Installation for investigation of optical and mechanical system of fiber optical sensors of parameters of liquid or air flows

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Abstract A special measuring unit has been developed for experimental studies of micro-optomechanical systems of fiber-optic micro-angle transducers based on a bellows and micrometer, which are the basic elements of fiber-optic sensors of aerodynamic angles, imitating the physical effect of the flux on the sensing element.

1. Introduction
In solving many problems of measuring the parameters of air or liquid flows, at present, either mechanical (potentiometric, pneumatic) or ultrasonic transducers and sensors based on them are used [1-6]. For example, in wind vane sensors of aerodynamic angles, the measuring circuit contains a mechanical conversion system, including gearing, bearing connections, etc. [11]. This factor leads to a decrease in the reliability of the sensor when exposed to various mechanical effects, the emergence of resonance phenomena in the vibrations of the aircraft, significant dynamic errors, large mass-dimensional characteristics. Therefore, these measuring instruments cannot guarantee the high accuracy of measuring the parameters of fluxes under severe mechanical, climatic, and electromagnetic environmental conditions [7].

A good alternative to "electrical" measuring instruments are fiber-optic sensors of flow parameters [8, 9].

2. Methods
It is proposed to use the fiber-optical conversion principle for measuring the parameters of fluid and air streams, which allows to completely move away from the mechanical conversion system with moving elements [10].

In papers [11, 12, 13] considered fiber-optic sensors (FOS) aerodynamic angles (FOSAA) and parameters of fluid flows of bellows type, the basic element of which are fiber-optic micro-angle transducers (FOMAT) with an elastic element in the form of a bellows (figure 1).

For many years, bellows have been the subject of close attention when considering the problem of compensating for the stretching and contraction of products subjected to movement under the influence of temperature, pressure and external sources.
Figure 1. Simplified design diagram, reflecting the processes occurring in the ULF bellows type.

The bellows basically performed the function of compensating or balancing the influence of various factors on the operation of a system or mechanism. Their use as compensators is characterized by reliable and effective protection of products against statistical and dynamic loads arising during deformations. Due to the use in the manufacture of high-quality materials, the bellows are able to work in the toughest conditions with working temperatures ranging from « absolute zero » before 1000 °C and perceive working pressures from vacuum to 100 atmospheres depending on the design and working conditions [14].

The listed advantages of the bellows make it possible to consider the possibility of its use as part of FOSAA a bellows type to convert the force effect of an air or liquid flow into the angular displacement of its axis (figure 2) [15, 16].

Figure 2. Sketch of the bend of the bellows under the influence of the load.

The elastic characteristic of any bellows is more or less nonlinear and manifests itself in the relationship between the movement of the bellows and the load value applied to it [14]. When designing the FOSAA, which is based on the FOMAT of the bellows type, we adhere to the statement that the bellows performs angular microdisplacements \( \theta = \pm 3 \ldots 5 ^\circ \) – thus, the linearity of the elastic characteristic of the bellows is ensured in a given range of microdisplacements (see figure 2). Studies
conducted by the authors of the article determined the restrictions on the angular micromovement of a reflecting element in the range ± 3°.

2.1 Objective
In order to achieve improved metrological characteristics of fiber optic sensors with FOSAA bellows type, it is necessary to determine the type of conversion function $I = f(\theta)$, angle range $\theta$, design parameters of the node alignment of the supply and output optical fibers, the optical modulating element: the distance between the common end of the optical fibers and the optical modulating element, the center-to-center distance between the optical fibers. This requires specialized metrological support.

3. Results
To conduct experimental studies of micro-optomechanical systems, a special laboratory measuring facility has been developed that simulates the physical effect of air or liquid flows on a perceiving element (Figure 3).

![Figure 3](image)

**Figure 3.** Installation simulating the effect of air flow on the sensing element.

Figure 4 shows the 3-D model of the mechanical part of this installation.

![Figure 4](image)

**Figure 4.** 3D-model of the mechanical system of the installation, simulating the processes occurring in the fiber-optic sensor aerodynamic angles.
The input and output optical fibers in FOMAT located relative to the reflective surfaces of the modulating element at equal distances and coaxially relative to each other. The element perceiving the measured physical quantity is made in the form of a metal plate having mirror outer surfaces. On both sides of the plate are optical fibers of two measuring channels, and the supplying optical fibers SOF1 the first measuring channel are located coaxially with the output optical fibers OOF2 the second measuring channel and, conversely, the supply optical fibers SOF2 of the second measuring channel are aligned with the outgoing optical fibers OOF1 of the first measuring channel. The width and length of the plate are chosen in such a way that the dimensions of the light spot in the measurement range do not exceed its dimensions. If the optical fibers have a core diameter $d_c = 0.2$ mm, external diameter $d_{OF} = 0.5$ mm, then the calculated dimensions of the plate: width $– 3$ mm, thickness $– 0.2$ mm, length $– 20$ mm, distances between optical axes of optical fibers $D = 0.7$ mm, and the initial distance from the fiber end to the plate $x_0 = 1.5$ mm.

The sensing element is rigidly fixed on the lid of the bellows with a certain displacement relative to the center of the bellows. In the inner part of the bellows, a metallic platynsa is also rigidly fixed with an offset from the center of the bellows, but in the opposite direction. The bellows is fixed at the base of the stopper. The limiter does not allow the bellows to shrink more than 5 degrees.

FOMAT optical scheme has design parameters that meet the following requirements:
- in the absence of an impact of the measured physical quantity on the sensing element, the light radiation emerging from the ends of SOF1 and SOF2 after reflection from the mirror surfaces of the plate should be distributed so that the overlap area of the light spot and the receiving ends of the OOF1 and OOF2 is half of;
- under the influence of a physical quantity on the sensing element, an angular displacement of the plate through an angle must occur and, accordingly, the change in the area of overlap of the light spot and the receiving ends OOF1 and OOF2;
- plate deflection at maximum angle $3^\circ$ to the right leads to a complete overlap of the area of the receiving end OOF1 the light flux reflected from the plate, and the light flux will not come to the receiving end of the OOF2.

Similar processes occur when the plate is deflected to a maximum angle $3^\circ$ to the left.

Installation for experimental studies consists of an optical tester, fiber-optic cable, installation to simulate the parameters of air or liquid flow (figure 5).

FOMAT is designed for contactless conversion of changes in the angle of inclination of the plate in the change in the amplitude of the DC.

Installation to simulate the parameters of air or liquid flow is designed to set the angle of inclination (offset from the vertical position) of the plate in the range $0...5^\circ$.

The angle is set using the angle setting system based on the microscrew. Since the micrometer screw is used, it is necessary to compare the displacements in microns (H) with a deviation from the vertical in degrees ($\alpha$) (table 1).
Figure 5. Block diagram of the laboratory layout:

FOC – fiber optic cable; P – photodiode; LED – Light-emitting diode; SOF – the supply optical fibers; OOF – the outgoing optical fibers.

Table 1. Correspondence of movement to angular movement.

| $H$, мкм | 0   | 0,261 | 0,525 | 0,768 | 1,047 | 1,308 | 1,569 | 1,83 | 2,094 | 2,355 | 2,616 |
|----------|-----|-------|-------|-------|-------|-------|-------|-----|-------|-------|-------|
| $\alpha$, град | 0   | 0,5   | 1     | 1,5   | 2     | 2,5   | 3     | 3,5 | 4     | 4,5   | 5     |

When mounting the plate in the lid of the bellows, it is necessary to ensure strict perpendicularity of their planes and parallelism of the reflecting planes of the plate and the working ends of optical fibers. To provide an initial distance, for example $x_0 = 1,5$ mm, it is necessary to install on both sides of the plate unambiguous measures of the length of 1.5 mm and to bring the tips with optical fibers close to them. At the same time, the output signals of photodiodes, docked to the tapping optical fibers should be minimal (the numerical value is determined experimentally for a specific sample FOMAT). If the values of the output signals are minimal, then the initial distance $x_0 = 1,5$ mm between the plate and the ends of the optical fibers corresponds to the calculated value. This position of the plate determines the point of reference in the measurements.

The installation works as follows. With the help of the micrometer screw, a force is applied to the perceiving element fixed in the upper part of the installation.

In the zero position with no inclination angle of the plate, the rays of light from the SOF1 and SOF2 under the aperture angle $\omega_{NA}$ to the optical axis of the fiber are in the forward direction $x_0$ to the reflecting plane of the plate and the path $x_0$ in the opposite direction to OOF1 and OOF2. In this case, in the plane of the receiving ends of OOV1 and OOV2, there is an illuminated annular zone with a width $h = r_C$, where $r_C$ – the radius of the core of the optical fiber. The annular zone is converted into an ellipsoid zone, which is displaced relative to OOF1 and OOF2 in the direction perpendicular to the common fiber end [10]. In this case, the areas of the receiving ends of OOF1 and OOF2, illuminated by light streams reflected from the mirrors, change. Then there is a further conversion of the output optical signal into a current signal.

In the optical tester circuit, two radiation detectors (photodiode) are provided to provide a differential circuit. The optical tester contains a radiation source (an infrared LED of type 3L107B) with adjustable radiation power, two photoreceiving channels (photodiodes with amplifiers), an
information processing unit (programmable microcontroller), a digital indicator and a power supply. Three buttons are located on the front panel of the tester: the first button allows you to compensate for the initial bias voltage of the photoreceiving channels (“Const. 0”); the second button is the choice of information processing mode; the third button turns off the display of the number of the selected information processing mode.

The current passing through the LED can take three values -0; 50; 80 nA, selected with the help of a toggle switch: “Const. 0” - to compensate for the initial bias voltage of the photodetector channels (zero setting), «50 nA» і «80 nA» – to measure. Used type photodiodes FD256 work in the photovoltaic mode, which ensures a low level of intrinsic noise. They are connected to a “current-to-voltage” converter, providing near-zero bias voltage (equally \( U_{SM} \) operational amplifier) and low (close to zero) load impedance of the photodiode. This allows to obtain a high linearity of the conversion function of the photodetector channels in the range of variation of the intensity of the received optical signal from 0 before \( 10^6 \) nA.

Maximum output of photovoltaic cells – 5 V, is determined by the ADC embedded in the microcontroller type PIC16F873/SP. In accordance with the program, the microcontroller provides three modes of information processing:
- in the first mode, the digital display shows the digital values of the signals from both channels (\( I_1 \) and \( I_2 \));
- in the second mode, the ratio of these signals is displayed (\( I_1/I_2 \));
- in the third mode, the result of the calculation by the formula \((I_1-I_2)/(I_1+I_2)\).

The microcontroller, if necessary, allows you to compensate for the initial bias voltage of the photoreceiver channels. When the radiation source is off, the button is pressed “Const. 0”. The controller remembers the voltages present at the moment at the outputs of the photoreceiver channels, and automatically takes them into account in further work.

### 3.1 The results of experimental studies

Experimental studies have been carried out that made it possible to obtain a graphical representation of the dependence of the photocurrent on the movement of the microscrew (figure 6).

Table 2 and figure 7 present the experimentally obtained results of the dependence of the photocurrent value on the angular displacement.

### Conclusion

The obtained experimental data confirmed the theoretical positions of the feasibility of the optical signal conversion circuit using FOMAT with bellows, allowed to determine the optimal design and technological parameters of the FOMAT optical system: \( \alpha = \pm 3^\circ \), \( x_0 = 1.5 \) mm, \( D = 0.7 \) mm, required for maximum sensitivity of optical signal conversion.

![Figure 6. Graphic dependences of the photocurrent on the movement of the microscrew.](image)
Table 2. Experimental Results.

| $h$ | 0    | 0.261 | 0.525 | 0.768 | 1.047 | 1.308 | 1.569 | 1.83  | 2.094 | 2.355 | 2.616 |
|-----|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| $\alpha$ | 0    | 0.5   | 1     | 1.5   | 2     | 2.5   | 3     | 3.5   | 4     | 4.5   | 5     |
| clockwise | $I_1$, first channel, nA | 0.21 | 0.18 | 0.16 | 0.14 | 0.12 | 0.11 | 0.1 | 0.09 | 0.08 | 0.07 | 0.06 |
| counterclock-wise | $I_2$, second channel, nA | 0.22 | 0.24 | 0.25 | 0.32 | 0.35 | 0.38 | 0.37 | 0.27 | 0.13 | 0.06 | 0.03 |

Figure 7. Graphic dependences of the photocurrent on the movement of the microscrew ($0^\circ < \alpha < 5^\circ$ both sides of the vertical).

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