Linearization of Positional Response Curve of a Fiber-optic Displacement Sensor

O.G. Babaev*, S.A. Matyunin and V. D. Paranin
Samara National Research University, Moskovskoe shosse, 34, Samara, 443086, Russia
E-mail: *orbaev@yandex.ru

Abstract. Currently, the creation of optical measuring instruments and sensors for measuring linear displacement is one of the most relevant problems in the area of instrumentation. Fiber-optic contactless sensors based on the magneto-optical effect are of special interest. They are essentially contactless, non-electrical and have a closed optical channel not subject to contamination. The main problem of this type of sensors is the non-linearity of their positional response curve due to the hyperbolic nature of the magnetic field intensity variation induced by moving the magnetic source mounted on the controlled object relative to the sensing element. This paper discusses an algorithmic method of linearizing the positional response curve of fiber-optic displacement sensors in any selected range of the displacements to be measured. The method is divided into two stages: 1 - definition of the calibration function, 2 – measurement and linearization of the positional response curve (including its temperature stabilization). The algorithm under consideration significantly reduces the number of points of the calibration function, which is essential for the calibration of temperature dependence, due to the use of the points that randomly deviate from the grid points with uniform spacing. Subsequent interpolation of the deviating points and piecewise linear-plane approximation of the calibration function reduces the microcontroller storage capacity for storing the calibration function and the time required to process the measurement results. The paper also presents experimental results of testing real samples of fiber-optic displacement sensors.

1. Introduction
Currently, the creation of optical measuring instruments and sensors for measuring linear displacement is one of the most essential problems in instrumentation. Of special interest are fiber-optic sensors (FOS) based on the magneto-optical effect [1-9]. They are essentially contactless (no mechanical contact with the controlled object), non-electrical (do not contain electrical components in the sensing element and do not require electrical power) and have a closed optical channel not subject to contamination [6-9].

The main problem of this type of sensors is the non-linearity of their positional response curve (PRC) due to the hyperbolic nature of the magnetic field intensity variation induced by moving the magnetic source mounted on the controlled object relative to the sensing element [5, 8]. Figure 1 shows the dependence of the output signal on the displacement of a typical FOS sensing element based on the Faraday magneto-optical effect in epitaxial films of yttrium iron garnet (YIG) [6-8].
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). The fiber-optic sensor consists of a laser diode (LD), a Wollaston prism (WP), a YIG on a transparent sapphire substrate and two film polarizers oriented at angles of ± 45° relative to each other (FP1 and FP2). The LD has a local circuit of temperature stabilization and radiation power stabilization. A secondary converter (electronic converter - EC) of the fiber-optic sensor contains two fiber-optic photodiodes (PD1, PD2) that convert the sensor’s optical signals into electrical ones, and amplifiers of their output signals. The converter is placed at a safe distance from the control object to avoid fire or explosion.

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

The output signal of the FOS is typically determined according to the following expression [6-8]:

\[
U(x) = \frac{U_1(x,t) - U_2(x,t)}{U_1(x,t) + U_2(x,t)},
\]

where \(U(x)\) is the dependence of the FOS output signal on the displacement;
\(U_1(x,t) = Y_1(x,t) \cdot k\), \(Y_1(x,t)\) are the output electrical and input optical signals of PD1;
\(U_2(x,t) = Y_2(x,t) \cdot k\), \(Y_2(x,t)\) are the output electrical and input optical signals of PD2;
\(k\) is the coefficient of conversion of the optical signal to an electrical one by photodiodes PD1, PD2.
However, as shown by the simulation results (Figure 3), formula (1) is applicable only if the condition (2) (curves 1 and 2 in Figure 3) is fulfilled:

$$U_1(x,t) + U_2(x,t) = \text{Const}$$  \hspace{1cm} (2)

If condition (2) is violated there is a sharp distortion of the FOS PRC (curves 3 and 4 in figure 3) and deterioration of the multiplicative error compensation using the expression (1). The algorithm described in this paper is free from these disadvantages.

Figure 3. The PRC of the differential FOS: curves 1, 3 – function $U_1(x,t) + U_2(x,t)$ for cases $U_1(x,t) + U_2(x,t) = 0.05...1.0$ and for $U_1(x,t) + U_2(x,t) = 1.08...1.1$ respectively; curves 2, 4 – function (1) for cases $U_1(x,t) + U_2(x,t) = 0.05...1.0$ and for $U_1(x,t) + U_2(x,t) = 1.08...1.1$ respectively.

3. Method of calibration and linearization of FOS PRC

The calibration function determines the correspondence of the arguments (FOS displacement and temperature) to the FOS output signal, processing of measurement results and storing the obtained dependence in the microcontroller (MC) memory. In the measurement mode FOC PRC linearization and temperature correction of the measurement results takes place. In addition, the algorithm under consideration significantly reduces the number of points of the calibration function due to the use of the points that randomly deviate from the grid points with uniform spacing. Subsequent interpolation of the deviating points and piecewise linear-plane approximation reduces the microcontroller storage capacity to store the calibration function and the time required for the processing of measurement results.

The method is divided into two stages: 1 – definition of the FOS calibration function, 2 – measurement and linearization of the positional response curve (including its temperature stabilization).

3.1. Definition of the calibration function of FOS

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

Obviously, the experimental values may not coincide with the specified nodes of the measurement grid (grid nodes are usually assigned at a constant step \( \Delta x = \text{const} \), \( \Delta t = \text{const} \)).

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

\[
U_{i,j}^R(x_i^R,t_j) \rightarrow U_{i,j}(x_i,t_j),
\]

(3)

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

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

(4)

where \( F_{i,j}^{-1} \) is the inverse function of \( F_{i,j} \). Hereinafter the arguments are replaced with numbers of grid points \( i,j \) for simplification.

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

3.2. PRC measurement and linearization algorithm

Both the linearization of the FOS PRC and temperature correction of the measurement results are carried out in the measurement mode:

1. Voltage values \( U1^R(x_i), U2^R(x_i) \) 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:

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

(5)

3. The temperature of the nearest grid point is calculated from equation (4).
4. Temperature deviation from the nearest grid point is determined:

\[
\Delta t_{i,j} = (t_i^R - t_{i,j}).
\]

(6)

5. Using linear interpolation temperature compensation of the voltage values is implemented:

\[
U1^R(x,t) \rightarrow U1'(x), \ U2^R(x,t) \rightarrow U2'(x),
\]

(7)
where $U_1^c(x)$, $U_2^c(x)$ are the measured voltage values after temperature correction.

6. The PRC is calculated from the calibration curve using the inverse function of PRC:

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

(8)

where $\Delta U_{1,2}(x) = U_1^c(x) - U_2^c(x)$. Thus, linearization and temperature correction of the PRC are carried out.

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

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

(9)

4. **Experimental study**

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

**Figure 4.** Determination of calibration values of FOS PRC.

**Figure 5.** External view of SAM.FOS.YIG-2/50 sensor.
Figure 6. (a) Experimental FOS PRC; (b) FOS PRC after linearization on an enlarged scale.

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

| Distance (m) | Velocity (m/s) |
|-------------|----------------|
| Dimensions of the sensing element, mm | Ø3.5 × 30 |
| FOS dimensions, mm | 79 × 18 (30) × 13 |
| Stroke of moving rod, mm | from 0 to 50 |
| Accuracy class | 0.5 |
| Additional temperature error, %/°C | 0.0025 |
| PRC nonlinearity, % | 0.01 |
| Operating temperature, °C | from 0 to +50 |
| Length of the fiber-optic cable, m | to 10 |
| Type of the fiber-optic cable | Ø0.9 MM (62.5/125) |
| Type of the optical connectors | FC/PC |
| Storage temperature, °C | from −40 to +85 |

5. Conclusions
1. The apparent advantage of the developed technique and the algorithm is that linearization and scaling can be performed in any range of the measured displacements and temperatures. This makes FOS calibration on the controlled object easy and speeds up the calibration process, which is essential for mass production of FOS.
2. High linearity of PRC is experimentally confirmed – PRC nonlinearity does not exceed 0.01% in the range of displacement from 0 to 50 mm.
3. High temperature stability of FOS is experimentally confirmed – the temperature coefficient does not exceed 0.0025%/°C in the temperature range from 0 to +50 °C.

Acknowledgements
The work is conducted with financial support of the Ministry of Education and Science of the Russian Federation. Unique ID: Applied research and experimental work RFMEFI57816X0209.

References
[1] Li C, Yoshino T and Cui X 2007 Magneto-optic sensor by use of time-division-multiplexed orthogonal linearly polarized light Appl. Opt. 46(5) pp 685-8
[2] Müller G M, Yang L, Frank A and Bohnert K 2014 Simple fiber-optic current sensor with integrated-optics polarization splitter for interrogation Proc. Imaging and Applied Optics 2014 (Seattle) paper AM4A.3
[3] Sohlström H and Svantesson K 1992 The performance of a fibre optic magnetic field sensor utilizing a magneto-optical garnet Proc. International Conference on Optical Fiber Sensors 1992 (Monterey) paper P25
[4] Deeter M N 1996 Fiber-optic Faraday-effect magnetic-field sensor based on flux concentrators Appl. Opt. 35(1) pp 154-7
[5] Garzarella A, Shinn M A and Wu D H 2015 Responsivity optimization in magneto-optic sensors based on ferromagnetic materials Appl. Opt. 54(26) pp 7904-11
[6] Matyunin S A, Fedotov Ŷ A, Babaev O G, Wirchenko M K, Gusev M Y and Neustroev N S 2015 Fiber-optical sensors based on mono-crystal films of garnet ferrites for mechatronic systems Procedia Engineering 106, pp 202-9
[7] Matyunin S A, Babaev O G 2015 Contactless fiber-optic vibration sensors for explosive manufacturings Proc. 22nd International Congress on Sound and Vibration (Florence), p 150
[8] Matyunin S A, Stepanov M V, Babaev O G 2016 Simulation of the characteristics of a magneto-optical displacement transducer Measurement Techniques 59(8), pp 832-7
[9] Babaev O G, Matyunin S A, Stepanov M V 2017 Simulation of Contactless Fiber-optic System for Valve Status Monitoring Procedia Engineering 176, pp 2-11