ISSN 1392 - 1215 ELEKTRONIKA IR ELEKTROTECHNIKA. 2005. Nr. 6(62)

T 125 AUTOMATIZAVIMAS, ROBOTOTECHNIKA

An Analytical Analysis of a Fiber-Optic Reflective Sensor

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Introduction

Investigation of the reflection fiber system arrangement and influence of cavity's physical and optical parameters on light transmission promises the creation of a lot of devices for measuring physical properties of the external optical media and cavity dimension changes.

In recent years W.H.Ko et al [1] have proposed an innovative external influence compensated method - a fiber-optic reflective displacement micrometer, which consisted of the light transmitting fiber and a pair of light receiving fibers all on a plane. The tips of the pair of the receiving fibers detect the light reflected from the mirror and form an angle and a distance to the light emitting fiber. The experimental dependence of the output signal of the micrometer having fixed but not well-founded parameters of the distance between these fibers was obtained in a narrow ±200 μm interval of displacement. The sensitivity of the micrometer was increased to a considerable extent in [3].

The aim of this paper was to investigate the influence of the distance between the tips of the fiber system and the light reflection body-mirror, the distance between the central point of the tip of light emitting and the point of the two light receiving fibers by modeling. This would enable us to obtain knowledge on the behavior of the whole system in a wide interval of the distance fiber tips mirror and to design displacement sensors of maximal sensitivity. With a view to obtain a high sensitivity and linearity the measurements, however must be performed in a narrow interval of displacement (±100μm) or even (±10μm).

Main Equations

The arrangement of the fiber tips (Fig. 1) was applied to explain the main physical principle of operation of the reflection fiber system. According to [2], the light intensity distribution function of the source *I(r,z)* in the position on the plane *z* away from the source and *r* away from the light beam axis is [2]

$$I(r,z) = I_0 K_0 \exp\{r^2 / R^2(z)\} / R^2(z) , \qquad (1)$$

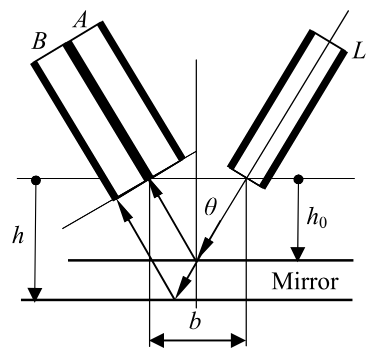


Fig. 1. Fiber tips arrangement of the reflection fiber-optic system [1]. *A, B* is light receiving fibers, *L* is light emitting fiber

where I_0 is the intensity of the light source, K_0 is the loss in the intensity of the input fiber, $R(z)$ is the effective radius of the output optical field, defined as

$$R(z) = a_0 + kz \tan\theta_c , \qquad (2)$$

where a_0 is the radius of the fiber core, θ_c is the aperture angle of the fiber, k is the constant of the light source. Contrary to [1, 2] ($R(z) = a_0 + kz^{3/2} \tan\theta_c$) we consider $R(z)$ to be a linear function, because of the well-known linear spreading of the light.

If the reflecting surface is not perfect but has the reflection coefficient R_M, the reflected light will be reduced by the factor *r*.

The transmitted light intensity at the end of the receiving fiber is [3]:

$$I(r,z) \approx \iint_S \frac{K_0 R_M \, K \, I_0 \exp(-r^2 / R^2(z))}{\pi R^2(z)} ds , \qquad (3)$$

where K is the loss in the intensity of the receiving fiber, and S is the receiving fiber core area.

If the intensity in the receiving fiber center is used to represent the average intensity received and the reflection coefficient of the mirror is included, then the intensity received by the *A* and *B* fibers can be simplified as follows:

$$A = I_A = \frac{S_1 K_0 R_M K_1 I_0}{\pi R^2(h,b,\theta)} \exp\left\{-\frac{(x(h,b,\theta)+d)^2}{R^2(z(h,b,\theta))}\right\}, \quad (4)$$

$$B = I_B = \frac{S_2 K_0 R_M K_2 I_0}{\pi R^2(h,b,\theta)} \exp\left\{-\frac{(x(h,b,\theta)+d)^2}{R^2(z(h,b,\theta))}\right\}, \quad (5)$$

where $2d$ is the distance between the centers of the light receiving fibers, $2a$ is the diameter if the fiber with clading. In our case $2d$ is equal to $2a$.

The parameters a, b, d, θ constructively define the geometry of the fiber-optic system. According to Fig. 1, the initial reference values are

$$h_0 = b/2\tan(\theta),\ z_0(b,\theta) = b/2\sin(\theta), \quad (6)$$

If the distance from the mirror position and to the emitting light source is h, then the total light path is equal to

$$z(h,b,\theta) = 2z_0(b,\theta) + \frac{h - h_0(b,\theta)}{\cos\theta}(1+\cos 2\theta) \quad (7)$$

and

$$x(h,b,\theta) = 2(h - h_0(b,\theta))\sin\theta. \quad (8)$$

Then, according to (2)

$$R(z(h,b,\theta)) = a_0 + kz(h,b,\theta)\tan(\theta_c) = \overline{a}_0 + \overline{a}_1 h \quad (9)$$

is a linear function of h, where

$$\overline{a}_0 = a_0 + 2kz_0(b,\theta)\tan\theta_c \sin^2\theta,\ \ \overline{a}_1 = 2k\tan\theta_c\cos\theta.$$

If the two receiving fibers are identical, ($K_1=K_2$, $S_1=S_2$) then function

$$D = \frac{(A-B)}{(A+B)} \quad (10)$$

can be expressed only as a function of variables h, b, θ, i.e., it does not depend on S_1, K_1, R_M, K_0, I_0, contrary to *(A-B)* which depend on them. The essence of the compensation mechanism is that the signal *(A-B)/(A+B)* does not depend on the reflection coefficient of mirror and on the intensity of the light source. Equations (4), (5) and (10) were used as functions of h for simulating sensor output signals U_{out} in order to compare the sensitivity $S = dU_{out}/dh$ of our fiber sensor constructions with those only for a narrow interval of h in affinity of h_0 [1].

Results

The characteristics of system signals

$$A(h,b),\ B(h,b),\ C(h,b) = A(h,b) - B(h,b),$$

$$D(h,b) = C(h,b)/[A(h,b) + B(h,b)$$

$$S_A(h,b) = G(h,b) = \frac{dA}{dh},$$

$$S_B(h,b) = F(h,b) = \frac{dB}{dh},$$

$$S_{sub}(h,b) = \frac{dC}{dh},\ S_{div}(h,b) = \frac{dV}{dh}$$

were calculated applying such parameter b values 1, 2, 3, 4 mm. The last value is the same as in [3] for comparison of the S_{sub} and S_{div} results. All the other parameters were: a_0=0.2 mm, d=0.3 mm, θ_c=19.5^0, θ=25^0, k=0.1, C_0=1.

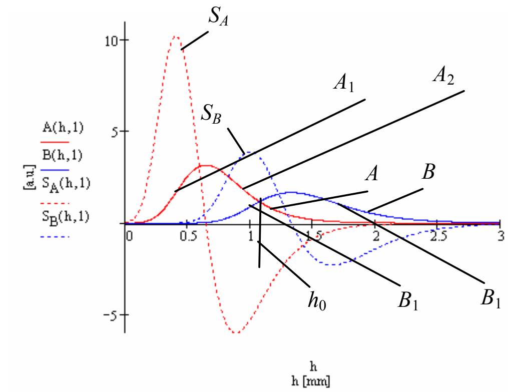


Fig.2. Dependencies of signals *A, B* and sensitivities S_A, S_B on the mirror position h as b=1. h_0 is the crossing abscissa of the signals *A* and *B*

The output signals *A(h)* and *B(h)* (Fig. 2) rise from zero to the maximum value and then diminish. The portion in affinity of the points A_1, A_2 and B_1, B_2 for these characteristics is linear. The maximum amplitude $A_{\max}(b) = \max_h A(h,b)$ of the signal $A(h,b)$ is always greater than $B_{\max}(b) = \max_h B(h,b)$ for the signal $B(h,b)$. Sensitivities $S_A(h)$ and $S_B(h)$ on the near sides A_1 ,B_1 of these characteristics are higher than that on the far side A_2 ,B_2 of them. The sensitivity of the curve $B(h,b)$ is less than that of $A(h,b)$ on both sides. Moreover, the characteristics $A(h,b)$ and $B(h,b)$ naturally cross each other at an appropriate value of h_0.

We have proved that $A_{\max}(b)$ and $B_{\max}(b)$ decrease according to the equation

$$A_{\max}(b) = A[h_A(b),b] \ \text{ and } \ B_{\max}(b) = B[h_B(b),b], \quad (11)$$

where $h_A(b)$ and $h_B(b)$ are the values of the parameter h at which the signal values are maximal

$$h_A(b_1) = -\frac{p_A(b_1)}{2} + \sqrt{\left(\frac{p_A(b_1)}{2}\right)^2 - q_A(b_1)},$$

$$h_B(b_1) = -\frac{p_B(b_1)}{2} + \sqrt{\left(\frac{p_B(b_1)}{2}\right)^2 - q_B(b_1)}\ ,$$

$$p_A(b,\theta,k,d) = 2\frac{2(\bar{a}_0 + \bar{a}_1 h_0)\sin^2\theta - \bar{a}_1[d\sin\theta - \bar{a}_0\bar{a}_1]}{\bar{a}_1^3},$$

$$q_A(b,\theta,k,d) = -\frac{4h_0(\bar{a}_0 + \bar{a}_1 h_0)\sin^2\theta}{\bar{a}_1^3} + \frac{-2d\bar{a}_1(\bar{a}_0 - 2\bar{a}_1 h_0)\sin\theta + \bar{a}_1(d^2 - \bar{a}_1^2)}{\bar{a}_1^3}$$

The calculation results of the characteristics *A(h)* and *B(h)* having different values of the system parameter *b* are represented in Fig. 3. The maximum values $A_{\max}(b)$ and $B_{\max}(b)$ of the characteristics *A(h)* and *B(h)* decrease as *b* increases (Fig 3). All the characteristics maximum points and their crossing points are at the higher values of *h* as *b* increases.

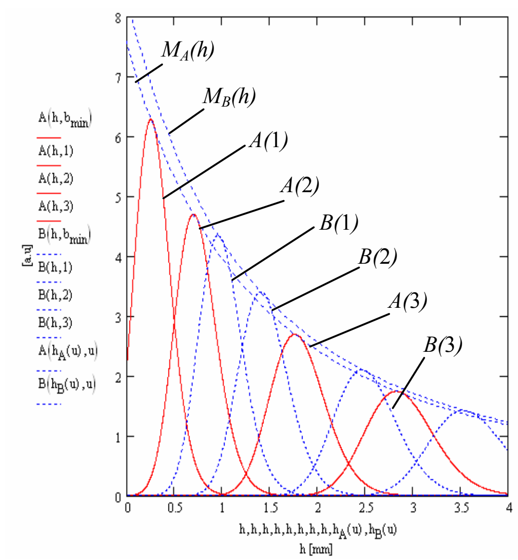
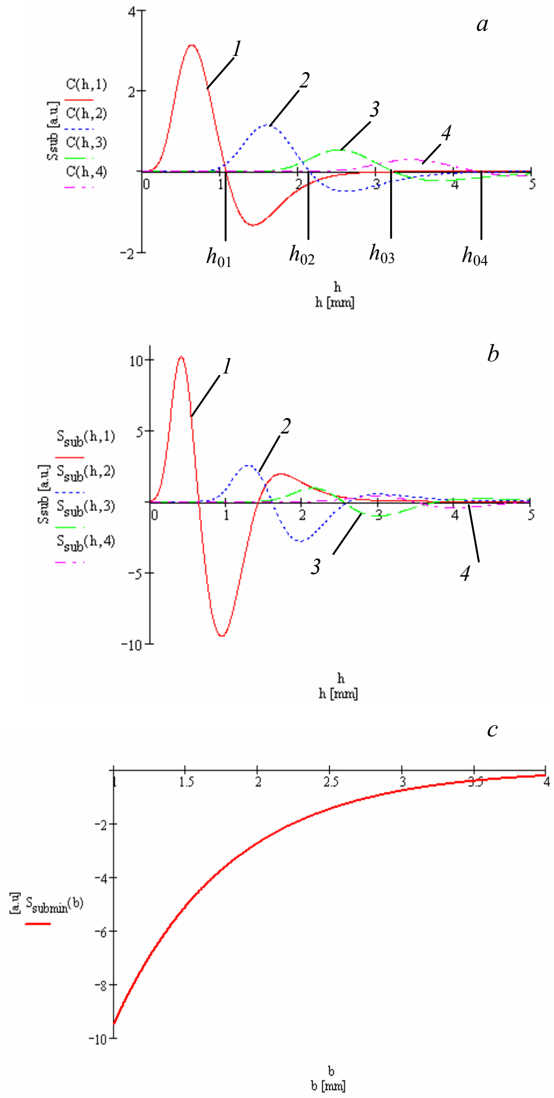


Fig. 3. Dependencies of signals *A(h,b)* and *B(h,b)* on the mirror position *h* where *b*=1, 2, 3. $M_A(h)$ and $M_B(h)$ are a theoretical curves crossing the maximum of signals *A* and *B*

The characteristics $C(h,b) = A(h,b) - B(h,b)$ (Fig. 4a) rise from zero to the positive maximum value, then drop to zero and rise to the negative maximum value and afterwards decrease to zero. Actually for application in a measurements, the linear part of the characteristic at the value $h=h_0$ is more important. Measuring the values *C(h)* everyone can determine value of the mirror or body displacement from h_0 position. The amplitude of the signal *C(h)* decreases as *b* increases, and the distance h_0 increase too. Characteristics $S_{sub}(h)$ in Fig. 4b. illustrate the sensitivity to the displacement to be very low as *b*=4 mm. This is the main reason why the values of $S_{sub}(h)$ are so low, because the distance *b* is not correctly chosen for the system. Moreover, the greater the signal *C(h)*, the beter the resolution of the system is $S_{sub}(h)$. The calculated results represented in Fig. 4b vs. *b* show the sensitivity $S_{sub}(b)$ in absolute value



increasing

Fig. 4. Behavior of the signal *C*(*h*)=*A*(*h*)-*B*(*h*). 4*a* shows the dependence of the system signals *C*(*h*,1,2,3,4) on the mirror position *h* mm.*1,2,3,4* are curves as *b* is in mm. $h_{01,02,03,04}$ are positions of the abscissa as signals *C*(*h*,1,2,3,4)=0. 4*b* shows the dependence of system signals $S_{sub}(h,1,2,3,4)$ curves *1,2,3,4* on the mirror position *h* mm as *b*=1, 2, 3, 4 mm. 4c illustrates the dependence of minimum (maximum in absolute value) sensitivity S_{sub} on the distance *b* mm

exponentially as *b* decreases to the constant minimal value restricted by the parameter of the fiber-optic system $b_{\min}$

$$S_{\text{sub min}}(b) = -\exp\{-(b-2.8)/0.8\}\ ,$$

where a is the diameter of the fiber with cladding. The modeling results in Fig. 4c shows that the sensitivity S_{sub} increases 20 times as b decreases from 4 mm to 1 mm (optimal: b_{min}=0.58).

Very important for compensated measurements is the system signal (Fig. 5a).

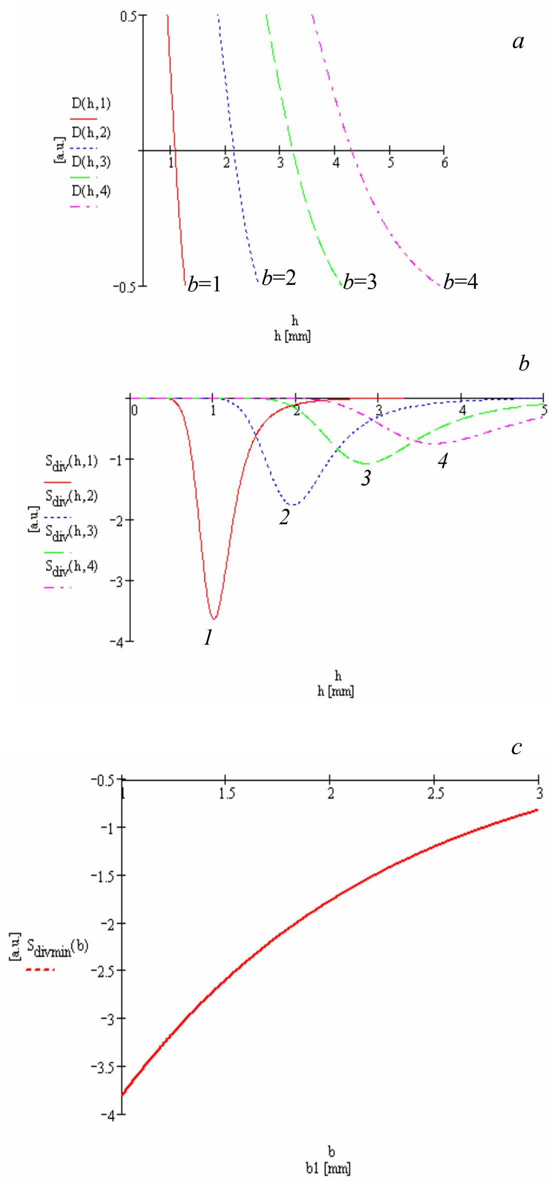


Fig. 5. Behavior of signal $D(h)= C(h)/[A(h)+B(h)]$. *5a* shows the dependence of system signals $D(h,$ 1,2,3,4) on the mirror position h mm. Curves *1,2,3,4* are as b in mm. Distance $h_{01,02,03,04}$ is positions of abscissa as signals $D(h;1,2,3,4)=0$. **5**b - dependence of system signals $S_{div}(h$, 1,2,3,4) curves 1,2,3,4 on the mirror position h mm as b=1, 2, 3, 4 mm. 5c - dependence of minimum (maximum in absolute value) sensitivity S_{div} on distance b_1 mm

$$D(h,b) = C(h,b)/[A(h,b)+B(h,b)].$$

This figure shows the maximal signal to be ±1 and zero at definite $h=h_0$ values. Those values of h increase as b increases. The characteristics $D(h,b)$ have linear parts in affinity of zero. Therefore there always is ability for measuring not only the mirror displacement h but also its direction. The absolute value of S_{div} increases exponentially as b decreases (Fig. 5b), which is restricted by the diameter of the fibers width cladding

$$S_{div\,min}(b_1) = -1.2\exp\{-(b_1-2.5)/1.3\}.$$

The modeling results in Fig. 5c show that the sensitivity S_{div} increases 4 times as b decreases from 4 mm to 1 mm (optimal: b_{min}=0.58).

Conclusions

1. Light transmission modeling in the reflection fiber-optic system revealed that the sensitivity of the sensors to displacement of the reflecting mirror could increase as the parameter of the system b was decreased as much as possible.

2. The minimal parameter of the fiber - optical system $b \approx 3a\cos\theta$ is defined by the diameter of the applied fibers with cladding or even with a jacket. The modeling results have showed that the sensitivity S_{sub} increases 20 times and S_{div} increases only 4 times as b decreases from 4 mm to 1 mm (optimal). Therefore for real measurements of displacement of the light source, the mirror reflection coefficient and ambient temperature are stable and it is more conventional to apply $C(h,b) = A(h,b) - B(h,b)$ because the sensitivity S_{sub} of the system is higher than S_{div} and signal electronic conversion is simpler than for $D(h,b) = C(h,b)/[A(h,b)+B(h,b)]$.

3. It has been determined that the sensitivity of S_{sub} and S_{div} increases exponentially dependent on b according to the equations

$$S_{sub\,min}(b) = -\exp\{-(b-2.8)/0.8\},$$

$$S_{div\,min}(b) = -1.2\exp\{-(b-2.5)/1.3\}.$$

4. All the modeling results are qualitatively coincidental with the experimental data [3]. The sensitivity of the system $S_{sub} = 192\ /\mathrm{mV}/\mu\mathrm{m}$ as $b = 4$ mm [2] and under certain conditions as b is optimal $S_{sub} = 1702\ /\mathrm{mV}/\mu\mathrm{m}$ ([3] Fig. 11 and Table 1)

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Pateikta spaudai 2005 03 15

V. Kleiza, J. Verkelis. Analizinis atspindžio šviesolaidžių jutiklio tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2005. – Nr. 6(62). – P. 77 – 81.

Šio darbo tikslas – sumodeliuoti atstumo tarp šviesą spinduliuojančio ir šviesą priimančių optinių šviesolaidžių sistemos šviesolaidžių centrų vertės bei atstumo tarp kūno (veidrodžio) ir optinių šviesolaidžių sistemos plokštumos įtaką jautriui. Toks tyrimas įgalino nustatyti visos optinių šviesolaidžių sistemos elgseną plačiame atstumų diapazone ir sukurti atstumo tarp veidrodžio ir optinių šviesolaidžių sistemos plokštumos jutiklį, turintį maksimalųjį jautrį. Norint gauti tiesinį didelio jautrio jutiklį, matuojami atstumai (slinktys) turi būti siauro intervalo, t. y. ±100 μm ar net ±10 μm. Todėl modeliuojant atspindžio optinių šviesolaidžių sistemą, sukurtas jos, kaip jutiklio, modelis. Sistemos jautris (veidrodžio slinkčių atžvilgiu) buvo tirtas kaip atstumo tarp šviesą spinduliuojančio ir šviesą priimančių optinių šviesolaidžių sistemos šviesolaidžių centrų vertės *b* funkcija. Parodyta, kad sistemos jautris yra minimalus, kai *b* maksimalus, ir maksimalus, kai atstumo *b* vertė minimali – $b \approx 3a\cos\theta$. Modeliuojant nustatyta, kad jautris S_{sub} padidėja 20 kartų, kai atstumo *b* vertė sumažinama nuo 4 iki 1 mm. Il.5, bibl.3 (anglų kalba; santraukos lietuvių, anglų ir rusų k.).

V. Kleiza, J. Verkelis. An Analytical Analysis of a Fiber-Optic Reflective Sensor // Electronics end Electrical Engineering. – Kaunas: Technologija, 2005. – No. 6(62). – P. 77–81.

The aim of this paper was to investigate the influence of the distance between the tips of the fiber-optic system and the light reflection body-mirror, the distance between the central point of the tip of light emitting and the point of the two light receiving fibers by modeling. This would enable us to obtain knowledge on the behavior of the whole system in a wide interval of the distance fiber tips mirror and to design displacement sensors of maximal sensitivity. With a view to obtain a high sensitivity and linearity the measurements, however must be performed in a narrow interval of displacement (±100μm) or even (±10μm). Light transmission in the reflection fiber-optic system was investigated by modeling for application as sensors. The sensitivity of the system to linear displacement was studied as a function of the distance between the tips of the light emitting fiber and the center of the pair reflected light collecting fibers by mirror positioning in wild interval. Sensitivity of the sensors will be maximal as distance *b* will be minimal approximately no bigger $3a\cos\theta$. Modeling results shoved that sensitivity S_{sub} increase 20 times as *b* decrease from 4 mm to 1 mm. Ill. 5, bibl. 3 (in English; summaries in Lithuanian, English and Russian).

В. Клейза, Й. Веркялис. Аналитическое исследование отражающего световодного датчика // Электроника и электротехника. – Каунас: Технология, 2005. – № 6(62). – С. 77–81.

Целью настоящей работы является моделирование влияния расстояния между центрами излучающего и принимающего световодов системы оптических световодов и расстояния между телом (зеркалом) и плоскостью системы оптических световодов на чуствительность системы как датчика. Такое исследование дало возможность установить поведение всей системы оптических световодов в широком диапазоне упомянутых расстояний и создать датчик расстояния между телом (зеркалом) и плоскостью системы оптических световодов, обладающий максимальной чувствительностью. Для создания датчика, обладающего линейностью и высокой чувствительностью измерения, необходимо производить в узком интервале расстояний (зеркало – плоскость системы оптических световодов), т. е. ±100 μm или даже ±10 μm. Поэтому чувствительность по отношению перемещению зекала, была исследована как функция растояния *b* между центрами излучающего и принимающего световодов системы оптических световодов. Показано, что чувствительность системы минимальна, если растояние *b* максимально, и является максимальной, если растояние *b* минимально ($b \approx 3a\cos\theta$). Моделированием установлено, что при уменьшении расстояния *b* от 4 до 1 мм чувствительность датчика S_{sub} увеличивается в 20 раз. Ил. 5, библ. 3 (на английском языке; рефераты на литовском, английском и русском яз.).