Development of the Tactile Sensor System Using Fiber Bragg Grating Sensors

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Abstract

This paper shows the development of flexible force sensor using the fiber Bragg grating. This force sensor consists of a Bragg grating fiber and flexible silicone rubber. This sensor does not have special structure to maximize the deflection or elongation, but have good sensitivity and very flexible characteristics. In addition, this sensor has the immunity to the electro magnetic field and can be multiplexed easily, which is inherited from the characteristics of fiber Bragg grating sensor. In the future, this sensor can be utilized the tactile sensor system minimizing the sensor size and developing the fabrication method.

1. Introduction

Many force sensors based on the strain gages, until now, have been used mainly to monitor the durability of bridges, buildings from the view point of safety, and control some material test machines and industry robots, and so on. However, recently, as some system is now small and need high sensitivity and accuracy, a new force sensor with small size and high sensitivity, not some conventional load cells, has been required to control small force accurately. On the other hand, MEMS shows the possibility of development of micro force sensor similar to the pressure sensor. Especially, some researchers have tried to develop tactile sensor combined small force sensors for intelligent robotics, teleoperational manipulators and haptic interfaces. These tactile sensors can detect normal forces on the taxel for gripping force control and generating tactile images for object recognition. However, in addition to acquiring tactile images and normal forces, detecting tangential forces is also critical. The fabrication process of sensor is very simple. This paper shows the development of three component force sensor based on the fiber optic sensors Until now, a few tactile sensors on behalf of the human skin have been developed compared with the other kinds of sensors, such as, image sensors and sound sensors. Because the tactile sensors have some requirements to adapt the practical engineering field, such as humanoid robot system and telerobotic system and so on. These sensors must have the flexibility and must have a good spatial resolution mimicking the human skin. Some researchers tried to make the tactile sensors using the MEMS(Micro Electric-Mechanical System) technology. Although these sensors have a good spatial resolution and sensitivity, they are not flexible and don't have sufficient durability[1-4]. In this paper, we will show the flexible optical fiber force sensor which can be the basis of the tactile sensor. This force sensor has very simple structure

2. The Structure of the Flexible FBG Sensor

2.1 The Principle of the FBG sensor

Fiber Bragg grating (FBG) sensors based on wavelength-division multiplexing (WDM) technology are attracting considerable research interest and appear to be ideally suitable for structural health monitoring of smart structure[5]. FBG sensors are easily multiplexed and have many advantages such as linear response and absolute measurement. As the spectral response of the FBG sensor signal renders the measurement free from intensity fluctuations, it guarantees reproducible measurements despite optical losses due to bending or connectors. The basic principle of a fiber Bragg grating (FBG)-based sensor system lies in the monitoring of the wavelength shift of the returned Bragg-signal, as a function of the measurand (e.g. strain, temperature and force). The Bragg wavelength is related to the refractive index of the material and the grating pitch. Sensor systems involving such gratings usually work by injecting light from a spectrally broadband source into the fiber, with the result that the grating reflects a narrow spectral component at the Bragg wavelength, or in transmission this component is missing from the observed spectrum. Fig.1 shows this simply and schematically. The intensity of the reflected optical signal is a function of the Bragg grating wavelength that relates to the applied strain on the fiber Bragg grating. Therefore, the dynamic strain can be derived from the intensity change measurement as function of the wavelength of the reflected optical signal. The operation of a FBG is based on a periodic, refractive index change that is produced in the core of an optical fiber by exposure to an intense UV interference pattern. This grating structure results in the reflection of the light at a specific narrow band wavelength, called Bragg wavelength. The Bragg condition is given by

$$\lambda_B = 2n_e\Lambda \quad (1)$$

where λ_B is the Bragg wavelength of the FBG, n_e is the effective index of the fiber core, and Λ is the grating period. The shift of the Bragg wavelength due to strain and temperature can be expressed as

$$\Delta\lambda_B = \lambda_B\left[\left(\alpha_f + \xi_f\right)\Delta T + \left(1 - p_e\right)\Delta\varepsilon\right] \quad (2)$$

$$p_e = \left(\frac{n^2}{2}\right)\left[p_{12} - \nu\left(p_{11} - p_{12}\right)\right] \quad (3)$$

where α_f is the coefficient of the thermal expansion (CTE), ξ_f is the thermo-optical coefficient, and p_e is the strain-optical coefficient of the optical fiber. The value of p_e =0.22[7] was measured experimentally and used for this study. If there is no temperature change, we can measure the strain from the wavelength shift as

$$\varepsilon = \frac{1}{\left(1 - p_e\right)}\frac{\Delta\lambda_B}{\lambda_B} \quad (4)$$

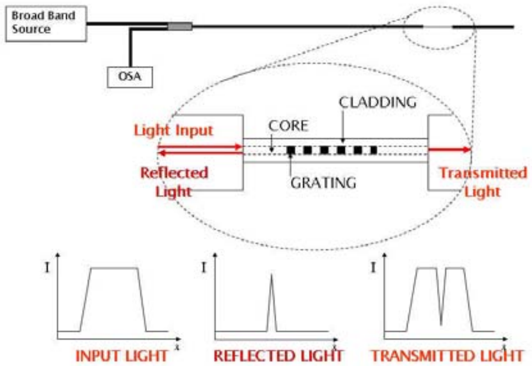

Fig.1 FBG sensor encoding operation

2.2 The Structure of Flexible FBG Force Sensors

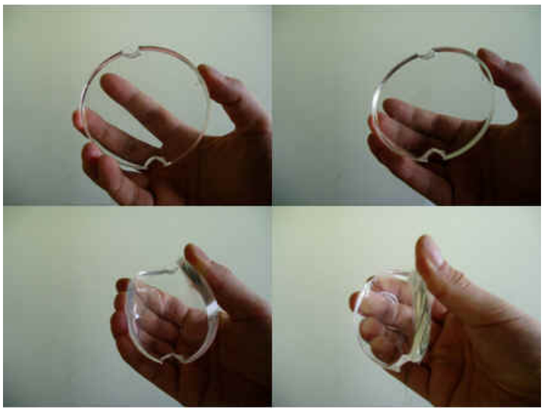

Fig.2 Prototype flexible FBG sensor

The sensor has the simple structure which is composed of FBG and silicone rubber (DC184 Dow corning Co. Ltd). The fabrication process of this sensor is easier than that of diaphragm type sensor. The FBG sensor with the length of 10mm is embedded in the silicone rubber.

Once the external force is applied on the silicone rubber, the fiber Bragg grating in the silicone rubber is deformed. The deformation of fiber Bragg gratings is induced on the change of the Bragg wavelength. Therefore, this sensor can detect the fore through the change of Bragg wavelength. Fig.2 shows the flexible characteristics of the prototype sensor.

3 Design of the Flexible FBG force sensor

3.1 FEM Analysis of Silicone rubber

We simulated the deformation of the silicone rubber to verify the resolution of the sensor. ABAQUS 6.3 was used and the 2-dimensional element model was applied to the silicone rubber. As the model is symmetric, the half geometric model was used. And the fixed condition on the all directions was applied on the base of the model. And the force (1~10N) was applied through the rigid ball with the diameter of 3mm to simulate the real experimental condition.

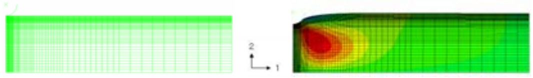

Fig. 3 Finite Element Model and FEA (Finite Element Analysis) of DC 184

The optical fiber was excluded from the FEM model. Because the optical fiber have the very small diameter (250㎛) compared with the whole size of the sensor. That is, the sensor model have only the silicone rubber and we assumed the deformation of the silicone rubber should be the deformation of the optical fiber. As the deformation of the silicone rubber is very small, we used the general elastic solver to verify the deformation[6]. The elastic modulus of the silicone rubber is 9.2MPa and the Poission's ratio is 0.49.

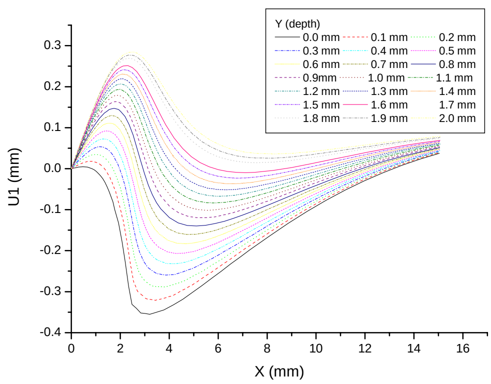

Fig. 4 U1 distribution of DC184 according to the depth (Load: 10N)

Fig. 4 shows the deformation of the U1 direction (the axial direction of the optical fiber). If the optical fiber is located on the surface of the silicone rubber, positive deformation is induced by the transverse load. As the optical fiber is deeper inside, the positive deformation is appeared. And the positive deformation is in the whole optical fiber above the 1.5mm deep inside the silicone rubber.

3.2 Determination of the Depth of FBG sensors

Using the results of the FEA, the efficient depth of the optical fiber can be determined. The large deformation is occurred in 1~4mm depth. And the output signal, the change of the Bragg wavelength can be easily influenced in 1~4mm depth. If the optical fiber is located on the surface of the silicone rubber, the output is most efficient, but the fiber can be easily broken because of the brittle characteristics of the optical fiber. Fig. 5 shows that the positive and concentrated deformation was occurred in the 2mm depth of the silicone rubber. Therefore, the 2mm depth was determined as the prototype flexible force sensor.

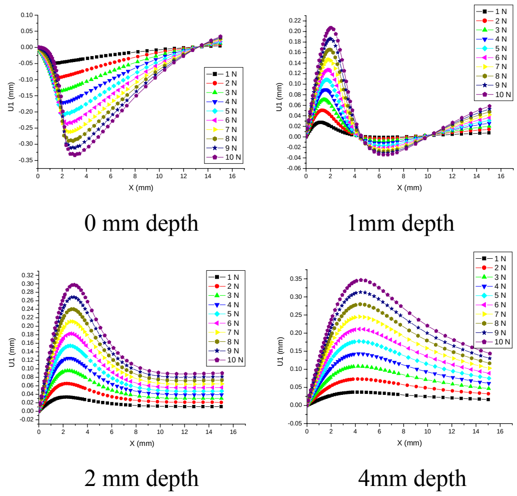

Fig. 5 U1 distribution of DC184 according to the load

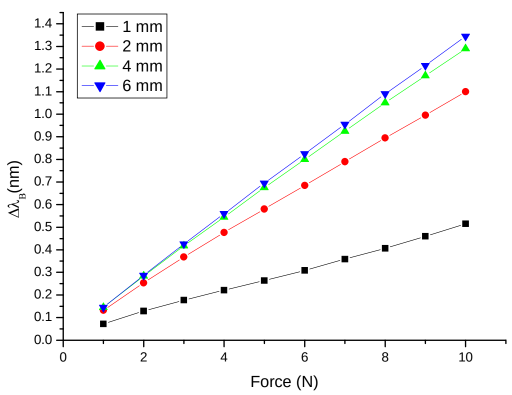

Fig. 6 Bragg wavelength shift analysis using FEM

Using the equation (4) and the results of FEA, we can calculate the change of Bragg wavelength. The photoelastic constant of the used optical fiber is 0.22[7]. Fig 6 shows the calculated the change of Bragg wavelength according to the applied force. The fiber Bragg grating sensor located in the 2mm depth has the about $1.0\times10^{-3}\,nm/gf$ sensitivity.

4. Experimental Results

4.1 Experimental Equipment

Fig. 7 shows the experimental setup. The broadband light source having the 1527~1602nm wavelength is incident in the optical fiber and the light is separated by the 2 by 1 coupler. The separated light is transmitted in the Bragg grating. And the reflected light is experienced the applied load is send the optical spectrum analyzer (OSA). Therefore we can know the applied force through the Bragg wavelength change of the reflected light. And the applied load is measured by the load cell like Fig.7.

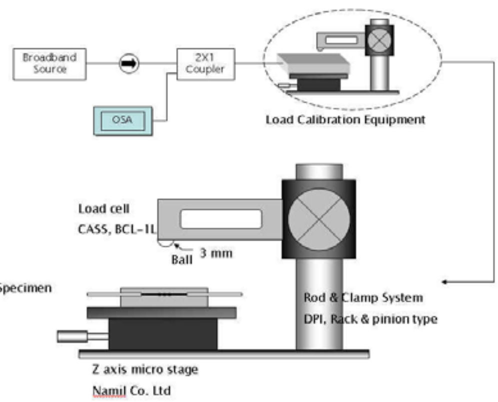

Fig. 7 Experimental setup

4.2 Evaluation of flexible FBG force sensors

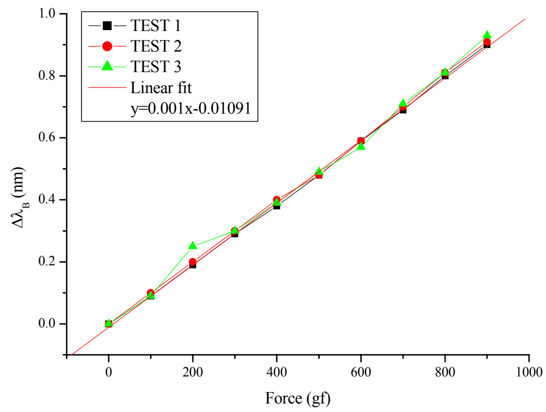

Fig. 8 Shifted wavelength according to the applied force of flexible FBG force sensor (depth 2mm)

Three flexible fiber Bragg grating force sensors were fabricated and tested in the same environment. Three sensors have the same sensitivity, about $1.0\times10^{-3} nm/gf$ which is the same resolution of the simulated results. This means that the 1.0nm Bragg wavelength was changed by the applied force, 1000gf. As OSA can detect the 0.01nm wavelength, these sensors can detect at least 10gf (0.1N).

5. Conclusion

In this paper, the flexible fiber Bragg grating force sensor was introduced and verified. The experimental results mated the simulated results by the FEA. The sensors are very flexible and can detect the absolute strain. And these sensors can attach the arbitrary surface. This characteristic is suitable to the artificial skin and the tactile sensors. The resolution of theses sensors is about 10gf (0.1N) and will be improved by the ability of the OSA or interrogation system of the fiber Bragg grating. Now these sensors cannot have the good spatial resolution to adapt the tactile sensors. In the future, the length of the FBG with the 1~5mm, the sensors can be minimized, that is, the spatial resolution of the sensor would be improved.

Acknowledgement

This research (paper) was performed for the Intelligent Robotics Development Program, one of the 21st Century Frontier R&D Programs funded by the Ministry of Science and Technology of Korea.

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