Smart Photonic Carbon Brush: FBG Length as Sensing Parameter

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Abstract. This article deals with problem of carbon brush’s length measurements. There are many applications where regular inspection is not feasible because of a number of factors including, for example, time, labor, cost and disruptions due to down time. Thus, there is a need for a system that can monitor the brush’s length to calculate it’s wear rate, while the component is in operation or without removing of the component from its operational position. We propose a novel method for characterization of carbon brush’s length. This method based on the usage of advantages of the multiplicative response of FBGs and FBG arrays: spectral parameters depend on several aspects, such as grating’s period, refractive index, it’s physical length and so on. We are the first, in our point of view, who proposed to use third parameter for sensing application and prospectively all three parameters for complex measurement: the change of FBG’s length is used to measure length of the brush and it’s wear rate, grating’s central wavelength shift for temperature (due to refractive index change) and mechanical stress (due to grating’s period variations) measurements. The results of modelling and experiments are presented.

1. Introduction

Surface-reducing wear occurs in machines by frictional contact of adjacent parts and by other forms of erosion. For example, turbine engines have bearings, shroud liners, combustor liner spring clips, and other areas where reduction wear occurs. Detecting such wear can be critical to safe operation of the machine [1]. The clearest example of the surface-reducing wear in electric machines is carbon brush. Modern brushes are mentioned for high speed and high current applications and have unique ability to share current at minimal frictions in order to provide cooler running and outstanding brush life. Despite of that, all manufacturers offer carbon brush wear detection systems, making maintenance operation easier.

Sensors have been designed to detect wear without disassembly of components. For example, electrical conductors may be embedded in a wear surface. A detector connected to these conductors senses an open circuit caused by wear through a conductor, and determines a wear depth [2]. Alternate device for wear magnitude measurement in friction is organized, for example, by positioning in product two control electric conductors, isolated at a certain depth from the product body [3]. Here the threshold wear value of the product determined by the depth location of control electrical conductors is controlled. When the determined depth reached friction products break down the isolation of the conductors which short-
circuit by the elements of the second friction products and the registration system receives an electrical signal of reaching the wear threshold. A disadvantage of such devices is the possibility of high voltage entering at control electrical conductors when the friction product is under it.

To eliminate this drawback, the control conductors are made by fibre optic. Patent [4] describes loops of optical fibres embedded in a wear surface. Each loop forms an optical circuit with a light source at one end and a detector at the other end. Reduction wear breaks one or more loops in succession, which is detected by respective losses of signal. This design requires enough sensor area for the embedded fibres to form loops, and requires both a source leg and a detector leg of each fibre loop to pass through the sensor block to the source and detector. Additional disadvantages of the device and the above mentioned one are the lack of temperature control and provision only the threshold wear index indication, but not its rate.

Our analysis showed that in practice there are exist only separate methods of wear and friction surfaces temperature measurement. For joint temperature and wear measurement was found a technology1, the point of which is that of the control fibre optic light guide is placed in the brush at a depth equal to or less than the distance to the friction surface, at which end the section from phosphor is formed. Phosphor is excited by a pulsed laser source probe and emits light energy at different wavelength because of luminescence for example. To measure the wear and temperature product value at friction the phosphor characteristics are used. The detector is characterized by the possibility of amplitude and spectral measurements with incoming probe wavelengths determination, determines the wear value based on the amplitude characteristics of re-emission, changing, when phosphor is being erased, and temperature based on the spectral characteristics of re-emission, namely, temperature-dependent wavelength re-emission. Note the obvious complexity of this joint technology and the possibility of its implementation on the narrow thickness of the phosphor, which leads to the necessity of using control fibre optic light guides at different depths.

Patent [5] also deals with an optical fibre in a wear surface. Light injected into the fibre reflects off the opposed abrading surface and returns through the same fibre. The fibre tip wears along with the wear surface, and the light circuit length is reduced. This length is measured by interferometry to determine a wear depth. The problems of this invention are necessity to analyse reflection from the abrading surface, which requires signal analysis that deals with variable reflectivity, and application of interferometry, thus eliminating elements such as reference beam optics. For temperature measurements, authors use additional fibre Bragg grating (FBG) sensor embedded in brush parallel to main fibre.

In present paper, we demonstrate smart photonic FBG sensor for brush wear monitoring with additional functions of brush wear rate, temperature and hanging monitoring with possibility to rotor speed measuring. We are first from our point of view who shown how to measure brush wear by means of FBG length monitoring and use of other FBG multiplicative properties to measure above mentioned characteristics. In second part, we analyse FBG characteristics. In third part we present modelling results and in fourth its practical confirmation. In conclusion, we will resume results of above mentioned rotor speed measurements and discuss the directions of researches development.

2. FBG’s length as sensing parameter. New way for fibre optic sensors

In our previous article [6] we proposed a new sensing method, based on dependence of FBG spectral characteristics on its length.

The FBG spectra in respect to reflection \( R \) is expressed through its length \( L \) and detuning \( \delta \) [7]:

\[ R(L, \delta) = \text{const} \times \exp(-\frac{2 \delta^2}{\sigma^2}) \]
where $\kappa$ – the coupling coefficient of the forward and reverse modes, $\left(\delta/\kappa\right)$ – relative detuning. FBG detuning with period $\Lambda$ equals to $\delta = \Omega - \left(\pi/\Lambda\right)$, where $\Omega = 2\pi n_{\text{eff}}/\lambda$.

![Figure 1](attachment:image.png)

**Figure 1.** FBG spectral characteristics:

- $a$ – reflectance for FBG of 5 mm length;
- $b$ – reflectance for FBG of 3 mm length;
- $c$ – reflectance for FBG of 1 mm length;
- $d$ – reflectance $R(\lambda)$ (red line) and FWHM $\Delta\lambda$ (blue line) as function of FBG length $L$.

To illustrate the changings in FBG spectral properties we present the dependence of the reflectance on the wavelength for several FBG lengths as shown on Figure 1, (a)-(c). The effective refractive index of the fundamental mode was chosen $n_{\text{eff}} = 1.5$. The grating period was selected so that the core for the unperturbed resonant wavelength matched $\lambda_{\text{FBG}}=1500$ nm. The initial length of the grating was chosen...
to be \( L = 5 \text{ mm}, \kappa L = 0.38 \). In the numerical modeling of the FBG spectral properties, we reduced the length of the grating. As the result, we show on Figure 1 (d) the dependence of the reflectance \((R)\) and the spectral width \((\Delta \lambda)\) from the length \((L)\) of the grating.

Typical length of FBG is 3-12 mm. In some cases, when the length of the measured product can reach tens of millimeters, this range of measurement becomes insufficient. In these cases we can offer other different structures, based on FBGs, such as phase shifted FBGs and Fabri-Perot interferometer, based on two FBGs [8]. For the first structure, measurement range can be increased to ~24 mm, for the second – up to ~36 mm.

Typical length of carbon brushes begins from several millimeters (for electric tools) to 60-70 mm for motor-wheels of dumpers and trains. It’s evident, that earlier structures can’t provide such measurement range, so here we propose to use FBG array, the structure, that consists of many identical FBGs fabricated in same fiber with a specific step. In this case, we have a number of trickles (3-12 mm length), within which we can ensure continuous measurement with free spaces between them. The use of an array of the same type FBGs allows the maximum effective use of the operational spectral range of the interrogator. The number of sensors located in the body of the measuring object is determined, firstly, by its length, and, secondly, by the requirement for the number of controllable wear levels (the areas where it is required to monitor the wear value with high accuracy). We called this quasi continuous length measurements.

3. FBG array for quasi-continuous length measurements

FBG arrays were described mathematically in [9]. The change in the spectrum response of the FBG array is caused by various types of crosstalk [9]. The first one is the spectral shadowing \( I_r(\lambda) \), which describes the phenomenon of the distortion of the reflection spectrum of the FBG (see Figure 2) at the near end (FBG1 and FBG2), caused by the insertion loss of reflected radiation from the FBG at the far end (FBG\( N+1 \) and FBG\( N \)). The second one is cross-distorions \( C_r(\lambda) \) caused by the multiplicity of the response associated with a large number of multiple reflection crosstalk. The resulting reflection spectrum from the i-th FBG is the sum of \( I_r(\lambda) \) and \( C_r(\lambda) \) (2).

\[
R_{AR}(\lambda, N) = I_r(\lambda) + C_r(\lambda),
\]

where \( N \) – total number of FBGs; \( I_r(\lambda) = [1 - R(\lambda)]^{2(N-1)} R(\lambda); C_r(\lambda) = \frac{(N-1)(N-2)}{2} R(\lambda)^3 [1 - R(\lambda)]^{2N-4}, N \geq 3, R(\lambda) \) described as (1).

The resulting reflection spectrum of the FBG array is the sum of the radiation reflected from the \( N \) FBGs (3):

\[
R_{AR}(\lambda, N) = \sum_{i=1}^{N} R_{AR_i}(\lambda, N) = \sum_{i=1}^{N} [I_r(\lambda) + C_r(\lambda)].
\]

For the Mathcad simulation, FBGs with the Gaussian reflection profiles, described in higher section, were selected. The number of gratings \( N=4 \) was chosen. The initial profile of the reflection spectrum of the array is shown in Figure 3 (a).
In the course of modeling the wearing of the FBG array, the resultant reflection spectrum was constructed according to the expression (3) for a different number of gratings: \( N = 4 \) (initial spectrum), 3 and 1, which are shown on Figure 3 (a)-(c). The change in the FBG spectrum at those times when any sensor wearing occurs is described in previous section.

According to these results, we can conclude that as the number of FBGs in the array decreases, the reflection coefficient \( R_{\lambda}(\lambda) \) decreases and the spectral width \( \Delta\lambda_{\text{AR}}(\lambda) \) slightly changes, as shown on Figure 3 (d).

![Figure 3. FBG array spectral characteristics:](image)

\( a \) – reflectance for \( N=4 \) FBG array; \( b \) – reflectance for \( N=3 \) FBG array; \( c \) – reflectance for \( N=1 \) FBG array; \( d \) – reflectance \( R_{\lambda}(\lambda) \) (red line) and FWHM \( \Delta\lambda_{\text{AR}}(\lambda) \) (blue line) as function of total number of FBG \( N \).

4. FBG wear sensor interrogation technique

There are many ways FBG interrogation. All of these methods can be divided into two classes: with a direct definition of the spectrum parameters [10-11] and radiophotonic [12-13].
These methods allow high-precision measurements, but these devices are very expensive. The requirements for the measurements accuracy (±2.5% of total length, according to state standards) is much lower than those achieved by these methods, therefore, an alternative scheme of the interrogation device implementing the power comparison method and consisting of the measuring and two reference FBGs can be proposed.

Structural scheme of such devise is shown on Figure 4.

![Figure 4. FBG interrogation scheme, based on power comparison method: LS – laser source; C – coupler; PD – photodiode; FBG1 – FBG sensor; FBG2 – FBG3 - reference FBGs.](image)

The device consists of a laser source (broadband laser diode), a set of Bragg gratings (sensing FBG and two reference FBGs), fiber splitters 50/50 (couplers) and photodiodes. Optical radiation from the source, through the optical fiber and the splitter, is fed to the sensing FBG. The radiation reflected from it is applied to a pair of reference FBGs, which, in turn, reflect a portion of the incident radiation on the photodiodes. Reference FBGs are thermally stabilized in order to avoid spectrum shifts. All elements of the device are made in fiber design, which increases the mechanical stability and doesn’t require additional adjustments.

Earlier (Figure 1) we showed that when the FBG’s length decreases, the reflection coefficient decreases and the spectrum broadens (Figure 5):

![Figure 5. Modeling the operation of the interrogation scheme.](image)
We use the total signal from two channels (reference FBGs: red and blue spectrums on Figure 5) $S_2 + S_3$ as shown on Figure 6.

![Figure 6. Measuring characteristic.](image)

It can be seen that the characteristic has a non-monotonous section. However, taking into account the fact that wear of the brush during its operation changes monotonously, and the work of the measuring system assumes continuous measurement of its length, this circumstance can be eliminated.

It is obvious that a wavelength shift due to temperature changes of the sensing FBG will affect the measuring characteristic. To estimate the introduced error, we simulated the measurement characteristics at different positions (temperatures) of the FBG (Figure 7) over the entire range of operating temperature $T$ of the sensor.

![Figure 7. A number of measurement characteristics for $T = -60 \ldots + 120 \, ^\circ C$.](image)

The main error is caused by the change in temperature at the initial section (with the maximum length of the FBG). Based on the steepness of the characteristics in this area (Figure 7), the amount of the introduced error is less than 2% (0.11 mm). That is connected, including the small slope of the measuring characteristic in this section.
5. Experimental results

For the experimental research, we fabricated a brush with integrated FBG sensor (Figure 8). Two fibers were placed in the brush: the main and backup.

![Scheme of placement of sensors (a) and the appearance of the brush with embedded FBG sensor (b).](image)

Figure 8. Scheme of placement of sensors (a) and the appearance of the brush with embedded FBG sensor (b).

The testing method that we used in experiment is based on the procedure for testing brushes of electric machines in accordance with state standards. According to the standard, brush length measurements are made by a precision tool before and after a test cycle of 50 hours. The test cycle is the continuous operation of the engine under investigation in nominal regime with brushes placed in it.

Figure 9 shows the measurement characteristic obtained during the experiment (orange line) and the calculated (blue line). An experimental study showed that the absolute error in brush length (wear) measurement was 0.11 mm.

![The dependence of the measured $S_{FBG\text{-meas}}(L)$ – the orange line – and the theoretically obtained $S_{FBG}(L)$ – the blue line.](image)

Figure 9. The dependence of the measured $S_{FBG\text{-meas}}(L)$ – the orange line – and the theoretically obtained $S_{FBG}(L)$ – the blue line.
6. Conclusion

A new smart photonic method for characterization of carbon brush wear is presented. It is based on the usage of spectrum variations, caused by sensor’s length reduction. Two types of sensors can be widely used: FBG (for measurement range ~3-12 mm) and FBG arrays (many tens of millimeters quasi-continuous measurement). The results of development and research of mathematical models of the proposed sensors are presented. The use of the power comparison method for interrogating of developed FBG sensor is proposed. The data obtained in the course of simulations was verified experimentally with high accuracy, which confirms the correctness of the proposed solution.

Prospectively three parameters can be used for complex brush and motor: the change of FBG’s length can be used for measurement of length of the brush and it’s wear rate, grating’s central wavelength shift (due to refractive index change) for temperature regime monitoring and wavelength shift due to mechanical stress (caused by grating’s period variations) for vibration and rotation speed control.

We are first from our point of view who shown how to measure brush wear by means of FBG length monitoring and use of other FBG multiplicative properties to measure above mentioned characteristics.

The clearest example of the sensor usage is electric machine brush-collector node. But it also can be used in car brake pads, bearings, another types of friction surfaces.

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