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OPTICAL SIGNAL PROCESSING FOR FIBER BRAGG GRATING BASED WEAR SENSORS

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ABSTRACT

In this study, we propose a simplified signal processing scheme for fiber Bragg grating (FBG) based wear sensing. Instead of using a chirped FBG and detecting the bandwidth, we use uniform gratings as sensors and measure the optical power reflected by the sensing grating to determine the length of the sensor grating, hence detect the wear. We demonstrate by the experiments that the proposed method is feasible and practical. The advantage of the proposed method lies in the fact that structure of the wear sensing system is simplified and therefore the cost can be significantly reduced. The principle of the proposed method, the design of the wear sensor, and the experiments are described.

1 INTRODUCTION

Wear happens in contact objects with relative movement. Monitoring the wear is critical for determining the lifetime and performance of many mechanical systems, including milling and drilling machines, and vehicle braking systems. Wear monitoring, especially real-time and on-line monitoring is a difficult task [1]. Different wear sensors based on resistive, capacitive and conductive techniques have been developed and designed [2-4]. These electric sensors inherently require electrical current to pass through the sensing elements. The issues related to that are the fact that they are sensitive to electromagnetic interferences which are normally exist in the machines where the wear sensors are used. Also this type of wear sensors suffers from short or open circuit problems. Compared with the electric sensors, optical fiber based sensors have a number of obvious advantages such as, (1) immunity to electromagnetic and RF interference, chemicals, radioactivity, corrosion and lightning; (2) high sensitivity and resolution, and fast response; (3) small size, and the ability for easily embedding into the part where wear to happen.

Among the many different types of fiber sensors, those based on fiber Bragg grating (FBG) have attracted lot of attention in recent years [5, 6]. A fiber Bragg grating is

formed by periodically modulating the refractive index of the core of an optical fiber [7, 8]. This all-fiber component can selectively reflect the light of a wavelength defined by the grating period and the refractive index of the fiber core. The potential applications of FBG devices in both optical fiber communications and fiber sensing areas had been realized immediately after its discovery in 1978 and, since then intensive research has been devoted to the development of FBG sensing systems and their applications. A wear sensor based on fiber Bragg grating (FBG) technique has been reported just recently [9]. In Reference 89 chirped gratings were adopted for constructing wear sensors. The principle is based on the detection of the changes of bandwidth of the chirped gratings as the bandwidth is related to the length of the FBG. As the FBG sensor wears off, the length of the sensing FBG is reduced, and as a consequence, the bandwidth will decrease. Since the bandwidth of the reflection or transmission spectrum has to be measured in order to determine the grating length, the reflection or transmission spectra have to be measured by using an optical spectral analyser (OSA). An OSA is suitable for laboratory tests, but not an ideal solution for field applications in term of cost and convenience.

In this study, we propose a simplified optical signal processing scheme for FBG based wear sensing. Instead of using a chirped FBG and detecting the bandwidth, we use uniform gratings as sensors and measure the optical power reflected by the sensing grating to determine the length of the grating, hence detect the wear. We demonstrate by the experiments that the proposed method is feasible and practical. The advantage of the proposed method lies in the fact that structure of the wear sensing system is simplified and therefore the cost can be significantly reduced.

This paper is organised as follows. In Section 2, the principle of the proposed method and a theoretical analysis is given, followed by a detailed description of the sensor design. In Section 4, experiments and results are presented to demonstrate the feasibility of the scheme. Discussions and conclusions are given in Section 5.

2 PRINCIPLE AND THEORETICAL ANALYSIS

The periodical refractive index modulation introduced to a fiber core to form a grating causes the interaction between the forward- and backward-propagation modes in the fiber. This process can be described by using the so-called couple mode theory. From the coupled mode theory, the reflectivity of a uniform FBG can be expressed as [4]

$$R(L, \lambda) = \frac{\Omega^2 \sinh^2(SL)}{\Delta\beta^2 \sinh^2(SL) + S^2 \cosh^2(SL)} \quad (1)$$

where, λ is the light wavelength; L is the length of the grating; Ω is the coupling coefficient; $\Delta\beta = \beta - (\pi/\Lambda)$; $\beta = 2\pi n/\lambda$, is the eigen propagation constant; Λ is the grating period; and $S = (\Omega^2 - \Delta\beta^2)^{1/2}$.

When a broadband light source is used to illuminate the grating, the total power reflected back by the grating is

$$P(L) = k \int_0^{\infty} R(L, \lambda) d\lambda, \quad (2)$$

where, k is a constant.

It can be seen that the total power reflected by the grating is a function of the grating length, L , and other grating parameters, such as refractive index modulation. Therefore, for a uniform grating, by measuring the optical power reflected by the grating, one can determine its length. Therefore, when a uniform grating is embedded into an object to which wear is going to happen, the grating length decreases with the increase of wear, and as a consequence the power reflected by the grating will be reduced. This forms the principle of operation of the wear sensor reported here. Instead of using chirped gratings and detecting the bandwidth of the reflection spectrum, uniform gratings, which are easier to fabricate than chirped gratings, can be used, reducing the cost for making the sensors.

Shown in Figure 1 are calculated powers for gratings fabricated with standard communications fibers under different refractive index modulations as a function of grating length.

It is clear that for a relatively weak grating ($\Delta n = 5 \times 10^{-4}$ as shown in Figure 1), a nearly linear relationship exists between the reflected power and the grating length. With the increase of refractive index modulation ($\Delta n = 10^{-3}$), the grating becomes stronger, and hence the reflected power by the grating will correspondingly increase. A non-linear relationship appears between the reflected optical power and the

grating length. Further increase of refractive index modulation will cause saturation in the optical power and grating length curve.

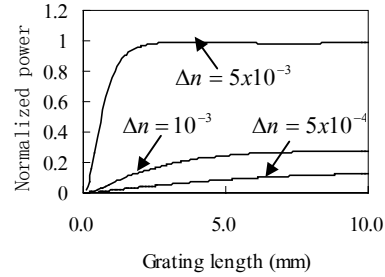


Figure 1. Calculated optical powers reflected by a grating with different refractive index modulation as a function of grating length.

In order to achieve a linear response, a weak grating is preferred in the sensor design. However, when high sensitivity is required, a stronger grating should be used. In this case, a calibration is necessary to cope with the non-linear response. Long and strong gratings should be avoided in designing this type of wear sensors as they are not sensitive to the grating length changes. However, short gratings with large refractive index modulation could be used when very high sensitivities are necessary.

3 SENSOR DESIGN

In order to test the proposed method, we designed and fabricated several FBG-based wear sensors and experimentally tested them. The gratings used for our sensors were fabricated by using the phase mask technique. Photosensitive fibers (GF1 from Nufern) were employed for fabricating the gratings. After fabrication, the gratings were thermally annealed for four hours at a temperature of 80°C to stabilize the change of the refractive index. The length of the gratings was determined by the beam width of the UV laser (BraggStar 200 from TuiLaser), and is proximately 8 mm. The refractive index modulation along the grating length was determined by the intensity distribution of the UV beam along the fiber direction. According to the laser specifications, a near uniform intensity distribution was expected in normal operation conditions. The Bragg wavelengths of the gratings used in the tests were measured as 1543.0 nm in a tension-free state at a temperature of 23°C . The refractive index modulation was estimated to be about $\Delta n = 10^{-3}$. A measured reflection

spectrum of a fabricated grating is shown in Figure 2. As can be seen that side-lobes exist in the reflection spectrum of the grating as there was no apodization was used during the fabrication process.

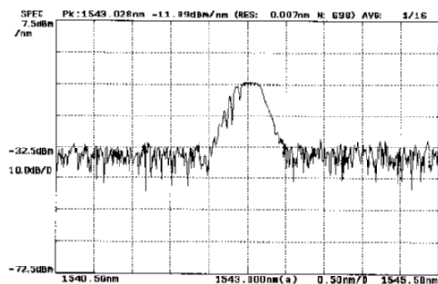


Figure 2. Measured spectrum of a grating used for wear sensor design.

Unpackaged FBGs are brittle and easy to break. In order to build wear sensors, gratings need to be attached to rigid objects. We constructed FBG wear sensors by sandwiching each sensing grating between two Perspex blocks using epoxy glue. The dimensions of the Perspex sheets used in our sensors are 80 mm (length) x 30 mm (width) x 5 mm (thickness). The gratings were cleaved and positioned in such a way that the tips of the sensors are at the ends of the gratings. V-grooves were machined on the surfaces of the Perspex blocks to accommodate the gratings. The sensors had been cured in the room temperature for 24 hours before testing.

4 EXPERIMENTS AND RESULTS

The wear sensors were tested with an experimental set-up as shown in Figure 3. The wear sensor was first connected to an optical circular, and then to a 3dB directional coupler to simultaneously measure the optical power reflected by the grating and the reflection spectra of the FBGs. An amplified spontaneous emission (ASE) light source with an output power of 5 mW and a bandwidth of approximately 40 nm (1525 nm to 1565 nm) was used as a broadband source. The output spectrum of the ASE was flattened by using a thin-film based gain flattening filter (GFF), resulting in a spectral flatness of 0.5 dB. The optical power reflected by the sensing gratings was measured by a power meter (Newport 2832-C). The reflection spectra of the FBGs were measured and recorded by using an optical spectrum analyser (OSA) (ADVANTEST Q8347).

In the experiments, the wear sensors were mounted to a translation stage with a micrometer to get the reading of

the wear to the sensor. In order to generate the wear, a bench grinder was used to grind off the sensor. During the process of experiments, the reflection spectra were monitored. Shown in Figure 4 is a spectrum recorded when the sensor was worn away by 2.4 mm. As expected, as a result of the reduction in the grating length, the grating strength became weaker compared with the original grating one (as shown in Figure 2).

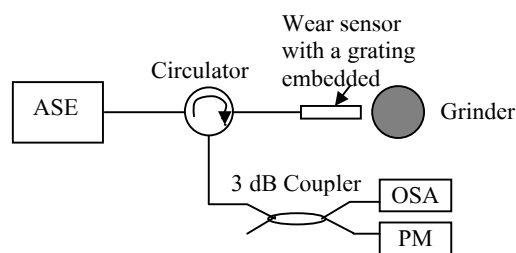


Figure 3. Experimental set-up to test the proposed signal processing scheme and the designed wear sensor.

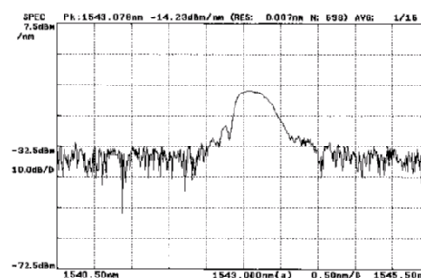


Figure 4. Measured spectrum of wear sensor with a wear of 2.4 mm.

The optical powers measured at different wear are shown in Figure 5. The experimental results show that the power reflected by the grating embedded in the wear sensor decreases with the increase of wear. Also plotted in Figure 5 are the calculated results. In the calculations, a refractive index modulation $\Delta n = 10^{-3}$ was used. Note that the optical powers from both measurements and calculations are normalized to their maximum values for comparison purpose. Also note that the measured optical power has a non-linear response to the wear because the grating used in the experiments is a relatively strong grating. It can be seen from Figure 5 that a reasonable agreement between the measured and calculated results has been achieved. This demonstrates that wear can be measured by using a

uniform grating and by simply measuring the power reflected by the sensing grating.

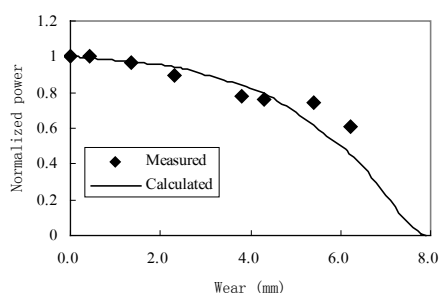


Figure 5. Measured and calculated optical powers at different wear values.

5 CONCLUSIONS

We have proposed a new optical processing scheme for measuring wears. Instead of using a chirped FBG and detecting the bandwidth, we use uniform gratings as sensors and measure the optical power reflected by the sensing grating to determine the length of the grating, hence detect the wear. It has been demonstrated that by the experiments that the proposed method is feasible and practical. The advantages of the proposed method include: (1) low-cost uniform gratings can be used to construct wear sensors; (2) the structure of the wear sensing system can be simplified and therefore the cost can be significantly reduced. It should be pointed out that although an OSA was used in our experiments, it was only for monitoring purpose.

Further investigations to characterize the accuracy and resolution of the proposed method are currently under way.

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