Fiber-optic Sensor of Tactile Force for Anthropomorphic Robot Grips

SA Matyunin* and O G Babaev

Samara National Research University, Moskovskoe shosse, 34, Samara, 443086, Russia

E-mail: *s.a.matyunin@yandex.ru

Abstract. This paper examines an operating principle of a Fiber-Optic Tactile Force Sensor (FOTFS), describes a linearization method and temperature compensation on transfer characteristics (TC) of the FOTFS. The high linearity of the FOTFS TC (the nonlinearity of the TC does not exceed 0.01% within the range of tactile forces from 0 to 1.4 N) and the high temperature stability of the FOTFS (the temperature coefficient does not exceed 0.0025%/°C) within the temperature range from 0 to +50 °C) are experimentally-confirmed.

1. Introduction

At the present time, intensive research is being carried out to create intelligent anthropomorphic robots for various applications: for use in everyday life, at work, in space, for example, for repairing space vehicles. To perform a variety of works anthropomorphic robots require a wide variety of "sense organs", including "force control organs" of robot grips [1].

When developing robotic systems, contactless Fiber-Optic Tactile Force Sensors (FOTFS) are of special interest, as they are basically "non-electrical" with a closed optical channel (nonfouling in the area of optical channel). The FOTFS can be implemented on the basis of various effects: on the magneto-optical effect, on the effect of bending losses modulation in an optical fiber, on microbendings of a Bragg grating, on the basis of an external Fabry-Perrot interferometer, etc. [2-10].

In [2] stretch sensors for soft robots with elastomeric actuators are described. These robots designed for the sphere of human-robot interaction (HRI) such as direct contact with the heart for ventricular assist devices and wearable robots for exocolettes with increased strength. However, sensors of this type can not be used in space, where the temperature drops to −150 degrees. In [3] FOTFS for an industrial robot with a two-fingered arm are described. These sensors are capable of operating over a wide temperature range. The main problem of such FOTFS is the dependence of the operating characteristics of their elements (mainly semiconductor lasers) on external influences, primarily on temperature, and also the nonlinearity of the transfer characteristic (TC). An interesting solution is proposed in [4] - the use of stretchable flexible fibers to determine the deformation in the prosthetic hand. In [5, 6] fiber-optic sensors of tactile force on Bragg gratings, which can be used for anthropomorphic robot grips, are described. Advantages of this solution: high accuracy of measurement, small overall dimensions. Disadvantages: a complex scheme of optical signal processing, low speed of a multichannel optical signal processing system, expensive equipment (high-resolution spectrometer). As well as stretchable sensors, they can not be applied in space. To prospective developments can be attributed sensors on the effect of bend losses modulation in an
optical fiber, described in [7, 8]. Advantages of such tactile sensors: a closed optical channel, small mass-dimensional parameters; low cost; wide operating temperature range. Disadvantages: the ambiguity of the measurement results - the sensors do not allow you to determine the location of the tactile load, but only the integral load along the entire length of the optical fiber. In [9, 10] many other options for implementing FOTFS are considered.

The main problem of such FOTFS is the characteristics dependence of their elements (mostly semiconductor lasers) on external effects, primarily on the temperature, as well as the nonlinearity of the transfer characteristics (TC) of the FOTFS caused by mode content variation of the emission for the sensors based on effect of the bending losses modulation, etc. [9, 10].

As noted above, according to minimization of dimensional-and-weight characteristics of the FOTFS, promising FOTFS are those, which are based on the effect of bending losses modulation in the optical fiber - the sensitive fiber diameter of such FOTFS is in the range of 0.125 mm without a protective coating and 0.8-0.9 mm with a protective coating.

However, the nonlinearity of TC and its dependence on temperature are typical for many FOTFS. Thus, there is a need to develop a linearization method and compensation of the temperature effect for the FOTFS TC.

2. Design and function of the FOTFS

This paper considers the linearization method of TC and compensation of the temperature effect on the FOTFS TC using the example of the FOTFS based on the modulation effect of bending losses in the optical fiber (this method can be applied practically unchanged also for fiber-optic sensors based on other principles of operation).

The schematic structure of the FOTFS based on the effect of bending losses modulation in the optical fiber is shown in Figure 1. The FOTFS consists of an intertangled optical fibers (OF) matrix forming a sensing element (SE), an optical emission source (ES) combined in a fiber-optic link (FOL), a reversal mirror (RM), a CCD matrix (CCDM) receiving emission and a microcontroller (MC). The temperature in the area of force exertion to the SE is measured by a fiber-optic temperature sensor TS, which can be used as one of the SE fibers, unaffected by tactile force.

Figure 1. Schematic structure of the FOTFS.

The operation principle of the FOTFS is based on the use of bending losses modulation in the optical fiber when it deforms within the elastic limit [9, 10]. The ES emission (semiconductor laser) passed through the RM gets into the FOL (in the form of a tow) and then into the SE. The SE is a pieces of optical fiber settled as a rectangular grid. The optical signals reflected from the ends of optical fibers get back into the FOL and being reflected from the RM, go to the CCD matrix and then to the MC for further information processing.

Figure 2 shows the experimental TC of one SE channel of the FOTFS (curve 1 - experimental values, curve 2 - polynomial approximation). In figure 2, a sharp nonlinearity of the TC can be
observed in the range of tactile forces $q$ from 0 to 1.2 N (displacement $x$ of optical fiber SE from 0 to 0.6 mm). It should be noted that the temperature coefficient of the output optical power change $P(q)$ (without stabilizing feedback) reaches a value of minus 1.2%/$^\circ$C.

Figure 2. Experimental TC of one SE channel of the FOTFS.

3. Method of linearization and compensation of the temperature effect on the TC

The method consists of two stages:

Stage 1 – identifying of the FOTFS calibration function;

Stage 2 – temperature compensation and linearization of the TC.

The identifying of the calibration function involves the determining of the correspondence between the arguments (tactile force and temperature of the FOTFS SE) and the FOTFS output signal, processing the measurement results and obtained dependence recording to the memory of the microcontroller (MC). The method under consideration allows to reduce significantly the number of the FOTFS calibration function points, which is especially important in the temperature dependence calibration, as it allows to use points deviating in a random way from the nodal points with uniform spacing. Subsequent points interpolation to the nearest nodal ones and piecewise-surface approximation of the calibration function allows to reduce used memory size of the MC for calibration function storing and the time required to process the measurement results.

Stage 1. Identifying of the calibration function

The output signal value of one CCDM channel denoted via $U_k(q, t)$, where $q$ is the value of the tactile pressure; $T$ is the temperature, $K$ is the number of the CCDM channel.

When the sensor is calibrated, the TC of each SE channel of the sensor is recorded into the MC memory for various values of the tactile force $q$ and temperatures $t$. It should be noted that the calibration is performed for a relatively small number of points in temperature and tactile force (16 to 64 points for each variable $q$ and $t$).

The grid nodes of the calibration matrix are practical to set with a constant spacing. It is obvious that the experimentally obtained values of the variables $q$ and $t$ cannot get exactly to the fixed grid nodes. Therefore, during the calibration procedure, a piecewise-surface (linear or nonlinear of a fixed order) interpolation (extrapolation) is performed to the nearest nodal points (Figure 3) of the calibration function, which are stored in the memory of the MC.
Stage 2. Temperature compensation and linearization of the TC

At stage 2, both the linearization of the FOTFS TC and the temperature correction of the measurement results are performed. For this purpose, it is necessary:

1. to measure the signal values of each CCDM channel - \( U_K(q, t) \);
2. to measure the grip temperature sensor signal \( U_T(t) \);
3. to determine the deviation of temperature from the nearest nodal point in temperature \( U^{\top}(t_j) \):

\[
U^{\top}(t) = U^{\top}(t_j) + \frac{dU^{\top}(t)}{dt}(t - t_j) \approx U^{\top}(t_j) + \frac{U^{\top}(t_{j+1}) - U^{\top}(t_j)}{t_{j+1} - t_j} (t - t_j) \rightarrow
\]

\[
\Delta t = (t - t_j) = \frac{U^{\top}(t) - U^{\top}(t_j)}{U^{\top}(t_{j+1}) - U^{\top}(t_j)} (t_{j+1} - t_j).
\]

(1)

4. Using, for example, linear interpolation, there are performed the temperature compensation and the linearization of the TC \( U_K(q, t) \). For this purpose, the measurement signal for channel \( K \) is set as a deviation from the nearest node points (Figure 4):

\[
U_K(q, t) = U_K(q_j + \Delta q, t_j + \Delta t) = U_K(q, t_j) + \frac{\partial U_K(q, t_j)}{\partial t_j} \Delta t + \frac{\partial U_K(q, t_j)}{\partial q_j} \Delta q \approx
\]

\[
= U_K(q_j, t_j) + \frac{U_K(q_j, t_{j+1}) - U_K(q_j, t_j)}{t_{j+1} - t_j} \Delta t + \frac{U_K(q_{j+1}, t_j) - U_K(q, t_j)}{q_{j+1} - q_j} \Delta q.
\]

(2)

It follows that:

\[
q = q_j + \Delta q =
\]

\[
= q_j + \frac{U_K(q, t) - U_K(q_j, t_j)}{U_K(q_{j+1}, t_j) - U_K(q_j, t_j)} (q_{j+1} - q_j) - \frac{U_K(q_{j+1}, t_j) - U_K(q, t_j)}{U_K(q_{j+1}, t_j) - U_K(q, t_j)} \frac{\Delta t}{(t_{j+1} - t_j)} (q_{j+1} - q_j),
\]

(3)

where \( \Delta t \) is determined from (1).

It is obvious that equation (3) is obtained from equation (2) by calculating the function of the inverse function \( U_K(q, t) \), which ensures a linear dependence of the output parameter \( q \) on the measured value of the tactile force.
5. After that, the obtained values of the argument $q$ are scaled to the appropriate range, (for example, to the range $[0 ... 4095]$). As a result, the microcontroller digital code $q^*$ corresponding to the tactile force is calculated:

$$ q^* = 4095 \frac{q - q_{\text{min}}}{q_{\text{min}} + q_{\text{max}}} $$

where $q_{\text{min}}$ and $q_{\text{max}}$ are the minimum and maximum values of the tactile force respectively.

4. **Experimental research**

Experimental research was carried out using the FOTFS samples, developed in the laboratory of NIL-53 of the Samara National Research University. The experimental research results are shown in figure 5. Figure 5 shows the FOTFS TC (curve 1) fed to the input of the electronic converter and the digital result code (curve 2).

Given approach (4) allows moving easily the operating range of the linearization of the TC to any part of the range.

The main characteristics of the experimental FOTFS samples are given in Table 1.

**Table 1.** FOTFS main characteristics
| Characteristics                        | Value                      |
|----------------------------------------|----------------------------|
| Dimensions of the sensing element, mm  | 10x15                      |
| Measured tactile force, N              | from 0 to 1.4              |
| Accuracy class                         | 0.5                        |
| Complementary temperature error, %/°C | 0.0025                     |
| Nonlinearity of TC, %                 | 0.01                       |
| Operating temperature, °C             | from 0 to +50              |
| Length of fiber-optic cable, m        | to 10                      |
| Fiber-optic cable Ø0.9 SM             |                            |
| Optical connectors FC/PC               |                            |
| Storage temperature, °C               | from −40 to +85            |

5. Conclusion
1. Certain advantage of the developed method is the fact that scaling and linearization can be carried out within any measurement and temperature range. This allows to calibrate the FOTFS in a simple way using the control object and speeds up the calibration process, which is extremely important for mass production.
2. The high linearity of the TC is experimentally confirmed - the nonlinearity of the TC does not exceed 0.01% within the range of tactile forces from 0 to 1.4 N.
3. The high temperature stability of FOTFS is experimentally confirmed - the temperature coefficient does not exceed 0.0025%/°C within the temperature range from 0 to +50 °C.

Acknowledgements
The work is performed with financial support from the Ministry of Education and Science of the Russian Federation. Unique ID: Applied research and experimental work RFMEF157816X0209.

References
[1] Sareh P and Kovac M 2017 Mechanized creatures Science 355(6332) p 1379
[2] Li S, Zhao H and Shepherd R 2017 Flexible and stretchable sensors for fluidic elastomer actuated soft robots MRS Bulletin 42(2) pp 138-142
[3] Park Y-L, Ryu S C, Black R J, Chau K K, Moslehi B and Cutkosky M R Exoskeletal force-sensing end-effectors with embedded optical Fiber-Bragg-Grating sensors 2009 IEEE Transactions on Robotics 25(6) pp 1319-31
[4] Zhao H, O’Brien K, Li S and Shepherd R F 2016 Optoelectronically innervated soft prosthetic hand via stretchable optical waveguides Science Robotics eaai7529
[5] Shao L-Y and Albert J 2010 Compact fiber-optic vector inclinometer OSA: Optics Letters 35(7) pp 1034-6
[6] Fernandez A F, Berghmans F, Decrèton M, Delchambre A 2001 Multicomponent force sensor based on multiplexed fibre Bragg grating strain sensors Measurement Science and Technology 12(7) pp 810-813
[7] Silva A S, Catarino A, Correia M V and Frazão O 2013 Design and characterization of a wearable macrobending fiber optic sensor for human joint angle determination SPIE: Optical Engineering 52(12) 126106
[8] Koyama Y, Nishiyama M and Watanabe K 2015 Multi-channel measurement for hetero-core optical fiber sensor by using CMOS camera Proc. SPIE 9655  ‘Fifth Asia-Pacific Optical Sensors Conference’ (Jeju) 965525
[9] Grattan K T V and Sun Dr T 1999 Fiber optic sensor technology: an overview Sensors and Actuators 82 (2000) pp 40-61
[10] Matyunin S A 2016 Fiber-optical measuring system of angular movements of finger falangs of the anthropomorphous robots hand Izvestiya SFedU. Engineering sciences vol 1 pp 240-252