

314. Fiber-Optic Sensors for Nanometric Displacement and Vibration Measurement in Mechatronics

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Abstract. Fiber-optic sensors are widely used for displacement and vibration measurements in mechatronic systems. Sensors can be of very small size and operate in blast danger conditions and strong electromagnetic interference environment. In this work modeling and experimental investigation of the characteristics $U-h$ of fiber-optic sensor of displacement have been accomplished with a view to obtain the maximal sensitivity in the displacement and vibration measurements. The modeling and experimental results were perfectly coincidental, therefore the limit sensitivity of sensors can be predicted by modeling. Configurations of non-contact fiber optic sensors of the maximal possible sensitivity have been found, the metrological parameters of which do not depend either on the degradation of the light source, intensity or on the elements used in the mechatronics system measurements as well as on the value of the mirror reflection coefficient and changes with the aging process. All that increases the reliability of mechatronics system monitoring, which is of utmost importance for their exploitation.

Keywords: Fiber-optic sensor, displacement, modeling, design, experiment.

Introduction

Fiber-optic non-contact reflection sensors and transducers are frequently used for precise measurements of slight displacements. The chips of only one multimode fiber-optic pair and sensors have been created and explored more in detail [1, 2].

To produce very stable sensors, another light receiving fiber was added [3] and an angle 2θ was formed between a light emitting (to a reflecting mirror) fiber axis and two reflected light receiving fiber axes located on the same plane. It has been shown in theory that, by using an output signal $(A-B)/(A+B)$ (here A and B are signals emerging in the light receiving fibers), it is possible to eliminate the influence on measurement results related with the light source intensity variations due to its aging and radiation fluctuations. Fiber-optic sensors of this kind were further investigated and improved in the works [4, 5, 6]. It has been proved in a theoretical and experimentally way that their sensitivity is exponentially increasing with a decrease in the distance between active fiber tips [7], that is of finite quantity due to fiber cross-section, and it is increasing if the angle θ increases [5].

Fiber-optic sensors and transducers of new kind have been created that consist of two fiber pairs [8]. The sensitivity of these sensors is higher by an order [5] than that of one-pair sensors [3]. It has been shown in this work that experimental signal U dependences of one fiber optopair reflection sensors on the distance h ($U-h$ characteristics) can be exactly described by mathematical expressions [9]. The target of this paper is to simulate a two-fiber optopair sensor by employing experimental one

optopair $U-h$ characteristics, that are quite congruent with the modeling results, and to establish limit sensitivity values of these sensors.

Experimental setup

The sensor $U-h$ characteristics have been evaluated by using device shown in Fig. 1. Fibers WE100/140P 0.22 (Fig. 1, 1 and 2) of the company AndaOptec installed in the SMA 905 connectors have been used. Active fiber tips 3, 4 are arranged at an angle $\theta = 35^\circ$, controlling maximal signal by a special mounting desk [9], and stuck into organic glass holder-head 5. An SMA p-i-n photodiode H22R880IR the sensitivity of which is 0.45 A/W, $\lambda_{\max} = 850$ nm served as a photo receiver 6. H22E4020IR was chosen as an SMA emitter 7 whose power is 15 dBm, $\lambda_{\max} = 850$ nm and the stabilized current supply is equal to 80 mA. Sensor output power was measured by a precise fiber radiation gauge LP-5025-8. Microprocessor OP-400 was used as a converter of current into voltage the feedback resistance of which was 6.2 k Ω . The fiber-optic sensor head 5 and mirror 9 were fastened on a positioning device (instrumental microscope), the positioning step of which was controlled by an electronic device KAMAK and in addition by a micrometer (± 0.5 μm precise). An Au film of 0.3 μm thick, evaporated on a silicon wafer, served as a mirror that reflected radiation up to 96%. The distance between the active fiber tips was $b=b_{\min}=2a\cos\theta$. The experimental $U-h$ characteristic of sensor is presented in Fig. 2a.

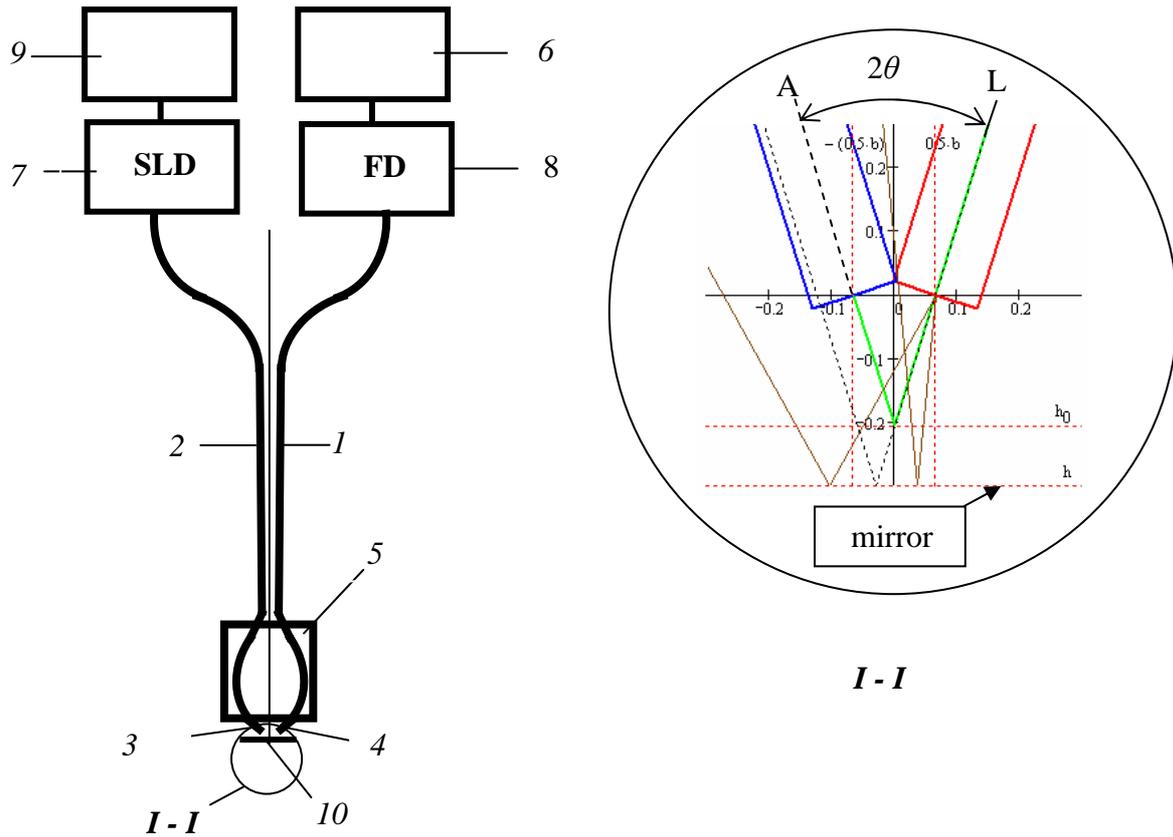


Fig. 1. Arrangement of fiber tips in the reflection fiber system. **A** is a light receiving fiber; **L** is a light emitting fiber; b is the distance between the centers of light emitting and receiving fiber tips; Distance b is minimal ($b=b_{min}=2a\cos\theta$). h is the displacement position of the mirror.

Modeling and experimental results

Sensors were modeled according to the formulas presented in the paper [1, 3] and specified in [8]. Modeling results and their comparison with the experimental ones are presented in Fig 2a. Two-fiber optopair sensor **A - A'** was modeled by the methods presented below. Let $A(h)$ and $A'(h)$ be signals emerging in the first and second optopair receiving fibers $A(h)$ and $A'(h)$. Let I_0 be the intensity of the light source, K - the loss of intensity in the input fiber, S - the receiving fiber core area, $R(z(h))$ is an effective radius of the output optic field, $2a_0$ - the radius of the fiber core, θ_c - the angular aperture of the fiber, k is a constant of the light source, and K_M be the mirror reflection coefficient.

Then from [8]

$$A(h) = I_A(h) = S K_M K I_0 \exp\{-x^2(h)/R^2(z(h))/\pi R^2(z(h)), \quad (1)$$

$$A'(h) = A(h-w)$$

where [6]

$$R(z(h)) = a_0 + k z(h) \tan(\theta_c) \quad (2)$$

$$z(h) = b/\sin \theta + 2\Delta h \cos \theta = 2h \cos \theta + b \sin(\theta), \quad (3)$$

$$x(h) = 2\Delta h \sin \theta = 2h \sin \theta - b \cos \theta, \quad (4)$$

$\Delta h = h - h_0$, $h_0 = b/2 \tan \theta$. Then, from Eq. 1 – Eq. 4

$$A(h) = \frac{C_0}{\pi R^2(z(h))} \exp\left\{-\frac{(2h \sin \theta - b \cos \theta)^2}{R^2(z(h))}\right\} \quad (5)$$

and for the second identical optopair (see Fig. 2b), we have

$$A'(h) = A(h-w) = \frac{C_0}{\pi R^2(z(h-w))} \quad (6)$$

$$\exp\left\{-\frac{(2(h-w) \sin \theta - b \cos \theta)^2}{R^2(z(h-w))}\right\}$$

where $C_0 = S K_M K I_0$. Next we explore the signals

$$U_{sub}(h) = A(h) - A'(h) \quad \text{and} \quad U_{div}(h) = \frac{A(h) - A'(h)}{A(h) + A'(h)} \quad (7)$$

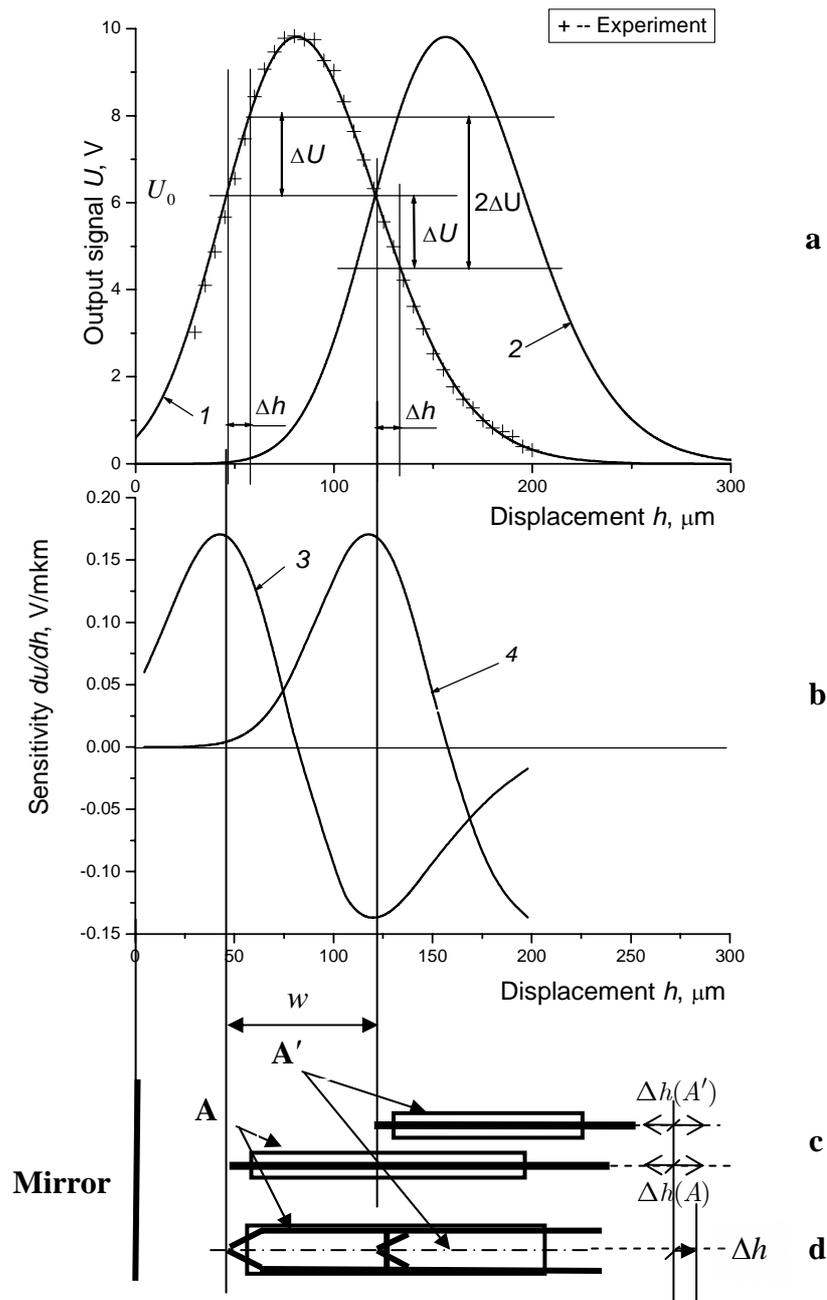


Fig. 2. The principle of operation of one and two fiber optopair sensors. **a** is $U-h$ characteristics (modeling results) of the one fiber optopair: 1 - $A(h)$, 2 - $A'(h)$, + - experimental results. Δh is the displacement of two fiber optopair assembly. **b** - 3 - dA/dh , 4 - dA'/dh . **c** - **A** and **A'** are one - fiber optopair sensor positions with respect to the mirror. **d** is the two - fiber optopair sensor, as **A** and **A'** optopairs are fastened for common displacement Δh .

and their derivatives by distance h . Note here that the signal $U_{div}(h)$ does not depend on C_0 .

In addition, analytic expressions of signals $A(h)$ and $A'(h)$ derivatives have been obtained in [6], therefore, by making use of the sum and ratio differentiation rules, we will also get analytic expressions of the derivatives

dU_{sub}/dh and dU_{div}/dh . Applying the above mentioned expressions, the calculation results are illustrated in Fig. 3 and Fig. 4. As can be seen from Fig. 2a, the values of signal $A(h)$ are calculated by Eq. 5 where $C_0 = 4.4 \cdot 10^6$, $k = 0.15$ (curve 1) are well coincidental with the experimental points marked "+".

2c, with the change in the distance with respect to the

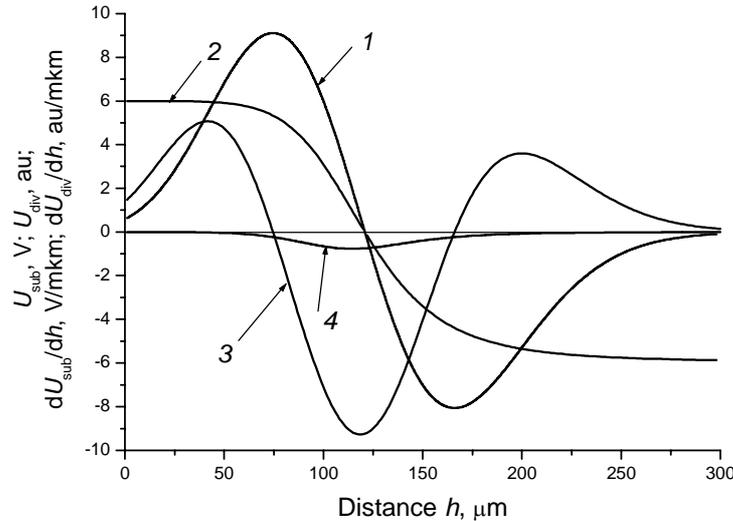


Fig. 3. Modeling results. 1 - signal $U_{sub}(h)$, 2 - signal $6 \cdot U_{div}(h)$, 3 - signal $30 \cdot dU_{sub}/dh$, 4 - signal $30 \cdot dU_{div}/dh$

This curve contains the rising part of higher sensitivity, and after reaching the maximum, it contains the descending part of lower sensitivity. In these parts of the curve we can find the surroundings of inflection points at which a signal is linear, i.e., sensitivity does not depend on h . This is illustrated in Fig. 2b by the derivative of curve of simulated signal $A(h)$. The maximal value of one-fiber optopair sensor dA/dh is $174 \text{ mV}/\mu\text{m}$ in the ascending part of curve 1, and $134 \text{ mV}/\mu\text{m}$ in the descending part. These values are congruent with that of maxima and minima in curve 3 (Fig. 2b). We can choose this point as an operation point of a one-fiber optopair sensor. The resolution of such a sensor is determined by p-i-n photodiode noises that are $10^{-14} \text{ W}\sqrt{\text{Hz}}$ for this photodiode, while the operation point current is $9.8 \cdot 10^{-5} \text{ A}$. Therefore the signal-noise ratio is $\approx 10^{10}$.

Thus, the resolution of such a one-fiber optopair sensor may be better than 1 nm.

Let us investigate what advantages we can have in the case of two-fiber optopairs. As shown by the modeling results, in this case we have two signals (Eq. 5 - Eq. 6) $A(h)$ and $A'(h) = A(h-w)$, $w = 75 \mu\text{m}$. These curves intersect each other at a single point, the abscissa of which is $h_0 = 121 \mu\text{m}$, and the ordinate is $U_0 = 6.116 \text{ V}$.

The position of one-fiber optopair sensor with respect to the mirror corresponds to these values, as shown in Fig. 2c. The signal $A(h)$ is equal to signal $A'(h)$, therefore the common signal (Eq. 7) $U_{sub}(h) = 0$. The sensor has a fixed zero position congruent with the value $h_0 = 121 \mu\text{m}$. Let us fasten these fiber pairs together and use them as one sensor. As can be seen from Fig. 2a and

mirror by value Δh , the signal of pair A increases, while that of pair A' decreases. In this case, the signal $U_{sub}(h)$ becomes two times larger than a change of signal $A(h)$, i.e., if we use one fiber optopair sensor. The dependence of signals $U_{sub}(h)$ and dU_{sub}/dh on h is presented in Fig. 3, curves 1 and 3, respectively. The value of signal $U_{sub}(h)$ changes its sign, which helps us define the direction of movement of the two-fiber optopair sensor, i.e., whether the sensor is approaching the mirror or moving away from it.

The sensitivity $dU_{sub}/dh = 308 \text{ mV}/\mu\text{m}$ of such a sensor is twice higher than that of one-fiber optopair (Fig. 3, curve 3). As usual the signal $U_{sub}(h)$ is amplified even more, no less than 30 times, i.e., three times less than in [3], while the sensitivity increases as many times again $dU_{sub}/dh = 9255 \text{ mV}/\mu\text{m}$. However, by increasing intensity, noises increase as well. Sensitivity can be increased by using the light source of higher capacity, but not diminishing fiber cross-sections, because when diminishing their cross-section, the light intensity into the fiber decreases. The value $U_{div}(h)$ of signal (7) is usually lower than 1 and equal to $0.746 \text{ a.u.}/\mu\text{m}$.

If we amplify the signal $U_{sub}(h)$ 30 times, then value of signal $U_{div}(h)$ becomes $22.380 \text{ a.u.}/\mu\text{m}$. The use of this signal is very useful because it does not depend on the light source degradation and fluctuations. In our opinion, it is most important that both the signal and sensitivity do not depend on the mirror reflection coefficient [8], therefore any light reflecting body of mechatronic equipment can be used as a mirror. The linearity of $U_{sub}(h)$ and $U_{div}(h)$ is

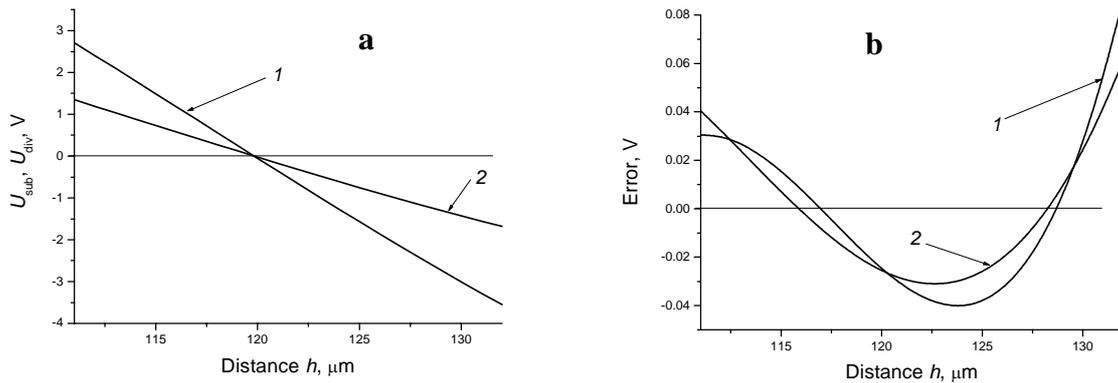


Fig. 4. **a** - signals 1 - $U_{sub}(h)$ and 2 - $U_{div}(h)$ in the interval of distance from 111 μm to 132 μm ; **b** - deviations of signals 1 - $U_{sub}(h)$ and 2 - $U_{div}(h)$ from the lines obtained by the least squares method

of utmost importance in measurements. As shown in Fig. 4, the linearity of these signals is sufficient only in the small area $121 \pm 10 \mu\text{m}$ of the point $h = 121 \mu\text{m}$. Fig. 4b illustrates the difference between the signals $U_{sub}(h)$ and $U_{div}(h)$ and straight lines obtained by the least squares method. We can see here that the least error is not at the point as $U_{sub}(h) = U_{div}(h)$. This strongly depends on $U-h$ characteristics and the value of an artificial intersection point at which the signal reaches the maximum, and the signal $U_{div}(h)$ is monotonously decreasing [8].

Conclusions

A prototype of one-fiber optopair sensor has been created where the angle between the axes of active fiber tips is 35° . The diameter of the sensor head is 4 mm, and the length is 10 mm. Fiber with SMA 905 connectors are 3 m long (may be up to 300 m). The $U-h$ characteristic of this kind of sensor has been measured. The distance between tips was made minimal on purpose by assembling technology with a view to attain the maximal values of signal U .

The experimental $U-h$ characteristic is described by modeling formula Eq. 5 accurately enough. The maximal sensitivity $dA/dh = 174 \text{ mV}/\mu\text{m}$ and $134 \text{ mV}/\mu\text{m}$, as I_0 is fixed. It has been shown that by employing a second optopair (identical with the first one) and choosing the operation point in the rising part and the descending one of $U-h$ for the first and second pair, respectively (artificial $U-h$ intersection), it is possible to create sensors whose signal U_{div} and sensitivity $S_{div} = dU_{div}/dh$ thereby are independent of light source fluctuations and degradation as well as of the mirror reflection coefficient variation in time.

The maximal sensitivity of the sensor $S_{sub} = dU_{sub}/dh = 9000 \text{ mV}/\mu\text{m}$, and if the signals $A(h)$ $S_{div} = dU_{div}/dh = 22.380 \text{ a.u.}/\mu\text{m}$ and $A'(h)$ are amplified

by 30 times then. The maximal sensitivity of the sensor $U-h$ characteristics depends on the measurement interval, however it can be increased by electronic devices.

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References

- [1] Cook R. O. and Hamm C. W. Appl. Opt. Vol. 18 (1979), p. 3230
- [2] Shimamoto A., Tanaka K. Appl. Opt. Vol. 34 (1995), p. 5854
- [3] Ko Y W. H., Chang K.-M., Hwang G.-J. Sensors and Actuators A Vol. 49 (1995), p. 51
- [4] Libo Y., Jian P., Tao Y., Guochen M. Sensors and Actuators A Vol. 36 (1993), p. 177
- [5] Verkalis J. Lithuanian Journal of Physics Vol. 42 (2002), p. 99
- [6] Kleiza V., Kleiza J. Lithuanian Mathematical Journal Vol. 45 (2005), p. 494-498
- [7] Kleiza V., Verkalis J. Electronics and Electrical Engineering Vol.62 (2005), p. 77
- [8] Kleiza V., Verkalis J. Proc. SPIE Vol. 6596 (2007), p. 142.
- [9] Kleiza V., Verkalis J. Proc. SPIE Vol. 6596 (2007), p. 253.