Fiber-optic sensors for complex monitoring of traction motors

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Abstract. The paper presents the results of solving a scientific and technical problem related to the development of the fundamentals of building fiber-optic measuring systems for integrated monitoring of the state of a traction motor based on fiber Bragg structures that allow to measure temperature, wear and vibration of a brush-collector unit. Mathematical models of the process of measuring these parameters were developed and tested, a solution was proposed for constructing devices for interrogating such sensors.

1. Complex monitoring of the traction motors: problem statement

Among electric motors, a special place is occupied by traction motors (TM), which are high-power electrical machines designed to drive vehicles, which are characterized by high traction and power characteristics.

Due to the harsh working conditions and tight overall constraints, traction motors are referred to as limiting use machines, with the majority of failures associated with TM malfunctions – winding breakdowns (anchors, excitations, auxiliary pole, etc.) caused by their overheating, arcs, caused by disturbances of switching stability in the brush-collector node (BCN) and the appearance of sparking. In sparking, there is a short-term increase in temperature at the brush-collector contact [1]. With prolonged sparking, the collector plates and the brush heat up considerably. However, the opposite situation is also possible - excessive heating of the brush-collector unit (caused by various factors) may lead to sparking, which, in turn, will cause a further increase in the temperature of the CCH. The factors influencing the heating of the electric motor components of the electric motor UHC can be divided into three groups: factors of electrical nature without arcing, factors of a mechanical nature, as well as factors caused by electric arc sparking.

Another feature of the operation of collector type TM, reducing its operational reliability is the natural wear of the elements of the BCN, caused by the presence of a sliding contact in a brush-collector pair. Currently, most often, the amount of wear of the brushes is monitored visually during the inspection, however, the design features and the location of the TM on the vehicle make this procedure time consuming.

The above circumstances, as well as trends in the development of traction rolling stock, associated with the construction of smart locomotives with built-in distributed monitoring system of the state of its units, necessitate the construction of an integrated monitoring system of the traction motor, as one of the most unreliable.
Among the existing classes of measuring systems, fiber-optic ones occupy a special place. Fiber-optic measurements today are a booming industry that opens up new horizons for itself, both in terms of expanding applications and the list of parameters measured by fiber-optic tools. The production of fiber-optic sensors of temperature, pressure, vibration, deformation, including multiplicative ones, the sensitive elements of which are fiber Bragg gratings (FBG) or structures based on them, has been mastered. The main advantages of fiber-optic sensors in comparison with traditional electric are small dimensions and weight, immunity to electric and magnetic fields (because the sensitive element is a dielectric), the simplicity of performance (most often the sensitive element is part of the fiber-optical fiber), the possibility multiplexing a large number of fiber-optic sensors and building measuring networks based on them. Currently, when constructing measuring systems based on fiber Bragg structures, the dependences of the shift of the central reflection wavelength on the applied action (mechanical and/or temperature) are used. The authors first proposed using the dependence of the reflection spectrum profile on the length of the FBG [2]. This dependence can be used to build a fiber-optic wear sensor, and together with the existing theory of fiber-optic sensors, to create a multiplicative sensor that allows simultaneous measurement of wear, temperature and mechanical deformations of an electric machine brush, not only at the stage of its operation, but and in the design, manufacture of prototypes and their testing by interstate standards. The development of the fundamentals of building such sensors as elements of integrated control systems is the focus of this work.

2. Fiber Bragg structures as an element of a multiplicative sensor

Fiber Bragg grating is a section of optical fiber, in the core of which the refractive index periodically changes in the longitudinal direction (Figure 1).

The radiation propagating through an optical fiber is a combination of the eigenmodes of the fiber: guided and radiative. The radiative modes of a fiber form a continuous function, and the directed ones correspond to a discrete set of propagation constants \( \beta_i \). In the absence of changes in the refractive index, the modes propagate without interaction with each other. Therefore, the period of modulation of the refractive index is chosen in such a way as to provide the necessary resonant interaction between the selected modes of the fiber. This modulation of the refractive index associates the main mode of the fiber with the mode propagating in the opposite direction. As a result, at a discrete wavelength, the radiation propagating through the optical wave is reflected from FBG. The reflection coefficient depends on the modulation depth of the refractive index, and the Bragg reflection wavelength \( \lambda_B \) determined by Bragg condition [3]:

\[
\lambda_B = 2n_{eff} \Lambda,
\]

where \( n_{eff} \) – effective refractive index of the core mode of the fiber core, \( \Lambda \) – period of FBG.

The profile of the FBG reflection spectrum is described by the following expression [5]:

\[
R_{FBG}(\lambda, L) = \frac{\sinh^2 \left[kL \sqrt{1 - \left(\frac{\delta}{k}\right)^2} \right]}{\cosh^2 \left[kL \sqrt{1 - \left(\frac{\delta}{k}\right)^2} \right] - \left(\frac{\delta}{k}\right)^2},
\]

where \( k \) – coupling coefficient of incident and reflected waves, \( \delta / k \) – relative detuning, \( L \) – FBG’s length.

It is known that when the fiber section with FBG is heated and/or stretched, its Bragg wavelength is shifted [3]:
\[ \Delta \lambda = 2n\Lambda \cdot \left\{ \frac{1 - \frac{n_{\text{eff}}}{2}}{\alpha + \frac{1}{n_{\text{eff}}} \cdot \frac{dn}{dT}} \cdot \Delta T \right\} \]

where \( \Delta T \) - temperature change, \( \varepsilon \) - applied mechanical stress, \( P_{ij} \) - Pockels coefficients of the elastic-optical tensor, \( \nu \) - Poisson's ratio, \( \alpha \) - quartz glass thermal expansion coefficient, \( n_{\text{eff}} \) - effective refractive index of the main mode.

It can be seen that the response of the FBG simultaneously contains information about its temperature and tension, and also depends on the length of the FBG. Such a phenomenon can be called a multiplicative response, implying that it contains information about several physical effects. Next, we briefly review the main aspects of the measurements of these parameters, including using various Bragg structures.

2.1. Wear measurements

Using relation (2), the reflection spectrum of a conventional FBG was modeled at various lengths (Figures 2-3). It was found that as the length decreases, the quality of the characteristic deteriorates: the spectral width increases \( \Delta \lambda_{\text{FWHM}} \) and decreases the reflection coefficient \( R_{\text{FBG-peak}} \):

![Figure 2](image1.png)  
**Figure 2.** Profile of the reflection spectrum of the original FBG: \( L_0 = 5 \text{ mm}, \ kL = 0.38, \ \lambda_B = 1500 \text{ nm.} \)

![Figure 3](image2.png)  
**Figure 3.** The dependence of the reflection coefficient (red line) and spectral (blue line) - the length of the FBG L.

To increase the range of measurement of wear, structures consisting of several consecutive FBGs, for example, FBGs with a phase shift, can be applied. FBG with phase shift represents two consecutive FBGs of length \( L_1 \) and \( L_2 \), with a length of optical fiber \( l \), not occupied by a lattice equal to one of its period.

FBG with phase shift reflection spectrum profile \( R_{PS} \) will be written as:

\[ R_{PS}(\lambda, L_1, L_2) = 1 - \frac{\gamma^4}{(\Omega^2 + (D_1 - \Gamma)[D_1 - \Gamma[1 - 2\cos(\Delta \varphi)]) + D_2[D_2 - 2\Gamma\sin(\Delta \varphi)]]} \]

where \( \Gamma = \Omega^2 sinh(yL_1)sin(yL_2), \ L_1 \) and \( L_2 \) - lattice length before and after phase shift, \( y^2 = \Omega^2 - \Delta \beta^2, \ \Omega = k, \ D_1 = \gamma^2cosh(yL_1), \ D_2 = \Delta \beta y sinh(yL_2), \ \Delta \beta = \frac{n_{\text{eff}}}{\Lambda} - \frac{2\pi n_{\text{eff}}}{\Lambda}, \ \Delta \varphi \) - lattice phase shift value. The reflection spectrum is shown in Figure 4.

As an information parameter, the power reflected from sensor was selected (Figure 5).
2.2. Temperature measurement

Let’s select from the expression (3) the term responsible for the shift of the wavelength from the temperature $\Delta \lambda_T$:

$$
\Delta \lambda_T = 2 \left( \Lambda \frac{\partial n_{\text{eff}}}{\partial T} + n_{\text{eff}} \frac{\partial \Lambda}{\partial T} \right) \Delta T
$$

(5)

where $\Delta T$ – temperature change. When the length of FBG is reduced, their measurement characteristics remain unchanged [2].

The main measurement problem using conventional FBGs with a Gaussian reflection profile is the measurement resolution associated with the relatively large width of the spectral characteristic. The increase in resolution is achieved by using the characteristic narrow-band features of the reflection spectrum profile, for example, an FBG with a phase $\pi$ - shift [6]. For comparison, the typical width of the spectral characteristics of a conventional FBG is 0.1 nm, and that of a FBG with a phase shift of 0.001 nm, thus potentially increasing the sensitivity by two orders of magnitude [6].

We carried out experimental studies of commercial FBGs with a phase shift to estimate the gain in sensitivity. For this, two FBGs were taken (see Figure 6): one is normal, recorded at the recording station in our laboratory (Figure 6-a), the second is FBG with a phase shift, made with a specialized phase mask (Figure 6-b). Asymmetry in FBG, shown in Figure 6-a is due to the fact that it was recorded using a Lloyd interferometer.

Hereinafter, the YOKOGAWA AQ6370AC spectrum analyzer is used to analyze the characteristics of FBGs.

The measured width of the FBG (or narrowband dip) spectrum was 1.4297 nm and 0.78 nm, respectively.
To confirm the hypothesis, the FBGs were placed under identical highly stable conditions and their characteristic wavelengths were measured. The obtained dispersion values are shown in Figure 7.

The experiment showed that for VBC, the spectral width of the characteristic regions of which differs almost twice, the determination error differs almost three times.

2.3. Vibration measurement
As mentioned earlier, FBG is sensitive to axial tension/compression. When it is glued into the brush, it perceives its deformation, thereby the brush acts as a sensor. Using the specified property, a brush with pasted FBG can act as a vibration sensor.

In [7], the results of the development of a fiber-optic vibration sensor and an optoelectronic circuit for its probing, allowing to provide measurements in a wide frequency range are presented. Its distinctive feature is the rejection of expensive and, mainly, low-speed interrogators in favor of simple schemes with amplitude measurements, where the boundary measured frequency “rests” on the characteristics of the sensor itself and for commercial products amounts to units of kilohertz.

It is worth noting that information about vibration, as well as about temperature, is incorporated in the displacement of the central wavelength. The question arises, how to distinguish them? For different mechanisms, the frequencies of vibrations are in the range from fractions to thousands of Hertz, and, most often, are periodic or quasi-periodic (especially when it comes to moving mechanisms with rotating parts). It is obvious that a change in temperature, in practice, does not meet any of these conditions, so it can be distinguished as a slowly changing process.

3. Multiplicative sensors’ interrogation
In the previous section, it was shown that to determine the length of a multiplicative fiber-optic sensor, it is necessary to measure the amplitude (power) of the radiation reflected from it, and to measure the temperature, the Bragg reflection wavelength.

There are many ways to determine the center wavelength of a FBG reflection. All of them can be divided into two classes conditionally [8]: with the direct determination of the optical wavelength value [9] and radiophotonic [10].

These methods allow for highly accurate changes, but these devices are very expensive. The requirements for accuracy of measurement of wear and temperature are significantly lower than those achieved by the above methods, therefore an alternative design of a polling device that implements a method of power comparison and consisting of one measuring and two reference FBGs (Figure 8 [11]) can be proposed.

The device consists of an optical radiation source (SLD), a set of Bragg gratings (sensor’s FBG and two reference FBG’s), optical coupler and photodiodes. Optical radiation from the source, through the optical fiber and the circulator enters the sensor’s FBG. The radiation reflected from it enters a pair of reference FBGs, which, in turn, cut part of the radiation incident on them to the photodiodes. All elements of the device are made in the fiber version, which increases the mechanical stability and does not require additional adjustments. The increase in the number of sensors is carried out by multiplexing methods, which will be discussed in the next section.

To study the proposed FBG survey method, its mathematical model was developed (for measuring temperature / vibration: Figure 9-a and wear: 9-b).
The described method of interrogating the sensor allows one to realize the possibility, including, of measuring vibration in a wide range of frequencies. Commercial interrogating devices are capable of measuring FBG parameters with a frequency of no more than kHz, in this case, the frequency is limited only by the speed of the ADC used, which is orders of magnitude higher.

4. Experience of practical implementation of a technical solution

The proposed technical solution was constructed and tested under laboratory conditions. The block diagram of the laboratory setup is shown in Figure 10. The installation consists of the studied electric machine (M) of the MSP-0.1 type in one of the brushes of which (Brush 1) are built-in multiplicative fiber-optic sensors (not shown conventionally in figure). Due to the small size of the brushes ($l_{br}=32$ mm) two FBGs were built into it, one of which was located in the middle of the brush (zone B), the other in close proximity to the brush-collector contact zone (A). Due to the fact that in this case the temperature fields for the two FBGs will be different, the use of two identical FBGs is not advisable, since it will not provide adequate information about the temperature distribution, therefore the FBGs selected for different wavelengths were selected. The laboratory thermometer LT-300 with an absolute error of measuring the temperature of $\pm 0.01$ °C (not shown in the diagram) was used as a verified temperature sensor. The operating modes of the electric motor are set using a tunable voltage source TVS, the control of operating parameters is carried out using sensors: collector current (at each of the poles) and engine speed (not shown conventionally in figure). For additional engine cooling during operation, a coolant C is used.

As a result of the experiment, the curves of the dynamics of temperature change in different areas of the brush (Figure 11) and vibration frequency (Figure 12) were obtained.

**Figure 9.** Simulation of the device when measuring temperature (a) and wear (b).

**Figure 10.** Block diagram of the laboratory setup.

**Figure 11.** The dynamics of the temperature of the brush in different areas.
5. Conclusion
Experimental studies have shown that the achievable amount of wear error is no more than 2% (0.11 mm), and the temperature is 0.8 °C, the vibration frequency is 0.1%, which meets the requirements of industry standards and guidance documents for measurement data.

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