58th ILMENAU SCIENTIFIC COLLOQUIUM
Technische Universität Ilmenau, 08 – 12 September 2014
URN: urn:nbn:de:gbv:ilm1-2014iwk:3

USE OF PHASE INVERSION POINTS OF THE LIGHT FIELD FOR ANGULAR DISPLACEMENT MEASUREMENT

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ABSTRACT

It is offered to use points of a phase inversion of the light field formed by diffraction or interference of light for angular measurements. Inversion points can be used as adjustment marks matching with which can be performed with very high accuracy. For determination of position of inversion point it is possible to use slit, as intensity distribution behind it depends on distance between center of a slit and an inversion point of the light field. If a slit intersects inversion points with different orders, then behind a slit the secondary interference pattern is appeared. It allows make measurements with limiting error no more than 1” in the measurement range ± 1 °

Index Terms – angular measurement, diffraction, interference, point of phase inversion, diffraction pattern

1. INTRODUCTION

Now noncontact angular measurements find wide application in many areas of a science and technics, for example assemblage and adjustment of optoelectronic devices, linearity and flatness control calibration of rotary tables etc. To the solution this problems most often apply the autocollimators [1] which operation is based on creation autocollimation images of an adjustment mark in a plane of the analysis and definition of value of its displacement. For creation of the image of a mark the qualitative objective with the big focal length and the big aperture is required. It leads to increase of dimensions of an autocollimator. Precision considerations of autocollimators are limited by design factors of an objective and a photodetector resolution.

Interference sensors of angular position have high accuracy, but their construction difficult, and they are sensitive to external action [2].

We offer to use instead of an adjustment mark points (lines) of a phase inversion of interference or diffraction pattern which position coincides with a position of their minima. Matching with a point of a phase inversion can be executed by means of the slit aperture with very high accuracy such as intensity distribution in a diffraction pattern of the Fresnel behind it depends on distance between the center of a slit and an inversion point [3].

2. PRINCIPLE

In the paper [3] the circuit design of the device for angular measurements, using for creation of a measuring signal matching of a point of inversion of a light field (fig.1) with the slit aperture has been offered. Researches showed that on intensity distribution in a diffraction pattern of the Fresnel behind the slit aperture it is possible to define distance between the center the slit aperture and an inversion point with an error 0.1 μm. Unfortunately, the offered method has too small measurement range (less than 40”), and signal intensity measurement is hampered because of low illumination of a photodetector.

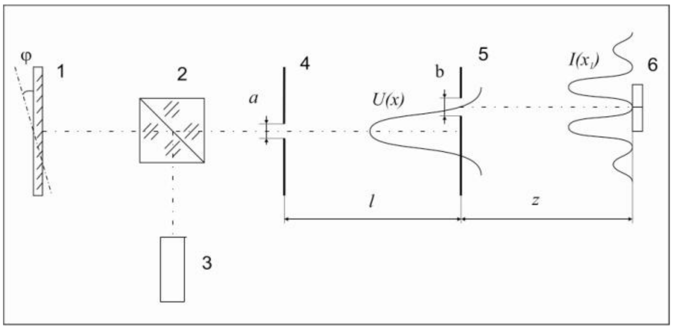

Fig.1. Diffraction gauge of angular measurement: 1 – specular reflector; 2 - beam splitting cube; 3 – laser; 4 – first slit; second slit; 6 – photodetector.

We offered to turn the slit aperture so that its center intersected lines of inversion of several interference orders (fig.2a). If the inversion point coincides with the slit center the signal phase behind a slit changes on π. As a result maxima in a diffraction pattern from a slit are replaced by minima. As the slit intersects minima of different interference orders, in a diffraction pattern from a slit there are additional fringes, perpendicular to slit edges (fig.2б).

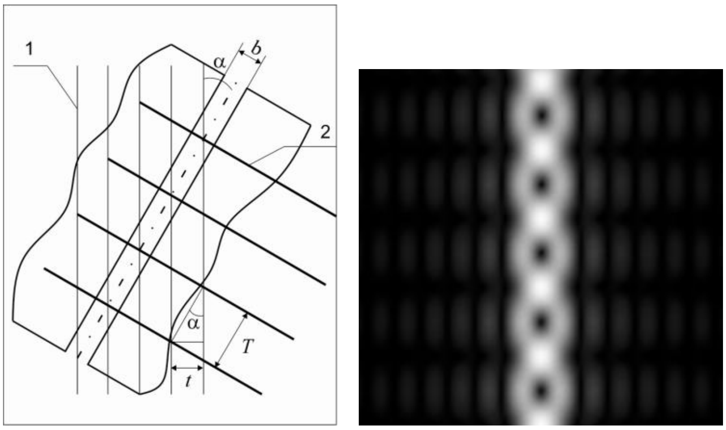

Fig. 2a. Fig. 2b.

Fig. 2.: Generation of fringes behind the slit at selection of inverse lines by turned slit: 1 – minimums of interference pattern; 2 – minimums of secondary fringes behind of the slit (a) and simulated result

Let's consider signal distribution behind a slit on distance $z > kb^2/2$, where k - a wave number, b - width of a slit. If in a plane of a slit amplitude distribution in an interference pattern is described by expression $U(x) = U_0 \cos(k\theta x) = U_0(e^{ik\theta x} + e^{-ik\theta x})/2$, where θ - angle of incidence of light wave on a slit, amplitude distribution to distance z behind a slit can be defined from expression

$$U(x_1) = A\int T(x)U(x)e^{ik(x-x_1)^2/2z}dx, \quad (1)$$

where $T(x)$ - transmission function of slit, $A = \sqrt{k/2\pi i z}\,e^{ikz}$.

If the slit is turned its center is displaced on distance $\Delta(y) = y\sin(\alpha)$, then expression (1) becomes

$$U(x_1, y_1) = A\int T(x + \Delta(y_1))U(x)e^{ik(x-x_1)^2/2z}dx, \quad (2)$$

where $y = y_1$.

Assumed that $z > kb^2/2$, we deduce (3) from expression (2)

$$U(x_1, y_1) = U_0\,AB\,(e^{ik\theta\Delta(y)}\mathrm{sinc}(kb(((x_1 - \Delta(y))/z) - \theta)/2) + \\ + e^{-ik\theta\Delta(y)}\mathrm{sinc}(kb(((x_1 - \Delta(y))/z) + \theta)/2)), \quad (3)$$

where $B = e^{ikx_1^2/2z}e^{ik\Delta(y)^2/2z}$.

Realizing transformation from amplitude to intensity, we deduce

$$I(x_1, y_1) = U_0^2\,A^2(\mathrm{sinc}(kb(((x_1 - \Delta(y))/z) - \theta)/2)^2 + \mathrm{sinc}(kb(((x_1 - \Delta(y))/z) + \theta)/2)^2 + \\ + 2\,\mathrm{sinc}(kb(((x_1 - \Delta(y))/z) - \theta)/2)\,\mathrm{sinc}(kb(((x_1 - \Delta(y))/z) + \theta)/2)\cos(k\theta\Delta(y))$$

The multiplier $I(y_1) = \cos(2k\theta\Delta(y))$ describes change of signal intensity in a detection plane on a y-axis, and the distance between maxima of this distribution is defined from expression

$T = \lambda/(2\theta\sin(\alpha))$.

The received expression allows saying that behind a slit the secondary interference pattern is appeared which period of fringes is linked with the period of fringes of an initial interference picture $t = \lambda/2\theta$ by expression $T = t/\sin(\alpha)$. As the ratio $\Gamma = 1/\sin(\alpha)$ at the small α is big, then small displacement Δt leads to big displacement ΔT.

The similar result is received if amplitude distribution in a plane of the turned slit is described by function $U(x) = U_0\mathrm{sinc}(kax/2l)$, where a - width of the first slit generating a diffraction pattern in a plane of a secondary turned slit, l - distance between slits (fig. 1). As in this case there are difficulties with solution of expression (2), according to paper [3] it is possible to expand into Taylor series function $U(x)$ and to use its first two members in the range of the center of a slit. Then the solution (2) will be the expression

$$U(x_1, y_1) \approx U_0\,A^2\,\mathrm{sinc}(ka\Delta(y_1)/2l)\,\mathrm{sinc}(kb(x_1 - \Delta(y_1))/z),$$

which analysis shows that in a detection plane on a y-axis signal change is described by expression $U(y_1) = \mathrm{sinc}(ka\Delta(y_1)/2l)$ with the period in $\Gamma = 1/\sin(\alpha)$ more than at an initial diffraction pattern.

3. EXPERIMENT

For check of possibility of use of inversion lines of an interference pattern for performance of angular measurements the breadboard construction represented on fig. 3a has been produced. It consisted of a laser source KLM-532 (1), the beam former (2), Fresnel biprism (3) ($\sigma = 16'$, $n = 1.53$), a rotary plane-parallel plate (4) ($d = 20.2$ mm, $n = 1.53$), the slit (5)($b = 0.05$ mm) and the CCD-sensor (6) (640×480, the dimension of pixel 12.4 microns). On fig.3б the breadboard model construction for research of possibility of application of inversion lines of a diffraction pattern where biprism is replaced by the slit (3) width $a = 0.4$ mm which is on distance $l = 350$ mm from the second slit is represented.

At rotation of a plate (4) interference or diffraction pattern in a slit plane was displaced on distance $\Delta t \approx (n_1 - 1)\, d\, \varphi / n_1$, where d -thickness of plate, n_1 - index of refraction of a plate.

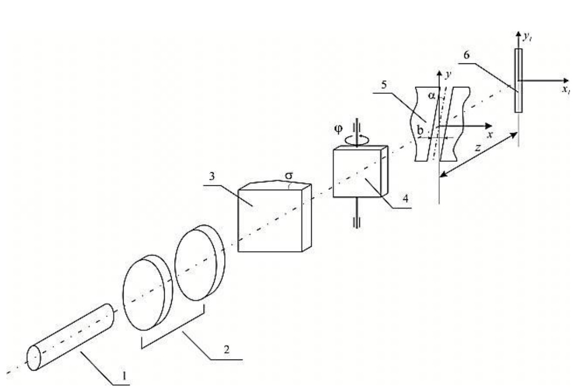

Fig. 3a.

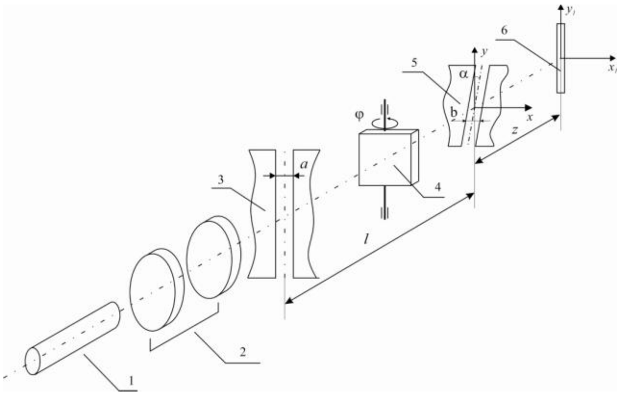

Fig. 3b.

Fig.3. Device for measurement of rotation angle of the plate with biprism (a) and slit (b): 1 – laser; 2 – beam former; 3 – biprism or slit; 4 – rotary plane-parallel plate; 5 – turned slit; 6 – CCD-sensor

As the angle of turn of a slit can be expressed as $\sin(\alpha) = t / T$ the expression connecting turn angle of a plate with shift of the secondary interference fringes behind a slit will be

$$\varphi = \frac{\Delta T\, n_1\, t}{(n_1 - 1)\, d\, T},$$

where t - the fringe period of an interferential or diffraction pattern. At biprism use $t = \lambda / 2\sigma(n-1)$, where σ - biprism angle, n - index of refraction of the biprism; at slit use $t = \lambda l / a$, where l - distance between slits, a - width of the first slit.

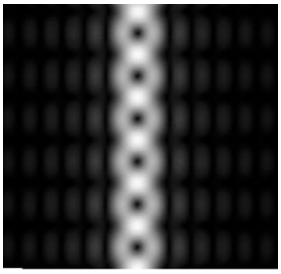

Fig. 4a.

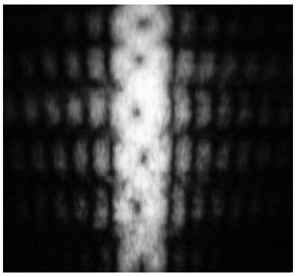

Fig. 4b.

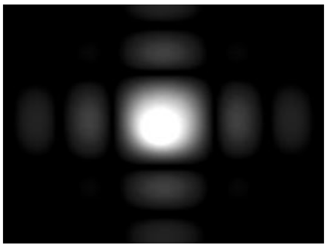

Fig. 4c.

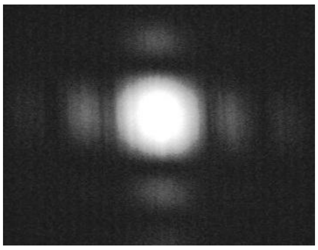

Fig. 4d.

Fig. 4. Results comparison of numerical simulation and experiment at extraction of inverse points from interference pattern (a – b) and from diffraction pattern (c – d).

Plate rotation was made by means of the worm gear with a scale interval 5'. Registration of images was made in the region of the principal maximum of the diffraction pattern. The received image cross-section was processed by means of the low-frequency filter, and its extremes were selected by the least squares method.

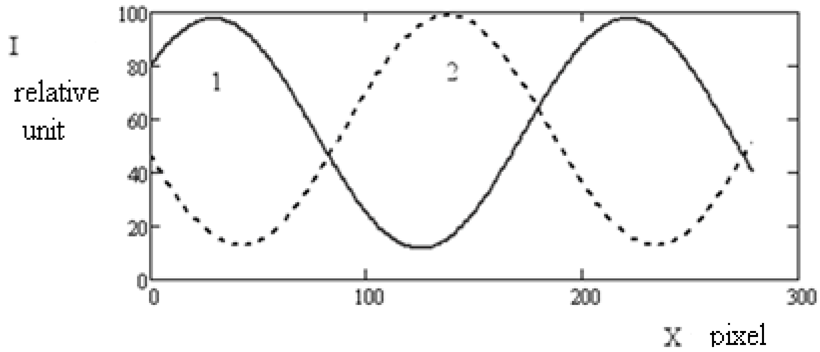

Fig. 5. Cross-section of secondary fringes in an initial position of plate (1) and its rotating on 30′ (2).

Comparison of distributions of intensity in a detection plane received experimentally and as a result numerical modeling showed close fit (fig. 4a - fig. 4d).

For the scheme figured on fig. 3a, the plate rotation angle was evaluated on displacement of secondary interference fringes (fig. 5). The measurement error was 40″ for plate rotation angle $\varphi = 30'$. This error is determined generally by an error of the worm gear which for rotation angle in 30’ is equal 30”, and also errors of angles of the biprism, an index of refraction etc.

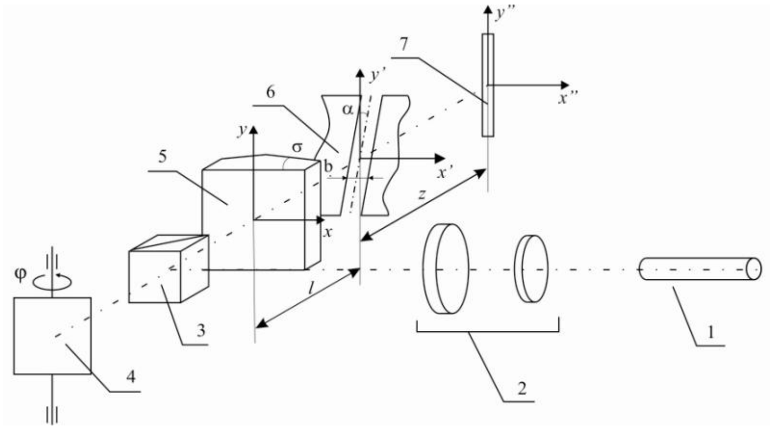

Fig. 6. Noncontacting gauge for angular displacement: 1 – laser; 2 – beam former; 3 – beam splitting cube; 4- specular reflector; 5 – biprism; 6 – turned slit; 7 – CCD-sensor

For the scheme figured on fig.4б, the plate rotation angle was evaluated on displacement of the principal maximum of a secondary diffraction pattern. The measurement error was 48″ for plate rotation angle $\varphi = 30'$. The error increase is explained by that through two crossed slits passes not enough energy and illuminance in the image is reduced. It complicates exact definition of an offset value of a maximum. For the solution of this problem it is necessary to register diffraction pattern points of inflexion instead of points of extremums.

Sensitivity of secondary fringes to a plate rotation is very high - if a resolution of the CCD-sensor is equal 0.1 pixel sensitivity is equal 0.5”.

4. CONCLUSION

We offer a method of measurement of angular displacements, using inversion lines of a light field. A numerical modeling and experiment showed that it can be used for creation of noncontacting gauges for angular displacements which can perform measurements in the range 1° with an error no more than 1". One of possible schemes of realization of a noncontacting gauge for angular displacements is figured on fig. 6. Rotation of specular reflector leads to displacement of an interference pattern in slit plane Problem of the offered way is a large energy loss at radiation propagation through system that leads to increase of an error of extremums point data. This problem can be eliminated at registration of points of inflexion of an image intensity distribution.

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