The linearization method of positional response curve of the fiber-optic displacement sensor

Sergey A. Matyunin\textsuperscript{a}, Orkhan G. Babaev\textsuperscript{a,*}

\textsuperscript{a}Samara University, Moskovskoye shosse 34, Samara, 443086, Russia

Abstract

Currently, one of the most actual problems in measuring technique is the creation of optical instruments for measuring of linear displacement. The most interesting fiber-optic sensors based on the magneto-optical effect. They are essentially contactless, non-electrical and have closed optical channel resistant to contamination. The main problem of this type of sensors is the non-linearity of positional response curve due to the hyperbolic nature of changing of the magnetic field intensity induced by moving magnetic source mounted on the controlled object relative to the sensing element. This paper discusses the algorithmic method of positional response curve linearization for fiber-optic displacement sensors in any selected range of measured displacements. The method is divided into two stages: 1 - definition of the calibration function, 2 – measurement and linearization of positional response curve (including its temperature stabilization). This algorithm significantly reduces the number of points of the calibration function due to usage of the points randomly deviate from grid points with uniform spacing. Subsequent interpolation of deviating points and piecewise linear-plane approximation reduces the amount of microcontroller memory for storing calibration function and the time required for processing of measurement results. This paper also presents test data of real samples of fiber-optic displacement sensors.

Keywords: Positional response curve; algorithmic linearization method; fiber-optic; displacement sensor; calibration function.

1. Introduction

Currently, one of the most actual problems in measuring technique is the creation of optical instruments for measuring of linear displacement [1-5]. The most interesting fiber-optic sensors (FOS) based on the magneto-optical effect. They are essentially contactless (non-mechanical contact with controlled object), non-electrical (does not contain electrical components in sensing element and does not require electrical power) and have closed optical channel resistant to contamination.

The main problem of this type of sensors is the non-linearity of positional response curve (PRC) due to the hyperbolic nature of changing of the magnetic field intensity induced by moving magnetic source mounted on the controlled object relative to the sensing element [6-16].

Figure 1 shows the dependence of the output signal versus the displacement of typical FOS sensing element based on the Faraday magneto-optical effect in epitaxial films of yttrium iron garnet [1].
2. The structure and operating principle of displacement FOS

Figure 2 shows a block schematic diagram of a differential FOS, based on the magneto-optical effect in epitaxial films of yttrium iron garnet (YIG). FOS consists of a laser diode (LD), a Wollaston prism (WP), YIG on a transparent sapphire substrate and two film polarizers oriented relative to each other at angles of ± 45 degrees (FP1 and FP2). LD has a local stabilization circuit of temperature and radiation power. Electronic converter (EC) of FOS consists of photodiodes (PD1, PD2) and amplifiers of their output signals.

Consider the FOS operating principle (Figure 2). The light beam from the light source LD with circular polarization by fiber optical cable enters to the WP, which splits the beam into two beams with orthogonal polarization 0° and 90°. Both beams pass through the YIG plate, which rotates the polarization plane of each beam to an angle proportional to the intensity of magnetic field induced on FOS. After YIG beams passes through the polarizers FP1 and FP2, initially configured to +45° and -45° for each branch of sensor. The resulting optical signals of FOS are applied to respective photodiodes of EC, in which amplification and the mathematical processing are performed.

The output signal of FOS determined typically according to the following expression [14-15]:

\[ U(x) = \frac{U(1(x,t)) - U(2(x,t))}{U(1(x,t)) + U(2(x,t))} \]

(1)

herein \( U(x) \) - dependence of the output signal on displacement;
\( U(1(x,t)) = Y(1(x,t)) \cdot k \), \( Y(1(x,t)) \) - output electrical and input optical signals of PD1;
\( U(2(x,t)) = Y(2(x,t)) \cdot k \), \( Y(2(x,t)) \) - output electrical and input optical signals of PD2;

Fig. 2. The block schematic diagram of a differential FOS.

Fig. 1. FOS output signal versus displacement.
conversion coefficient of the optical signal to an electrical by photodiodes PD1, PD2.

However, as shown by the simulation results (Figure 3), formula (1) is applicable only when the condition (2) (curves 1 and 2 in Figure 3):

\[ U_1(x, t) + U_2(x, t) = \text{Const} \]  

(2)

In terms of violation (2) there is a sharp distortion of FOS PRC (curves 3 and 4 in Figure 3) and the deterioration of the multiplicative error compensation using the expression (1).

An algorithm described in this paper is devoid of these weaknesses.

3. The method of calibration and linearization of FOS PRC

Calibration function is determining the correspondence of argument (FOS displacement and temperature) to FOS output signal, processing of measurement results and recording obtained dependence to the microcontroller (MC) memory. In the measurement mode is carried out the linearization and temperature correction of the measurement results.

In addition, this algorithm significantly reduces the number of points of the calibration function due to usage of the points randomly deviate from grid points with uniform spacing. Subsequent interpolation of deviating points and piecewise linear-plane approximation reduces the amount of microcontroller memory for storing calibration function and the time required for processing of measurement results.

The method is divided into two stages:

1 – definition of the calibration function of FOS,
2 – measurement and linearization of positional response curve (including its temperature stabilization).
3.1. Definition of the calibration function of FOS

To calibrate the sensor in the microprocessor memory is recorded positional response curve of FOS. This calibration is carried out for a relatively small number of points (16 to 64 points in each variable) \( F(x,t) \). Consider FOS calibration for some portion of the PRC (Figure 4). Let experimentally were obtained following points of PRC: \( U_{i,j}^R(x_{i,j},t_{i,j}) \), \( U_{i+1,j}^R(x_{i+1,j},t_{i+1,j}) \), \( U_{i,j+1}^R(x_{i,j+1},t_{i,j+1}) \), \( U_{i+1,j+1}^R(x_{i+1,j+1},t_{i+1,j+1}) \), herein \( U_{i,j}^R(x_{i,j},t_{i,j}) \) – output voltage of the amplifiers connected to the PD1, PD2 photodiodes, which are located in the FOS electronic converter, [mV], \( x_{i,j}^R \) – predetermined value of linear displacement, [mm]; \( t_{i,j}^R \) – predetermined value of temperature, [°C]; \( i, j \) – number of points on the displacement and temperature axis, respectively; \( R \) – index indicating experimental data.

Obviously, the experimental values may not match with the specified units of measurement grid (grid nodes are usually set at a constant pitch \( \Delta x = const \), \( \Delta t = const \)).

Therefore, during the calibration procedure is carried out piecewise surface (linear or non-linear) interpolation (or extrapolation) of a predetermined order and calculated values of the calibration function \( U_{i,j}[x_j,F_{i,j}(t_j)] \) in the adjacent grid points (Figure 4):

\[
U_{i,j}^R(x_{i,j},t_{i,j}) \rightarrow U_{i,j}(x_j,t_j)
\] (3)

Since the FOS does not contain built-in temperature sensor, and there is no way of determining the temperature explicitly, the change of temperature of the FOS sensing element can be taken into account implicitly (2) according to the change of function value \( F_{i,j}(x_j,t_j) \) (for \( i, j \) – grid points):

\[
F_{i,j}(x_j,t_j) = U1(x_j,t_j) + U2(x_j,t_j) \Rightarrow t_j = F^{-1}_{i,j}[U1(x_j,t_j) + U2(x_j,t_j)],
\] (4)

wherein \( F^{-1}_{i,j} \) - inverse function of \( F_{i,j} \). Hereinafter arguments \( x_j,t_j \) for simplification are replaced with numbers of grid points \( i, j \).

Usually, the development of industrial sensor applications used operating temperature range (0..50) °C. In the case of determining the calibration function of PRC with 10 °C pitch obtains 6 reference points on the temperature axe \( j = 0...5 \). For the displacement range (0..31) mm and a 1 mm quantization step obtain 32 reference points on the displacement axe \( i = 0..31 \). In this case, to store the calibration function of PRC in the space of two variables \( x_i,t_j \) need 192 points of the function values \( U2_{i,j} \).

3.2. Measurement and linearization algorithm of PRC

The measurement mode is carried out linearization of FOS PRC and temperature correction of the measurement results:

1. Voltage values \( U1^R(x) \), \( U2^R(x) \) of the electronic converter amplifiers connected to the FOS are measured.
2. The nearest grid points of \( i, j \) for the measured voltage values are defined:

\[
U_{i,j}^R(x_{i,j},t_{i,j}) \in [U_{i,j}(x_{i,j},t_{i,j}),U_{i+1,j}^R(x_{i+1,j},t_{i+1,j})].
\] (5)

3. Calculate temperature of the nearest grid point from equation (4).
4. Determines the temperature deviation from the nearest grid point:
\[ \Delta t_{i,j} = (t_{i,j}^R - t_{i,j}). \]  

5. Using linear interpolation to implement temperature compensation of voltage values:

\[ U_1^R(x,t) \rightarrow U_1^c(x), \quad U_2^R(x,t) \rightarrow U_2^c(x), \]

wherein \( U_1^c(x), \ U_2^c(x) \) – measured voltage values after temperature correction.

6. The PRC calculated from CC using inverse function of PRC:

\[ x = x_i + U^{-1}[\Delta U_{1,2}(x)], \]

wherein \( \Delta U_{1,2}(x) = U_1^c(x) - U_2^c(x) \). Thus, the PRC linearization carried out.

7. Then scaling of the obtained values range is performed to the full measurement range of the argument \( x \in [x_{\text{min}}, x_{\text{max}}] \) (for example, to the range [0 ... 4095]). The result is ADC digital code \( \text{ADCcode}(x) \) of converter microcontroller corresponding to the displacement:

\[ \text{ADCcode}(x) = 4095 \frac{x - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}}. \]

4. Experimental study

Experimental studies were carried out on displacement FOS samples SAM.FOS.YIG-2/50, developed in the laboratory NIL-53 of Samara University (Figure 5). The experimental results are shown in Figures 1, 3, 6. Figure 6a shows the FOS PRC (curve 1), supplied to the input of the electronic converter, and digital result code (curve 2). There linearization carried out on the site of displacement [20 ... 32 mm] (site of displacement can be anything in the range [0 ... 32 mm]). Figure 6b shows the same FOS PRC after linearization on an enlarged scale. This algorithm makes it easy to move the
operating range of linearization PRC to any part of the displacement range including the entire range. Designed FOS (SAM.FOS.YIG-2/50) has the following operating characteristics (table 1).

Fig. 5. External view of SAM.FOS.YIG-2/50 sensor.

Table 1. Operating characteristics of SAM.FOS.YIG-2/50.

<table>
<thead>
<tr>
<th>Operating characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions of the sensing element, mm</td>
<td>Ø3.5 x 30</td>
</tr>
<tr>
<td>FOS dimensions, mm</td>
<td>79 x 18(30) x 13</td>
</tr>
<tr>
<td>Stroke of moving stock, mm</td>
<td>from 0 to 50</td>
</tr>
<tr>
<td>Accuracy class</td>
<td>0.5</td>
</tr>
<tr>
<td>Additional temperature error, %/°C</td>
<td>0.0025</td>
</tr>
<tr>
<td>PRC nonlinearity, %</td>
<td>0.01</td>
</tr>
<tr>
<td>Operating temperature, °C</td>
<td>from 0 to +50</td>
</tr>
<tr>
<td>The length of the fiber optic cable, m</td>
<td>to 10</td>
</tr>
</tbody>
</table>
5. Conclusions

1. The virtue of the developed technique and an algorithm is that linearization and scaling can be performed in any range of the measured displacements $x \in [x_{\text{min}}, x_{\text{max}}]$ and temperatures. This allows to calibrate FOS by simple way on controlled object and speeds up the calibration process, that is essential in case of mass production of FOS.

2. Experimentally confirmed high linearity of PRC – PRC nonlinearity does not exceed 0.01% in a range of displacements from 0 to 50 mm.

3. Experimentally confirmed high temperature stability of FOS – temperature coefficient does not exceed 0.0025%/°C in the temperature range from 0 to +50 °C.

References