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A novel ice-pressure sensor based on dual FBGs

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ABSTRACT

Ice pressure is one of the most important loads in high-latitude area. It is challengeable to build a durable and stable real-time structural health monitoring system for ice-pressure under such aggressive environment as windiness, coldness, and even vibrating, which can not be met by strain gauge based sensors, whereas FBG fits it well due to its great advantage of corrosion resistance, absolute measurement, high accuracy, electro-magnetic resistance, quasi-distribution sensing, absolute measurement and so on. In this paper, a novel FBG based ice-pressure sensor has been developed. Firstly, in consideration of the monitoring of ice-pressure of offshore platform, a novel ice pressure sensor structure has been designed and it sensing principle is given in details, which theoretically shows the properties of temperature self-compensation and independence of the load position. And secondly, the properties of FBG-based ice-pressure sensor have been tested by experiments. Finally, theoretical sensitivity has been compared with that from experiments. The research results show that the FBG-based ice-pressure sensor has good linearity, repetition, immunity of temperature changes and loading position. Such kind of FBG-based ice-pressure sensor can be used to monitor ice load of offshore platform conveniently.

Key words: FBG, temperature self-compensation, ice-pressure sensor, structural health monitoring, offshore platform

1. INTRODUCTION

Ice pressure is an important load of the offshore platforms and even bridges across rivers in the high-latitude area. Many offshore platforms were damaged by ice pressure, even collapsed. The 2# exploitation platform in Bo Hai oil field in China was push over by ice in winter, 1986. Ice-pressure data is the base of design of offshore structures. Moreover, due to that ice-pressure is also the main factor of fatigue accumulative damage, it is important to get long–term information of ice-pressure to evaluate the safety and integrity of offshore structures. Traditional ice-pressure monitoring device is based on electrical strain gauge, which is easy to be damaged by moisture, corrosion, electro-magnetic disturbance and so on. So, it is very important to develop reliable sensors for monitoring of ice-pressure.

Optical fiber sensors, especially the fiber Bragg grating (FBG) sensors, have more and more become the focus for strain sensor in structural health monitoring due to their distinguishing advantages: electro-magnetic resistance, small size, resistance to corrosion, multiplexing a large number of sensors along a single fiber, etc. Fiber Bragg grating sensor is suitable for the measure of ice force. FBG strain sensor has now been widely investigated and applied in infrastructures (Ou and Zhou, 2002, 2003, 2004). Some researchers have studied and developed FBG strain sensing based pressure sensors (Zhang, 2001; Zhao, 2002, 2004). However, FBGs are sensitive to both strain and temperature, and thus temperature compensation technique is unavoidable for practical engineering application of strain sensing based sensors. Common methods to distinguish the cross-sensitivity between strain and temperature depend on additional gratings and special technique (Zhou, 2004; Zhang, 2001). As for ice pressure sensor, moreover, the position of ice load, which is sometimes huge, changes along the sea level, so we must make the ice-pressure sensor adaptive to or independent of the changes of loading position.

In consideration of the monitoring of ice-pressure of offshore platform, a novel ice pressure sensor structure has been designed and its sensing principle is given in details. And the properties of FBG-based ice-pressure sensor have been tested by experiments and analyzed theoretically.

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2. SENSOR STRUCTURE AND BASIC SENSING PRINCIPLES

2.1 Sensor structure

To meet the demand of ice-pressure monitoring of platform, the sensor structure should show: 1) Easy for construction; 2) Pressure sensing without additional temperature compensation, namely self-compensation; 3) Independent of ice loading position; 4) strong enough for durability; 5) Stability for long-term service, etc. Based on above points, we configured our novel ice-pressure sensor as figure 1.

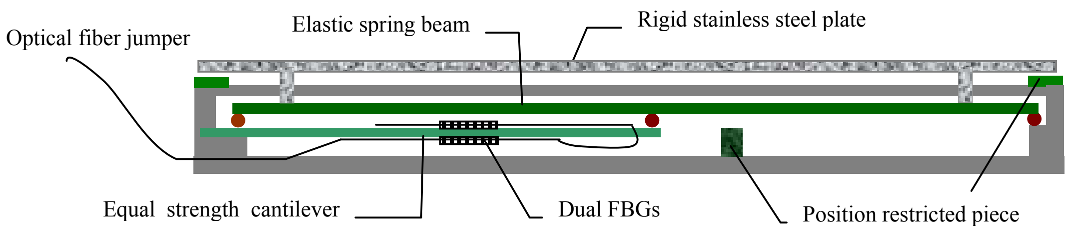


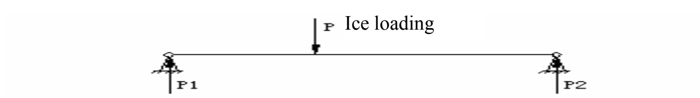
Figure 1: Sketch of novel ice-pressure sensor structure

The novel ice-pressure sensor structure is mainly composed of: 1) Rigid stainless steel plate used to endure ice loading without too much deformation; 2) Elastic spring beam used to transfer the load to displacement which can be sensed by equal strength cantilever; 3) Equal strength cantilever used for sensing the displacement; 4) Position restricted piece used to control the maximum deformation of the load transfer beam, which can assure the whole structure avoidable of too huge ice loading.; 5) Rigid stainless steel box used to protect the whole sensor; 6) dual FBGs used to sense strain of the bilateral cantilever induced by the displacement of mid-point of the elastic spring beam.

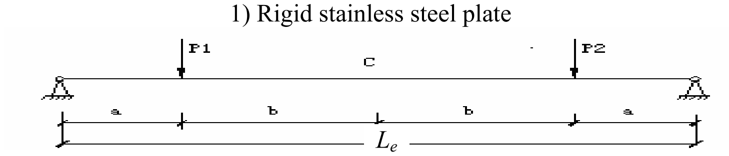
2.2 Sensing principle of FBG-based ice-pressure sensor

The basic sensing principle of the FBG based ice-pressure can be described like that: when ice load acts on the rigid stainless steel plate, the load can be transferred to the elastic spring beam, and the mid-point of the beam will bring displacement to the cantilever, so the strain state of the surfaces of the bilateral cantilever will be changed. The strain can be sensed by the attached FBGs. The strain state of the 2 surfaces is opposite, but same at value. Because the two FBGs are very close to each other, shifts of their Bragg wavelengths due to temperature are considered to be identical. Thus we can get the strain state by differential method by the 2 FBGs. So we can get the ice loading accordingly. The detailed basic sensing principle is following.

(I) Mid-point displacement of elastic spring beam



1) Rigid stainless steel plate



2) Elastic spring beam

Figure 2: Sketches of rigid steel plate and spring beam under ice pressure

Figure 2 shows the sketches of rigid stainless steel plate and elastic spring beam under ice loading. According to material mechanics theory, the displacements, V_{e1} and V_{e2}, of mid-point of the elastic spring beam under P_1 and P_2, respectively, can be expressed as

$$v_{e1} = \frac{P_1 a(3L_e^{\ 2} - 4a^2)}{48E_e I_e} \qquad v_{e2} = \frac{P_2 a(3L_e^{\ 2} - 4a^2)}{48E_e I_e} \tag{1}$$

where L_e, E_e and I_e is the length, Young module and inertia moment of elastic spring beam, respectively. So we can find that

$$v = v_1 + v_2 = \frac{P\,a(3L_e^{\ 2} - 4a^2)}{48E_e I_e} \tag{2}$$

which shows that displacement of the mid-point of spring beam is independent of ice loading position. So once the a is given, the displacement is linear to ice load.

(ii) Expression of bilateral equal strength cantilever under displacement

Generally speaking, the span of the equal strength cantilever beam (L_C) *is* bigger than height (H_C), over 10 times, and the cantilever is mainly under micro bending deformation, so we can neglect shear force and the beam satisfies the hypotheses of plane section. So the relationship between strain (ε) and end point displacement (v) of the cantilever can be given as

$$V = \frac{L_C^2}{H_C}\varepsilon \tag{3}$$

Here, the end point displacement (v) is equal to that of mid-point of spring beam. The expression shows that the strain of cantilever is linear to the displacement of mid-point of elastic spring beam.

(iii) Interaction of cantilever and elastic spring beam

Given that the cantilever is acted by end point displacement, v, we can get the stress (σ) of surface

$$\sigma = E_c\varepsilon = \frac{E_c H_c v}{L_c^2} \tag{4}$$

According to the loading feature of the cantilever, the load F acting on the end point is

$$F = \frac{E_c H_c^3 B_c v}{6L_c^3} \tag{5}$$

where B_c is the width of the fixed end of the cantilever. So the displacement (v_{cr}) of the spring beam acted by above F can be given as

$$v_{cr} = \frac{B_c H_c^3 L_e^{\ 3} E_c}{288 L_c^3 E_e I_e} v \tag{6}$$

In general, considering of the interaction of cantilever and elastic spring beam, combining (2) and (6), we can get

$$v = \frac{Pa(3L_e^{\ 2} - 4a^2)}{48E_e I_e} - \frac{B_c H_c^3 L_e^{\ 3} E_c}{288 L_c^3 E_e I_e} v \tag{7}$$

So we can get

$$P = (1 + \frac{B_c H_c^3 L_e^{\ 3} E_c}{288 L_c^3 E_e I_e}) \cdot \frac{48E_e I_e}{a(3L_e^{\ 2} - 4a^2)} v \tag{8}$$

Above expression is the general relationship between ice load and displacement of end point of cantilever.

(IV) Relationship between ice pressure and FBG wavelength

According to FBG technology, the general expression of the 2 FBGs attached on the bilateral cantilever , one up and the other down, acted by strain and temperature can be described as

$$\frac{\Delta\lambda_1}{\lambda_1} = \frac{\Delta\lambda_{\varepsilon 1}}{\lambda_1} + \frac{\Delta\lambda_{T1}}{\lambda_1} = (1-P_e)\varepsilon_1 + (\alpha+\varsigma)\Delta T_1 \tag{9}$$

$$\frac{\Delta\lambda_2}{\lambda_2} = \frac{\Delta\lambda_{\varepsilon 2}}{\lambda_2} + \frac{\Delta\lambda_{T2}}{\lambda_2} = (1-P_e)\varepsilon_2 + (\alpha+\varsigma)\Delta T_2 \tag{10}$$

where λ, ζ, α, P_e and T is wavelength, thermal-optics coefficient, thermal expansion coefficient, optical elasticity coefficient and temperature, respectively. And the sign, 1 and 2, is to show the different 2 FBGs. Here $\Delta T_1 = \Delta T_2$, and considering the strain feature of the cantilever, we can get

$$\frac{\Delta\lambda_1}{\lambda_1} - \frac{\Delta\lambda_2}{\lambda_2} = 2(1-P_e)\varepsilon \tag{11}$$

Combining (3), (8) and (11), we can get

$$P = \left(1 + \frac{B_c H_c^3 L_e^3 E_c}{288 L_c^3 E_e I_e}\right) \cdot \frac{48 E_e I_e}{a(3L_e^2 - 4a^2)} \frac{L_c^2}{2(1-P_e)H_c} \cdot \left(\frac{\Delta\lambda_1}{\lambda_1} - \frac{\Delta\lambda_2}{\lambda_2}\right) \tag{12}$$

Let $K = \left(1 + \frac{B_c H_c^3 L_e^3 E_c}{288 L_c^3 E_e I_e}\right) \cdot \frac{48 E_e I_e}{a(3L_e^2 - 4a^2)} \frac{L_c^2}{2(1-P_e)H_c}$, then

$$P = K \cdot \left(\frac{\Delta\lambda_1}{\lambda_1} - \frac{\Delta\lambda_2}{\lambda_2}\right) \tag{13}$$

(V) Simplification of the FBG-based ice-pressure sensing expression

Considering the practical engineering application, if force induced by the cantilever is very small, which means that $\frac{B_c H_c^3 L_e^3 E_c}{288 L_c^3 E_e I_e} \ll 1$; and the original wavelength of the 2 FBGs is the same or close enough, above expression can be changed to

$$P = K(\lambda_1 - \lambda_2) \tag{14}$$

where $K = \frac{48 E_e I_e}{a(3L_e^2 - 4a^2)} \times \frac{L_c^2}{2(1-P_e)\lambda H_c}$

3 EXPERIMENTS AND ANALYSIS

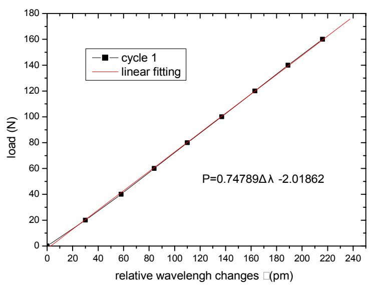
3.1 Sensor model fabrication

Considering the aggressive environment where the ice-pressure sensor will serve, we chose proper materials and optimized the size of the FBG-based ice pressure sensor. Here, the rigid stainless steel plate is made of high strength stainless alloy; the elastic spring beam and equal-strength cantilever are from spring stainless steel which show properties of high fatigue and corrosion resistance; And the protective box must be strong enough to support the structure of the ice-pressure sensor. Dual FBGs are bonded by high performance glue named J133. The fabricated FBG-based ice pressure sensor is depicted as figure 3.

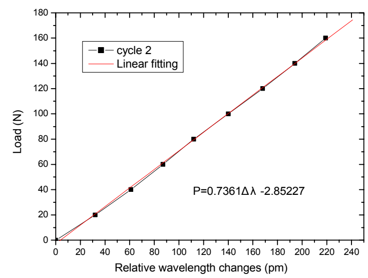
Figure 3: Picture of FBG-based ice pressure sensor

3.2 Calibration experiments

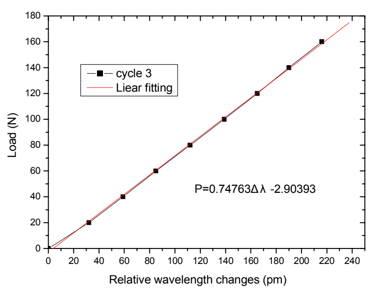
In order to test the reliability of the ice-pressure sensor, we fixed it on an experimental table. The load is given through mass pieces, and the wavelength is monitored by SI425 provided by Micron Optics Inc. in USA. The data of load and wavelength of the 2 FBGs were recorded simultaneously. The 4 cycles data of relative wavelength changes and load are given as figure 4 a) ~e).



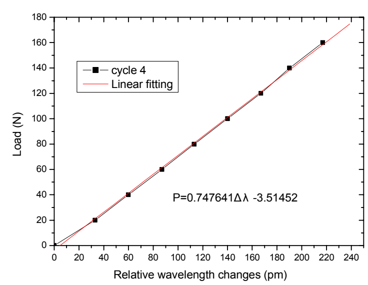
a) Cycle 1



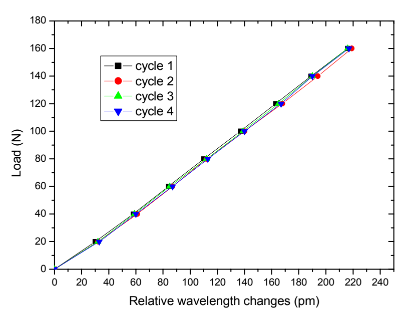
b) Cycle 2



c) Cycle 3



d) Cycle 4



e) Comparison of the 4 cycle data.

Figure 4: Relative wavelength changes and load relationship of the ice pressure sensor

From figure4 a)~e) we can find that the FBG-based ice pressure sensor shows good linearity and repetition, and the sensing coefficient is stable to be 0.74 *N/Pm* or so, which shows that such kind of sensor is good enough for practical engineering application.

3.3 Loading position experiments

In order to test the stability of the ice-pressure sensor under different position loading, we carried out above experiments by changing the loading positions. And the data of relative wavelength changes and load under different position is given as figure 5.

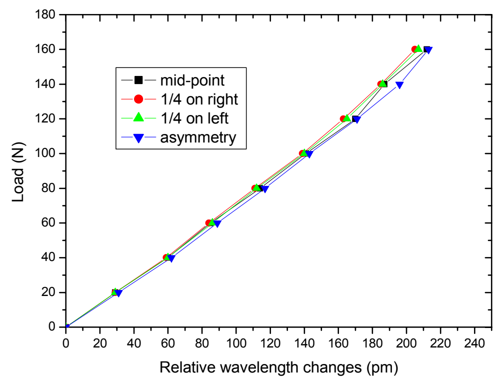


Figure 5: Comparison of ice-pressure sensor under different position loading

From figure 5 we can find that the relationship between relative wavelength changes and load under different position agrees well, which shows that the ice-pressure sensor is independent of the style and position of ice-pressure loading.

3.4 Temperature self-compensation experiments

In order to test the stability of the ice-pressure sensor under different temperatures, we carried out above experiments by changing the temperatures. And the data of relative wavelength changes and load under different temperature is given as figure 6.

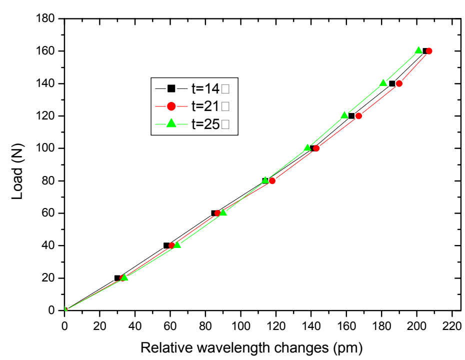
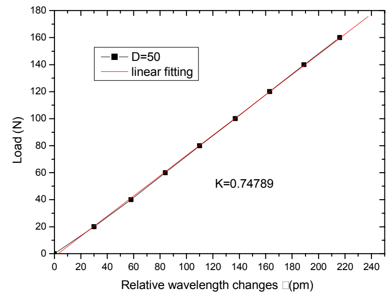


Figure 6: Comparison of ice-pressure sensor under different temperature

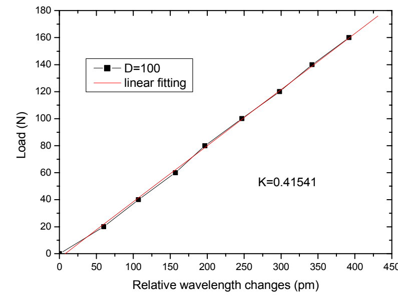
From figure 6 we can find that the relationship between relative wavelength changes and load under temperature agrees well, which shows that the ice-pressure sensor is independent of temperature. So the dual FBG-based ice-pressure sensor shows independent of temperature, namely temperature self-compensation.

3.5 Experiments of ice-pressure sensor under loading at different span (D)

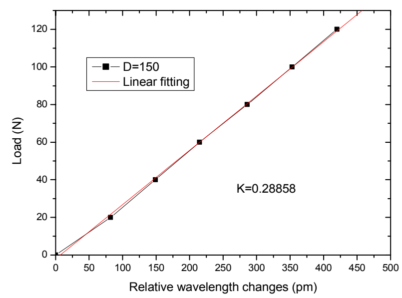
According to (12) and (14), the coefficient of load and relative wavelength changes is affected seriously by the span of the 2 acting points depicted in figure 2 , which means $D = (L_e - 2b)/2$. In order to test the relationship between D and coefficient K, the experiments of ice-pressure sensor under loading by changing the loading span have been carried out. The comparison of relationship between relative wavelength changes and loading under different D is given as figure 7.



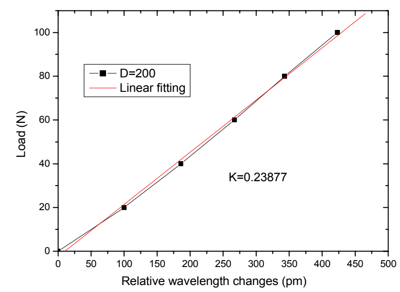
a) D=50 mm



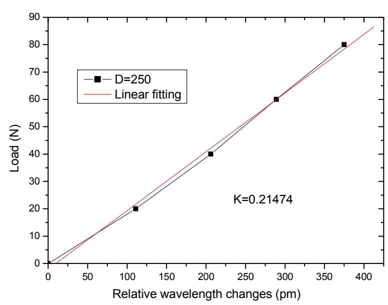
b) D=100 mm



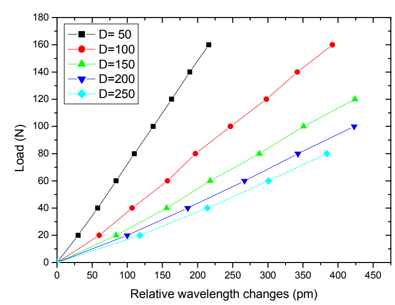
c) D=150mm



d) D=200mm



e) D=250 mm



f) Comparison

Figure 7: Comparison of relationship between relative wavelength changes and loading under different D

From figure 7, we can find that the relationships are very different between relative wavelength changes and loading of different D, which shows: the less for the D, the bigger for K. And linearity is also much better. So we can change the resolution or accuracy easily by changing the loading span of D. Here, if we choose D=50, 100, 150, 200 and 250 mm, respectively, the K is 0.75 *N/pm*, 0.42 *N/pm*, 0.29 *N/pm*, 0.24 *N/pm* and 0.21 *N/pm*, respectively.

4 COMPARISON OF THEORECTIC AND EXPERIMENTAL RESULTS

As for the fabricated FBG-based ice pressure sensor, the basic parameters are following:

$$L_e = 600mm\,,\quad B_e = 50mm\,,\quad H_e = 4mm\,,\quad E_e = E_c = 2.0\times 10^5 N/mm^2\,,$$

$$a = 50mm\,,\ P_e = 0.22mm\,,\ \lambda = 1537.372nm\,, H_c = 4mm\,,\ L_c = 300mm$$

Using (13), we can get the theoretical $K_{theory} = 0.6788$ *N/pm*, where as the average experimental value is $K_{\exp} = 0.74418$ *N/pm*, so the error is

$$\frac{K_{theory} - K_{\exp}}{K_{\exp}} = \frac{0.74418 - 0.6788}{0.74418} = 0.087 = 8.7\%$$

The results from theory agree well with that from experiments. And the error is acceptable by practical engineering application.

5 CONCLUSIONS

It is very important to develop reliable sensors for monitoring of ice-pressure for offshore platform. A novel ice pressure sensor has been designed and its sensing principle is given in details. Moreover, the sensing properties of FBG-based ice-pressure sensor have been tested by some experiments. The researches results show that the novel FBG-based ice pressure is independent of loading position and temperature changes, and has good linearity and repetition. Its resolution and accuracy can be adjusted according to the practical engineering need. Such kind of FBG-based ice-pressure sensor can be used to monitor ice pressure of offshore platform conveniently.

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