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STUDY ON A NOVELTY WIND PRESSURE MONITORING TECHNOLOGY IN CIVIL ENGINEERING INFRASTRUCTURE

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ABSTRACT

As an important part of structural health monitoring, monitoring the wind load of structure timely and accurately not only can enhance study on the structural wind engineering, but also help evaluation and pre-warning on serviceability and safety of the structure in service under wind loading condition. Presently, there are two major measures for wind loading monitoring. The first one is wind speed monitoring, which suffers a demerit on poor ability to obtain the ideal information of wind field by measured data for real structure. The second one is wind pressure monitoring, which measured the wind pressure on the surface of structure directly for testing structural model. Compared with wind speed monitoring, wind pressure monitoring of structural surface, which acts as a direct wind load measure, can reduce some intermediate links. Whereas, some difficulties in the arrangement of pipes and wires, the installation of instruments, and the shakedown test of the whole system have hindered the application of wind pressure monitoring on real structure and prevented us from obtaining the high-quality information of wind field. In view of this situation, this paper will develop a novelty system of wind pressure and wind attack angle monitoring technology which centralized with the wind pressure sensor based on Fiber Bragg Grating techniques. The proposed technology is expected to serve as a standard configuration of civil engineering structural monitoring and provide a technical support for the onsite measurement for the study of structural wind engineering, so as to compensate for the lack of on-site wind pressure monitoring techniques.

KEYWORDS

Civil engineering structure, wind load, structural health monitoring, wind pressure, Fiber Bragg Grating wind pressure sensor.

INTRODUCTION

In the face of the requirement for monitoring the wind load of a large number of structures, simple and high-quality on-site wind pressure monitoring techniques are needed. Due to the poor quality and installation difficulty on the real structures, the present wind speed and wind pressure measuring devices are unsuitable in the onsite structures. In order to overcome difficulties in the field of wind loading monitoring techniques, and to obtain high quality of the measured wind pressure on the surface of the structures, this paper developed a novelty wind pressure sensor and an onsite wind pressure measurement system based on Fiber Bragg Grating (FBG) sensing technology. The wind pressure sensor is ingenious with small size, concise in inner display, and easy to install on the surface of target structure. It can monitor positive and negative wind pressures, fluctuating pressures and wind angles at the same time. The wind pressure sensor also has all the advantages of the optical fiber sensing technology because it uses FBG as sensing element, works normally in harsh and extreme environment such as environment with strong electromagnetic interference, rain and high temperature. In this paper, the static performance of the structure is studied, which aims to lay the groundwork for research on phase of trial-produce.

DESIGN AND OPERATING PRINCIPLE OF FBG WIND PRESSURE SENSORS

Design of Wind Pressure Sensor

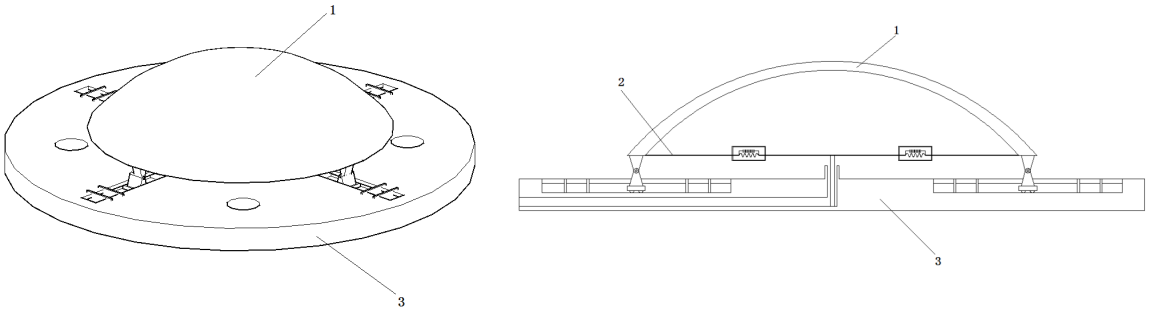
As shown in figure 1, the FBG wind pressure sensor (patent license number: ZL201320012780.2) includes the structural system, the sensing system and the displacement restricting system.

Four blocks of the structural system are fixed to the bottom of the thin spherical shell in symmetrically and orthogonally and the blocks are hinged with sliding support belonging to the displacement restricting system.

Corrosion preventive measures are adopted to the thin spherical shell, in order to ensure that the sensor has a much longer service life.

The connection of the sensing system and the displacement restricting system is achieved through the four dowel bars connecting to the four sliding support. Four dowel bars are in cross and the intersection is fixed on the locating rod which is inserted into the total line pipe. Four dowel bars and sensing element are connected in series.

According to the design of wind pressure sensor, it not only can monitor positive and negative wind pressures, fluctuating pressures, but also can measure wind angles at the same time. Compared with general sensors, wind pressure sensors can achieve spatial resolution with high accuracy, wide linear range output, wide band and high signal-to-noise ratio, and work normally in harsh and extreme environment such as environment with strong electromagnetic interference, rain and high temperature with fiber grating as the main sensing element.



1- structural system 2-sensing system 3- displacement restricting system

Figure 1. Structure of wind pressure sensor

Operating Principle of the Wind Sensor

Scholars at home and abroad have studied on the FBG for many years. According to their research, considering elastic-optic effect and waveguide effect, the sensitivity of the FBG to transverse stress is much lower than that to axial stress. So, under the complex stress, we usually only consider the wavelength change caused by axial stress. The central wavelength shift of FBG has good linear relationship with axial strain and temperature respectively. Suppose the influence of the strain and temperature to the wave change are independent, under the influence of the two factors, the central wavelength shift of the FBG is shown as follows:

$$\frac{\triangle\lambda_B}{\lambda_B} = \left(\alpha_f + \xi\right)\triangle t + \left(1 - p_e\right)\triangle\varepsilon \tag{1}$$

In the formula, λ_B is the wavelength of the FBG; α_f is the intrinsic coefficient of thermal expansion of FBG; ξ is the thermo-optical coefficient of FBG; p_e is the coefficient of elastic-optic of FBG; $\triangle t$ is the change of temperature; $\triangle\varepsilon$ is the change of strain.

From the Eq. 1 we can find that, as a strain sensor, the FBG has a good linear output. Since the FBG is sensitive to both temperature and strain, we use symmetric orthogonal layout of the FBG to do the temperature compensation and solve the cross-sensitivity problem during the manufacture of the sensor.

The new FBG sensor is based on the mechanical principle of arch. The main structure of the sensor is the thin spherical shell, which can bear the wind pressure directly. The deformation of the thin spherical shell makes the spring extend or contract, which can be used to solve the function relationship of the wind pressure and the change of the spring length. In this way, we can turn the monitoring of the wind pressure into the monitoring of the strain of the length of the spring. Since the FBG and spring are in parallel connection, the space change of the FBG grid area can be regarded as the change of the spring length. For this reason, this sensor can calculate the wind pressure and wind direction by the FBG monitoring data.

THIN SHELL STATIC ANALYSIS THEORY

As shown in Figure 2, the radius is R, the central angle is α_0, the thickness is h, and the principal radius of curvature in the middle surface is $R_1 = R_2 = R$. The Lame coefficients in the middle surface, H_1, H_2 in Figure 2

are $H_1 = R$ and $H_2 = R\sin\alpha$, respectively. An orthogonal curvilinear coordinate system $\alpha\beta\gamma$ is built. α and β are the principal curves of curvature. γ is a straight normal line pointing towards the convex side.

Geometric Equation

The basic hypothesis of shell theory is adopted. The normal in the middle is perpendicular to the middle surface even after deformation. The line, which is perpendicular to the middle surface, is trivial.

The normal strain ε_1、ε_2 of the points in the middle surface along the α and β directions are as follows:

$$\left.\begin{aligned}\varepsilon_1 &= \frac{1}{R}\left(\frac{du}{d\alpha} + w\right)\\ \varepsilon_2 &= \frac{1}{R}\left(u\cot\alpha + w\right)\end{aligned}\right\} \tag{2}$$

Where u and w are the displacements of the points on the middle surface going through α and γ, respectively. The changes of their principal curvatures χ_1 and χ_2 are as follows:

$$\left.\begin{aligned}\chi_1 &= -\frac{1}{R^2}\frac{d^2w}{d\alpha^2}\\ \chi_2 &= -\frac{1}{R^2}\frac{dw}{d\alpha}\cot\alpha\end{aligned}\right\} \tag{3}$$

The strain e_1 and e_2 of any points in the shell can be expressed as follows:

$$\left.\begin{aligned}e_1 &= \varepsilon_1 + \chi_1\gamma\\ e_2 &= \varepsilon_2 + \chi_2\gamma\end{aligned}\right\} \tag{4}$$

For deep thin spherical shell, from (1.3) we have components of strain of the whole shell's deformation status. For a deep thin spherical shell, the components of the strain that reflect the whole shell's deformation status are obtained according to (1.3).

Physics Equation

On the basis of the basic hypothesis of shell theory, the normal stress parallel to the middle surface's cross section is far less than the normal stress on the cross section. Regardless of its effect to the strain, the following physics equation is obtained:

$$\left.\begin{aligned}\sigma_1 &= \frac{E}{1-\mu^2}\left(e_1 + \mu e_2\right)\\ \sigma_2 &= \frac{E}{1-\mu^2}\left(e_2 + \mu e_1\right)\end{aligned}\right\} \tag{5}$$

The internal forces N_1, N_2, M_1 and M_2 can be described by the mid-surface deformation component as below:

$$\left.\begin{aligned}N_1 &= \frac{Eh}{1-\mu^2}\left(\varepsilon_1 + \mu\varepsilon_2\right)\\ N_2 &= \frac{Eh}{1-\mu^2}\left(\varepsilon_2 + \mu\varepsilon_1\right)\\ M_1 &= D\left(\chi_1 + \mu\chi_2\right)\\ M_2 &= D\left(\chi_2 + \mu\chi_1\right)\end{aligned}\right\} \tag{6}$$

In (1.4) and (1.5), μ is the Poisson's ratio of the shell, D is flexural rigidity, $D = \frac{Eh^3}{12\left(1-\mu^2\right)}$.

According to (1.5), $\varepsilon_1 + \upsilon\varepsilon_2$, $\varepsilon_2 + \upsilon\varepsilon_1$, $\chi_1 + \upsilon\chi_2$ and $\chi_2 + \upsilon\chi_1$, then the following formula is obtained:

$$\left.\begin{aligned}\sigma_1 &= \frac{N_1}{h} + \frac{12M_1}{h^3}\gamma\\ \sigma_2 &= \frac{N_2}{h} + \frac{12M_2}{h^3}\gamma\end{aligned}\right\} \tag{7}$$

From the equations above, it can be seen that in the shell, the stresses caused by film forces N_1 and N_2 are uniformly distributed along the shell thickness. The bending stresses caused by bending moments M_1 and M_2 are distributed in a straight line along the shell thickness.

Equilibrium Equation

By converting the external load into load components X and Z per unit area of middle surface, the following differential equilibrium is obtained by listing all the internal force components' projecting along α and γ and

the projection of axial moment along α and γ.

$$\left.\begin{aligned}&\frac{dN_1}{d\alpha}+\left(N_1-N_2\right)\cot\alpha+Q_1+XR=0\\&\frac{dQ_1}{d\alpha}+Q_1\cot\alpha-\left(N_1+N_2\right)+ZR=0\\&\frac{dM_1}{d\alpha}+\left(M_1-M_2\right)\cot\alpha-Q_1R=0\end{aligned}\right\}\tag{8}$$

Perturbation Solution for Axisymmetric Bending Boundary Value

By substituting geometric equations (1.1), (1.2) into the physics equation (1.5), the elastic equation describing the relationship between internal force and displacement is obtained:

$$\left.\begin{aligned}&\frac{du}{d\alpha}+w=\frac{R}{Eh}\left(N_1-\mu N_2\right)\\&u\cot\alpha+w=\frac{R}{Eh}\left(N_2-\mu N_1\right)\\&M_1=-\frac{D}{R^2}\left(\frac{d^2w}{d\alpha^2}+\mu\frac{dw}{d\alpha}\cot\alpha\right)\\&M_2=-\frac{D}{R^2}\left(\frac{dw}{d\alpha}\cot\alpha+\mu\frac{d^2w}{d\alpha^2}\right)\end{aligned}\right\}\tag{9}$$

Elastic equation (2.1) and the three equilibrium equations (1.7) together with the boundary conditions constitute the boundary value problem of axisymmetric bending of a deep thin spherical shell. Seven unknown functions can be solved in total, including 5 internal forces N_1, N_2, M_1, M_2, Q_1 and 2 displacements u, w.

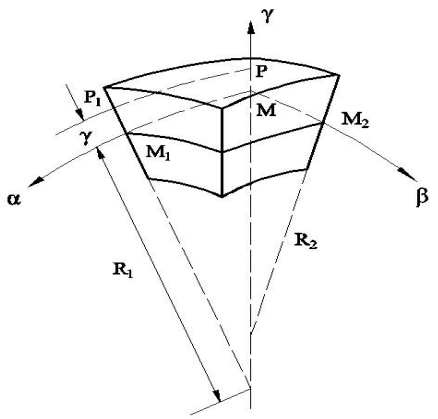


Figure 2. Orthogonal curvilinear coordinate system on the middle surface of a deep thin spherical shell

PARAMETER ANALYSIS OF THE WIND PRESSURE SENSORS

The geometrical parameters and material mechanics parameters of the wind structure are very important to the optimal design of the wind sensor, so it is necessary to do the parameter analysis of the wind structure using the ANSYS finite element software. Select plate element Shell63 to establish the structure model, suppose the maximum design wind speed of the wind sensor is 50m/s. The influence of different parameters (the span of the spherical shell L, the thickness t, the central angle α, the elasticity modulus of the spherical shell E, the Poisson's ratio μ, the elastic constant of the spring Es) to the strain ε of the wind sensor is discussed in the paper.(Figure 3-9):

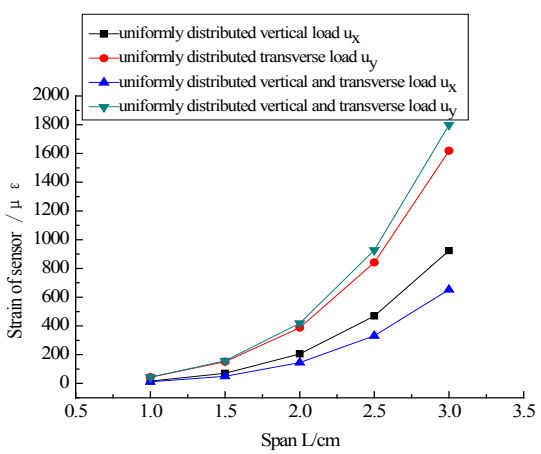


Figure 3. Strain relationship with span

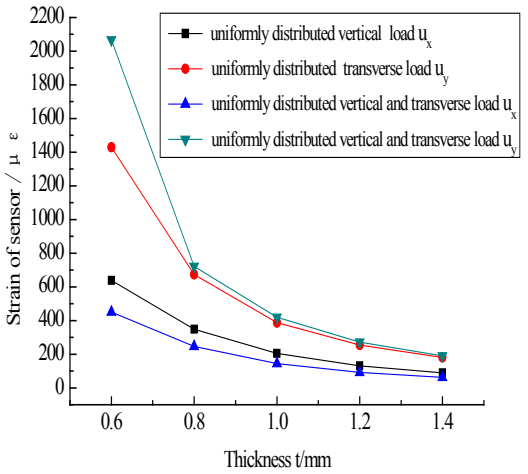


Figure 4. Strain relationship with thickness

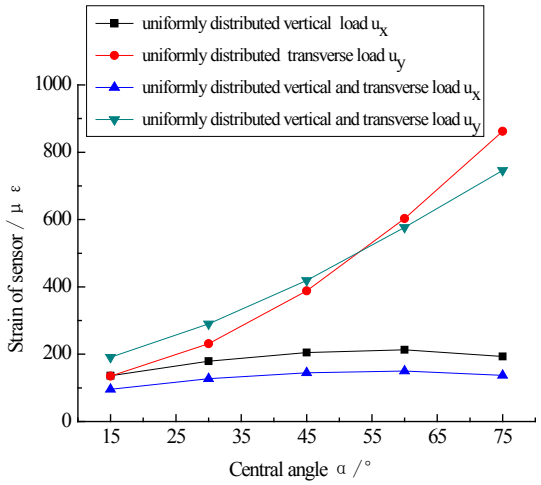


Figure 5. Strain relationship with central angle

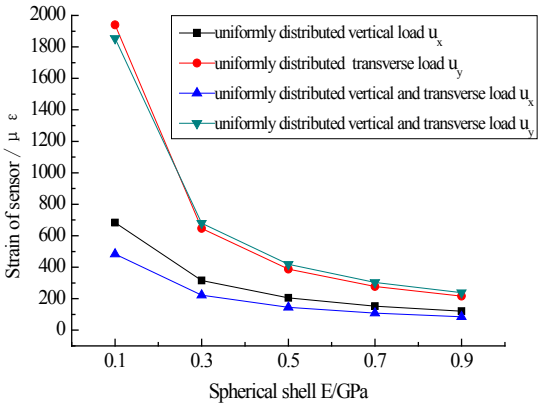


Figure 6. Strain relationship with spherical shell

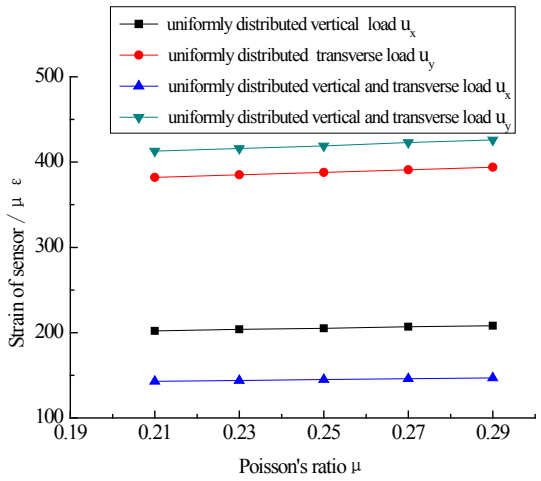


Figure 7. Strain relationship with Poisson's ratio

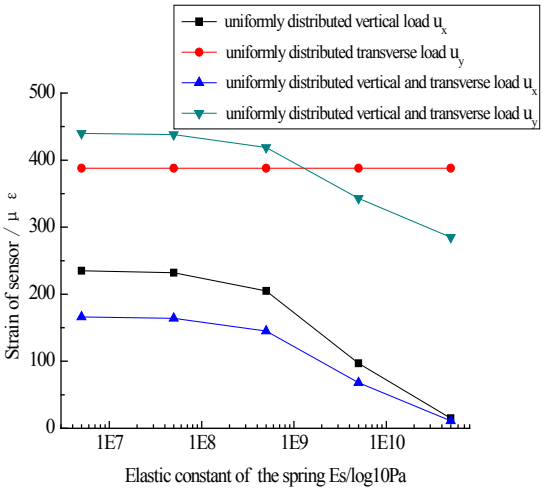


Figure 8. Strain relationship with elastic constant of the spring

Three kinds of wind direction is considered in the analysis, i.e. vertical wind, horizontal wind and the wind from both direction. From Fig.4-9, we can draw these conclusions:

(1) With the increase of the spherical shell L, the central angle α and the Poisson's ratio μ, the strain of the wind sensor is increasing at the same time. But the strain of the wind sensor decreased as the elasticity modulus of the spherical shell and the elastic constant of the spring increased.

(2) The influence zone of the strain of the wind sensor caused by wind from different directions can be divided to 3 parts. When the central angle of the spherical shell is small, the strain of the wind sensor induced by the horizontal wind is smaller than the strain induced by the vertical wind and the wind from both directions. The feature of the spherical shell is similar to the plate. With the rising of the central angle, the strain of the wind sensor induced by the horizontal wind increased rapidly, the feature of the spherical shell is similar to the shell. When the central angle is 45° , the maximum strain of the wind sensor is caused by the wind from both direction, while the minimum strain of the wind sensor is caused by the vertical wind. When the central angle is 75°, the strain of the wind sensor induced by horizontal wind is greater than that induced by the wind from other directions.

(3) The span of the spherical shell L, the thickness t, the central angle and the elasticity modulus of the spherical shell have a significant impact on the strain of the wind sensor, while the influence of the Poisson's ratio is unimportant. So the Poisson's ratio is not the control parameter of the design of the wind sensor. The elastic constant of the spring only make a difference to the strain caused by the vertical wind and the wind from both directions.

RESEARCH ON THE STRUCTURAL PERFORMANCE OF THE STANDARD WIND SENSOR

The measuring range of the FBG sensor for the standard wind sensor is from -1000με to +1000με. According to the result of the parameter analysis, the structural parameters of the standard wind sensor is determined as follows: the span of the spherical shell L is 2cm, the thickness t is 1mm, the central angle α is 45°, the elasticity modulus of the spherical shell E is 5×10^{8}Pa, the Poisson's ratio μ is 0.25, the elastic constant of the spring Es is 5×108Pa. Referring to the elastic modulus of the common material, the material of the spherical shell can be used as polyethylene, which has a yield strength of 20MPa.
Check out the sensitivity, linearity and safety of the standard wind sensor. When the variation of the wind speed is 1m/s, the minimum strain of the standard wind sensor is 2.6με, so the standard wind sensor has high sensitivity. When the wind pressure changed from 0 to 1000Pa, the change of the strain of the standard wind sensor is linear, as shown in Fig.9. Suppose the ultimate wind speed is 60m/s, the maximum stress of the standard wind sensor under the wind from both directions is 0.8MPa, as shown in Fig.10. It shows that the structure has adequate safety degree. The results show that, the standard wind sensor can meet the basic requirements of the field measurement.

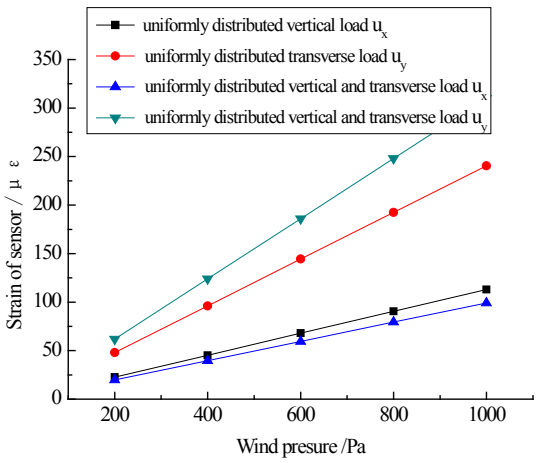


Figure 9. Strain relationship with span

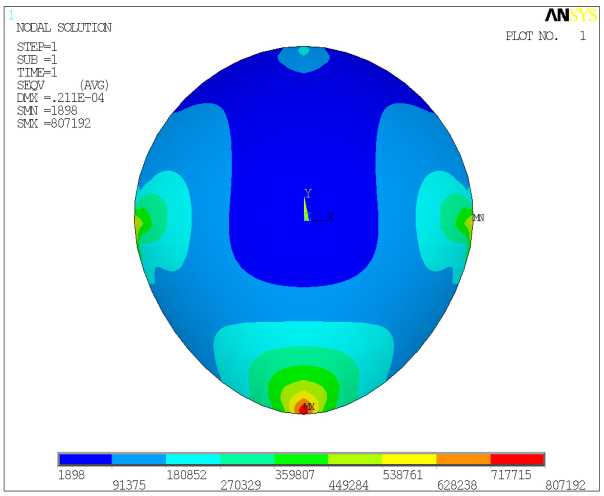


Figure 10. Two-way spherical shells under wind load stress

CONCLUSION

In this paper, a novelty FBG based wind pressure sensor are investigated. The structure of sensor enable the surface wind pressure into the strain of fibre Bragg grating installed in the bottom plane of shell. The static deformation and inner force analysis of sensor shows that there is a good linear relationship between the wind pressure and strain in FBGs. The sensibilities of the sensor is pretty good to meet the need of slight air pressure measure like nature wind pressure. The scope of measure also can be limited into a reasonable range. The parameters of designed sensor are proposed and optimal ultimate schemes is feasible to be used in the phase of trial-produce.

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