A High-Frequency Acceleration Sensor for Monitoring Sloshing Response of Ships

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Abstract: This article introduces a high-frequency acceleration sensor for monitoring sloshing response of ships. The ship is not only threatened by the external environment during the voyage. At the same time, the hull will sway when the frequency of movement in the waves approaches the natural frequency of the liquid in the tank, thereby seriously damaging the hull structure. Therefore, it is necessary to monitor the acceleration outside the hull in real time and respond in time according to the situation. The sensor will move relative when the sensor is installed on the ship and subjected to external acceleration, and the optical fiber connected between the bosses will be stretched or compressed accordingly, both of which change the center wavelength of the Fiber Bragg grating (FBG). The magnitude of the acceleration experienced by the vessel will show the change in wavelength on the displacer through the fiber grating. The sensor is designed to face the harsh natural environment of marine ships, which can realize automatic real-time monitoring of acceleration and ensure the safety of the ship during sailing.

Keywords: Sloshing response, Fiber Bragg Gratings, High-frequency acceleration sensor

1. Introduction

As a large-scale transportation tool, marine ships have the advantages of huge cargo capacity and low transportation costs, which ensures the demand of marine ships in daily use. However, many risks and challenges faced by maritime vessels in transportation contrast sharply with their advantages. For example, strong winds and waves, collisions between reefs and ships may pose a serious threat to ships [1]. In view of these various unexpected circumstances, it can be found that the subjective judgment of the ship operator alone is not reliable. Various sensors have been developed to monitor the vibration, stress, hydraulic pressure and other indicators of the ship during sailing to protect the safety of the ship.

It is worth mentioning that the threats a ship faces during navigation not only come from the external natural environment, but also from the inside of the ship. Sloshing generally occurs when the hull's motion frequency in waves is close to the natural frequency of the liquid in the ship's tank. The sloshing response will cause the liquid to violently impact the internal structure of the hull, which will seriously threaten the ship's navigation safety. It is therefore particularly important to design a sensor that can monitor the ship's sloshing response.

Over the years, with the burgeon of optical communication technology and optical fiber technology, fiber is used as a sensitive means of optical fiber sensing technology has made great progress. Compared with traditional piezoelectric sensors, fiber grating sensors has a small volume, large amount of sensing information, corrosion resistance, high temperature resistance, and electromagnetic interference resistance, and easy formation of sensing networks. Fiber grating sensors are more suitable for harsh natural environments, such as marine vessels. Currently, fiber grating sensors are widely used in the measurement of physical quantities such as stress, acceleration, pressure, and temperature [2]. In the field of acceleration monitoring, the sensor for monitoring the sloshing response of the ship needs further research and improvement. To this end, a new type of fiber grating high-frequency acceleration sensor is proposed.

2. Theory

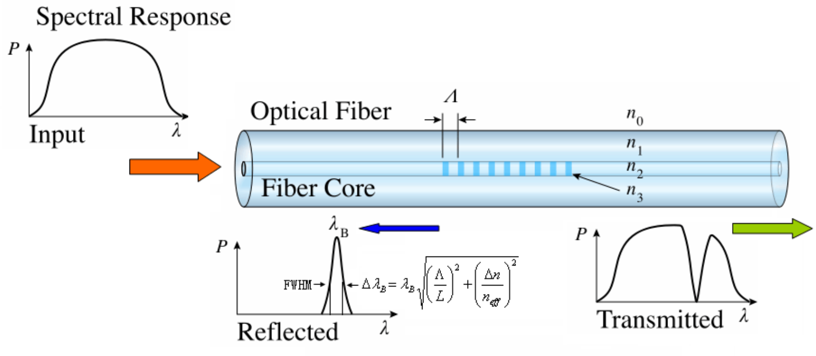

Fig.1 Reflection and Transmission Spectrum of FBG

FBG actually formed in the narrow-band filter or reflective fiber core. Figure 1 shows that when a beam of light passes through FBG, except for broadband light, there is no obvious attenuation of light at other wavelengths. Only broadband light will manufacture mode coupling [3] , while light that meets the Bragg condition is reflected back to the incident end, and its reflection spectrum is a narrow-band spectrum, and its central wavelength satisfies the formula:

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

where Λ represents the grating period. n_{eff} represents the effective refractive index of the fiber core region; λ_B represents the center wavelength of the FBG;

Alters in temperature and strain on the fiber grating will result in the effective refractive index n_{eff} of the fiber core and the center wavelength λ_B of the FBG to change [4]. According to formula (1), the impact of these changes can be calculated using the following function:

$$\Delta\lambda_B = 2\left(\Lambda\frac{\partial n_{eff}}{\partial l} + n_{eff}\frac{\partial\Lambda}{\partial l}\right)\Delta l + 2\left(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial\Lambda}{\partial T}\right)\Delta T \tag{2}$$

where the first part shows the wavelength, drift caused by the axial strain, which is determined by the refractive index change due to elastic light effect and the alter of the fiber grating period Λ. Therefore, the wavelength drift caused by axial strain can also be presented as:

$$\Delta\lambda_B = \lambda_B(1 - p_e)\Delta\varepsilon \tag{3}$$

In the function, p_e is the effective elasticity coefficient of FBG. For the FBG whose grating core is usually ordinary germanium-doped quartz, $p_e \approx 0.22$ [5].

In the function (2), the second part represents the wavelength drift due to the changes of temperature, which is the wavelength drift caused by the grating period and refractive index changes caused by thermal expansion. Wavelength drift due to temperature changes can be presented as:

$$\Delta\lambda_B = \lambda_B(a_\Lambda + a_n)\Delta T \tag{4}$$

where a_Λ represents the thermal expansion coefficient of the fiber. For germanium-doped fibers, $a_\Lambda = 0.55 \times 10^{-6}$, a_n represents the thermo-optic coefficient of the fiber. For germanium-doped fibers, it is about 8.6×10^{-6}.

To prevent the sensor measurement process from being disturbed by temperature changes, the sensor network uses the reference grating method to perform temperature compensation[6].There are two fiber gratings in the sealed box, one is affixed between the two bosses of the sensor and is simultaneously affected by the temperature and strain; the other is stuck on the inside of the sealed box wall and is only affected by the temperature change. Link the pigtails of the two optical fibers to the demodulator and record the readings of their center wavelengths. Assuming that the offsets of the center wavelengths of the two gratings are $\Delta\lambda_1$ and $\Delta\lambda_2$, these two offsets can be presented as:

$$\Delta\lambda_1 = \Delta\lambda_1(\Delta\mathrm{T}) \tag{5}$$

$$\Delta\lambda_2 = \Delta\lambda_2(\varepsilon, \Delta\mathrm{T}) \tag{6}$$

With this temperature compensation method, the effects of temperature changes can be separated from the measurement process. This method of temperature compensation is not only cheap and easy to realize, but also can better separate temperature and strain, which is suitable for use in such a harsh environment as marine vessels [7].

3.High-frequency acceleration sensor structure

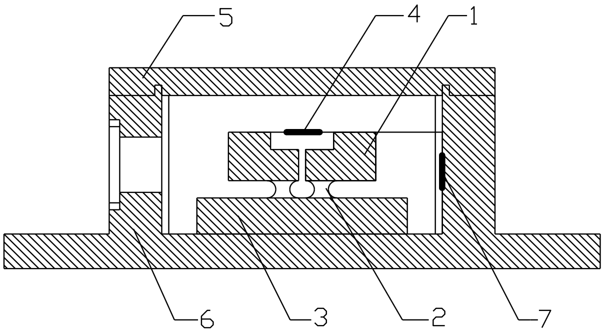

Fig.2 Fiber grating high-frequency acceleration sensor plan view

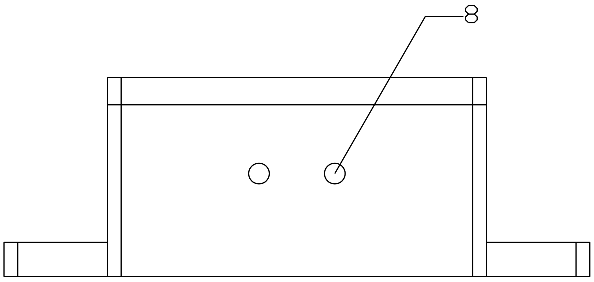

Fig.3 Fiber grating high frequency acceleration sensor front view

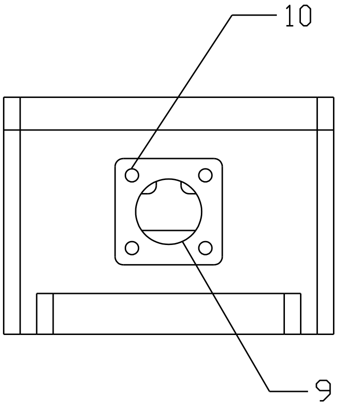

Fig.4 Fiber grating high-frequency acceleration sensor side view

The fiber grating high-frequency acceleration sensor used for ship sloshing response monitoring is composed of fixed part, sensitive part and sealed part.

The fixing part includes an optical fiber sticking boss, a sensor base, and a lateral fixing hole. The two ends of the optical fiber are respectively attached to the bosses on both sides. When the sensor is subjected to external acceleration in the up and down direction, the circular hinge drives the mass block including the adhesive boss to move, and the optical fiber is deformed accordingly. The sensor base passes four screws. The hole and the watertight box are fixed to ensure that the sensor and the watertight box are relatively stationary. The horizontal fixing holes are located on both sides of the watertight box. After the package is completed, the thimble is inserted through the fixing hole to ensure that the sensor will not have excessive lateral displacement during the movement. Reduce lateral interference.

The sensitive part consists of a circular hinge, a fiber grating, and a temperature-compensated grating. There are a total of four circular hinges. The mass block containing the optical fiber sticking boss connected to sensor base by a hinge. The mass blocks on both sides will be displaced in different directions from left to right when the sensor is subject to acceleration in the up and down direction, so that the corresponding extension or compression of the FBG; the deformation and wavelength variation of FBG are approximately linear. The compensation algorithm of the demodulator can be used to discover the wavelength of the FBG and the sway response of the ship structure. As the ratio changes, the external acceleration experienced by the hull structure will be displayed in the form of a wavelength change through the FBG on the demodulator side. The temperature compensation grating is affixed to the inside of the watertight box. It is only affected by temperature changes and not affected by acceleration. Temperature compensation can be achieved through a compensation algorithm to remove the passive influence of temperature on the acceleration measured by the sensor.

The sealing part includes a watertight box cover, a watertight box body, an optical fiber waterproof aerial jack, and an optical fiber waterproof aerial plug fixing hole. The watertight box cover and the watertight box body form a watertight box. The sensor is fixed inside by a screw hole. The connection between the box cover and the box body is sealed with a rubber ring in the sealing groove to ensure that the entire watertight box is completely sealed. It is not affected by seawater erosion and other external conditions; the optical fiber waterproof aerial jack and the optical fiber waterproof aerial plug fixing hole are located on the side of the watertight box. It is designed to access the optical fiber waterproof aerial plug, and the optical fiber is connected to the demodulation through the waterproof aerial plug. Instrument to ensure that the fiber optic exit is also protected by watertightness.

4.Experimental process

The sensor is simulated and tested by ANSYS simulation software [8]. The sensor simulation structure is shown in Figure 5.

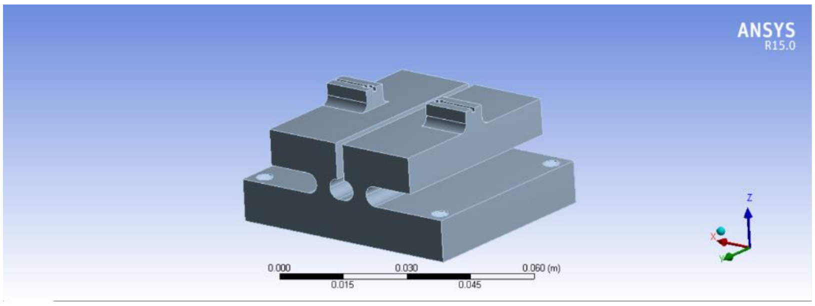

Fig.5 ANSYS simulation structure

The sensor is first modal analyzed. The sensor material is set to beryllium bronze, because beryllium bronze not only has good elastic properties and elastic recovery ability, but also is easy to process and resistant to corrosion. It is suitable for use in harsh natural conditions in the ocean. Before the modal analysis, the sensor structure needs to be meshed. Considering the complexity of the meshing of the sensor hinge, intelligent meshing is used in this experiment. The specific partitioning is shown in Figure 6 below:

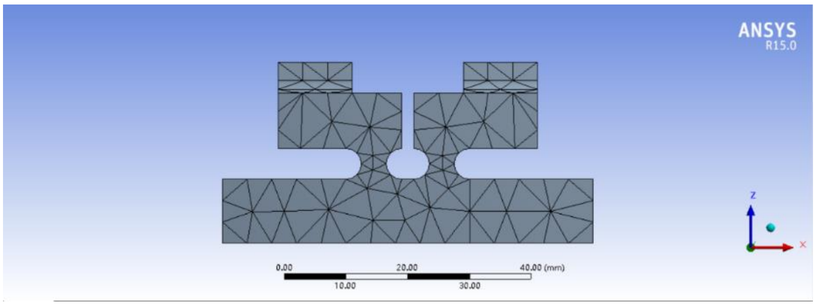

Fig.6 Sensor structure meshing

Constraints need to be placed on the sensors after meshing. After constraining the bottom surface of the sensor to ensure that there is no lateral interference during the modal analysis, the modal analysis of the sensor is shown in Figure 7:

	Mode	☑ Frequency [Hz]
1	1.	3079.4
2	2.	3100.8
3	3.	8758.2
4	4.	8877.9
5	5.	10700
6	6.	10888

Fig.7 Modal analysis results

From the results of the above modal analysis, it can be known that the natural frequency of the sensor structure is 3079.4HZ, such a result fully meets our expected needs for designing the sensor.

The static analysis of the sensor is to determine the strain of the sensor by imposing various constraints on the sensor. The first few steps of the static analysis are the same as the modal analysis, and you need to set up the sensor material and mesh. Set an additional acceleration of 20G to the sensor, and fix the bottom surface so that the sensor base will not be displaced under acceleration. The sensor strain under acceleration is shown in the following figure:

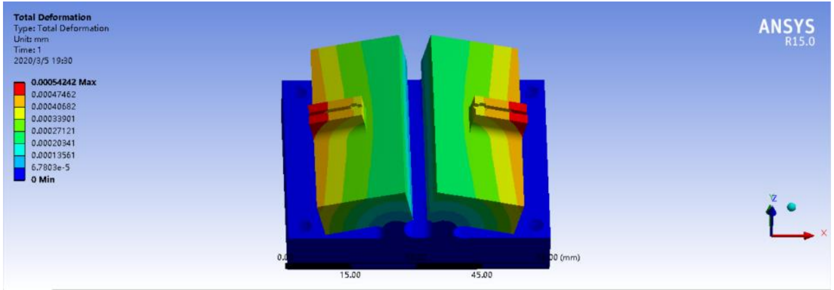

Fig.8 Sensor Static analysis

From the results of the static analysis combined with the calculation formula of microstrain, it can be obtained that the sensor generates about $37.6\mu\varepsilon$ under the acceleration of 20G, and the sensitivity of the sensor can be estimated by the formula to be about $2.26pm/\mu\varepsilon$, which is in line with the Claim.

5.Conclusion

The high-frequency acceleration sensor developed in this study is used to monitor the sloshing response of a ship. The optical fiber connected between the sensor bosses will be deformed accordingly when the sensor is installed on the ship and subjected to external acceleration. Further, the center wavelength of the FBG increases. Thus, the magnitude of the acceleration experienced by the ship will be displayed on the demodulator through FBG wavelength shift. The sensor has a compact structure and can be installed in a small space on a ship without occupying the working space on the ship. According to the results of simulation experiments, the sensor has excellent performance. Structure or building. The sensor uses the reference grating method for temperature compensation to ensure that the sensor can effectively separate the interference of temperature changes on the measured value of the sensor during the measurement process. The sensor is provided with a completely sealed watertight box, and the fiber end is also protected by the fiber optic waterproof plug, which ensures the watertightness of the entire sensor system and the reliability and stability when used on marine vessels.

Acknowledge

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