) Error distribution on the improved differential FBG sensor.

4. Conclusion
The application of FBG sensing technology in stress monitoring towards hull structure is studied by a series of sensor tests. The test results show that the differential FBG strain sensor has high accuracy and good linearity on structural measurement, compared with the traditional strain gauge. And the defects of three-dimensional FBG sensor used in bending stress measurement are analyzed and improved. Finally, the improved three-dimensional fiber Bragg grating strain sensor is verified effectively and can be used to monitor the complex stress state of hull structure.

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