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FRESNEL MEASURING METHOD FOR DIMENSIONAL INSPECTION

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Abstract: Accuracy characterization of a Fresnel method for objects dimensions measurement in coherent and partially coherent light is investigated. The major sources of a systematic measurement error are estimated analytically including non-uniform illumination of the object, the interference effect of the diffraction object edge images, the integration properties of the linear multi-element photodetector, influence of extended size of partially coherent light source. Effective algorithms for account of basic error components and for increase accuracy in low measuring range are proposed. The obtained results are confirmed by experiments.

Keywords: dimensional inspection, Fresnel diffraction.

1. INTRODUCTION

Product quality improvement takes the development of dimensional inspection noncontact meters with high technical performances. These meters must have a resolution from 0.01 mkm to 0.1 mkm, a high speed of operation more than 10^3 meas./s and a wide measurement range from several µm to tens of mm. These measurement means must be inexpensive, compact and easily built-in into different technological production lines. The optoelectronic systems used for these purposes do not always satisfy the above – mentioned technical requirements. It takes to investigate new phenomena or use well-known ones for the purpose of measuring the dimensions of objects.

One of the available possibilities for dimensional inspection is to use the Fresnel diffraction patterns formed at some distance from their objects. In this case, free space transforming the input image of an object into its Fresnel image with a high accuracy operates as an optical element [1].

Moreover, usage of the Fresnel diffraction for dimensional measurements allows to improve considerably the technical performances of measurement instruments and produce new, compact, inexpensive and competitive sensors for solving different practical problems. However, all this requires detailed investigations.

The essence of the Fresnel measurement method is presented below. Four components of the error are investigated in detail. One of them is caused by nonuniform illumination of the object, another one is due to the interference effect produced by the diffraction images of its edges, the third one is caused by the integration properties of the used photodetector (CCD linear array) due to finite sizes of its pixels, and last one is caused by the extended dimensions of radiation source. The effective algorithms for increasing the measuring range by Fresnel method, as well as for accuracy increasing in low range are presented.

2. THE ESSENCE OF FRESNEL MEASURING METHOD

This method is based on using the object diffraction Fresnel pattern for dimensional inspection (Fig. 1). The measured object with M geometrical parameters $\{D_i\}$ ($1 \le i \le M$), described by amplitude transmittance $f(x_1,y_1)$, is illuminated by a plane monochromatic light wave with amplitude E_0 and wavelength λ. A Fresnel pattern (Fresnel image) as an amplitude distribution $g(x_2,y_2)$ is formed at the distance z from the object under the condition $z < D^2_{min}/\lambda$ (D_{min} is the object minimum size). As known, this distribution is equal to the convolution of the input distribution $f(x_1,y_1)$ with the impulse response of free space $h(x_2-x_1,y_2-y_1)=(1/i\lambda z)exp(ik[(x_2-x_1)^2+(y_2-y_1)^2]/2z)$ [3]:

$$g(x_2,y_2)= E_0 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x_1,y_1)h(x_2-x_1, y_2-y_1)dx_1dy_1 \quad (1)$$

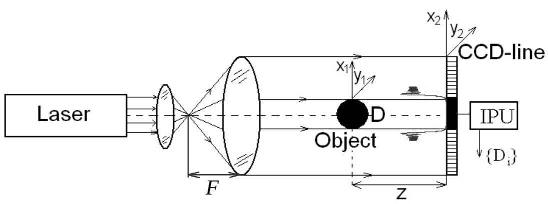

Fig. 1. Structure scheme of the Fresnel meter.

The obtained intensity distribution $I(x_2,y_2)=|g(x_2,y_2)|^2$ is recorded by a multielement photodetector (for example, CCD-line array). The signal from the photodetector enters to the electronic unit for measurement information processing. The sought-for geometrical parameters $\{D_i\}$ of the object are calculated in this unit by the appropriate algorithms. If, for instance, a one-dimensional slit of width D (Fig. 2) with amplitude transmittance as a rectangular function $f(x_1) = rect(x_1/D) = Y(x_1 + 0.5D) - Y(x_1 - 0.5D)$ is taken as an inspected object, the Fresnel image $g(x_2)$ of this object, in accordance with Eq. (1), has the following form:

$$g(x_2) = E_0[\tilde{Y}(x_2 + 0.5D) - \tilde{Y}(x_2 - 0.5D)], \quad (2)$$

where $Y(x_1)$ is the Heaviside step function that describes the object's edge, and $\tilde{Y}(x_2)$ is its Fresnel image.

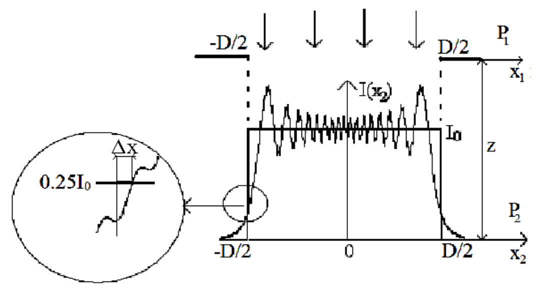

Fig. 2. Slit Fresnel image: P_1 –object plane, P_2 –image plane.

Let us consider the structure of the slit Fresnel image and the algorithm used for measurement information processing in detail. According to Eq. (2), the light intensity distribution $I(x_2,)$ for this image is described by the equation:

$$I_{out}(x_2) = |g(x_2)|^2 = I_0[|\tilde{Y}(x_2 + 0.5D)|^2 + |\tilde{Y}(x_2 - 0.5D)|^2 - Z(x_2, D)] \quad (3)$$

where $I_0 = |E_0|^2$ is the incident wave intensity, $Z(x_2, D) = 2|\tilde{Y}(x_2 + 0.5D)||\tilde{Y}(x_2 - 0.5D)| \cos[\varphi(x_2 + 0.5D) - \varphi(x_2 - 0.5D)]$ represents the cross member, which describes the interaction (interference) of edges diffraction images, and $\varphi(x_2)$ is the argument of the complex function $\tilde{Y}(x_2)$. As known, under the condition $D >> \sqrt{\lambda z}$ Fresnel pattern of the object resembles its shadow image in general. Actually, the distribution $I(x_2,)$ has light and shadow zones with the light zone size equal to the inspected geometrical parameters D. However, the slit Fresnel image has some important differences from the shadow one. At first, the illuminated part of the object has oscillations (fringes), the number of which $N_{fr} = D^2/4\lambda z$ (Fresnel number) [2]. Secondly, there is a transitional region between the light and shadow with dimension Δ, proportional to the Fresnel zone size $\Delta \sim \sqrt{\lambda z}$. For example, if we take z=10 mm and λ=0.63 mkm, the size of this zone equals to Δ~80 mkm. Moreover, the Fresnel pattern of the object, due to interference of the object diffraction edges images, contains a microstructure as high-frequency oscillations with period $\Delta_D \sim \lambda z/D$. If these parameters are chosen as N_{fr}>>1, the locations of the object boundaries (coordinates $x_1 = \pm D/2$) in the Fresnel image, as known, correspond to the points $x_2 = \pm D/2$ with a sufficient accuracy [3]. The distribution intensity at these points constitutes 25% from the intensity of incident illumination I_0. Thus, the sought-for size D in the slit Fresnel pattern is determined by standard algorithm as threshold processing of the output distribution:

$$I_{out}(x_2 = \pm D/2) = I_{thr} = 0.25 I_0 \quad (4)$$

where the I_{thr} is threshold.

Preliminary estimates show that such meters can have potentially good technical performances: a wider measurement range (from tens of mkm to tens of mm) and a high accuracy of measurements (an error from tenth fractions of mkm to several mkm).

Under this consideration some factors that can deteriorate the above characteristics are not taken into account. The most significant among them are the following: the nonflatness of illuminating object wavefront within the meter working field (the nonuniformity of the illuminating beam), a microstructure as high-frequency oscillations, the deviation of the output signal profile from the initial optical one due to the finite sizes of photodetector pixels, the influence of volumetric properties of objects (3D effects), etc.

In this paper we investigate the first three factors. The used standard threshold algorithm for determination of parameter D is sensitive to the above-mentioned factors. Actually, if an object is illuminated by nonuniform wave $E_{in}(x_1)$, the problem of the threshold level I_{thr} choice is actual. For instance, if this level is chosen as $I_{thr}=0.25|< E_{in}(x_1) >|^2$, i.e. proportional to the space-averaged wave $E_{in}(x_1)$, one doesn't allow to increase significantly the measurement accuracy. So it means that such threshold processing algorithm is not optimal. It is confirmed by a well-known fact from the Fresnel zone theory of image formation, namely, the field $g(x_2)$ at the point with coordinates (x_2) is mainly determined by the influence of the nearest zones in field vicinity. In other words, the operation of formation of the field $g(x_2)$ is mainly local in spite of the fact that the impulse response is unlimited in space.

Thus, to find the sought-for geometrical parameter of an object under indicated factors with high accuracy using the Fresnel diffraction pattern, one needs to perform thorough investigations. These ones must result in effective algorithms for Fresnel image processing taking into account these factors.

3. NONUNIFORM ILLUMINATION

The non-uniform wave illuminating the object as half-plane Y(x1) (Heaviside step function) was simulated by using a harmonic distribution (Fig. 3):

$$E_{out}(x_1) = E_0[1 + \alpha \cos(\omega x_1 + \varphi)]Y(x_1) \quad (5)$$

Here, ω = 2π/T is the angular spatial frequency of oscillations (T is the period), φ is the initial phase of oscillations, and the parameter α denotes the amplitude of nonuniformity ($0 \le \alpha \le 1$). Using Eq.(1) and Eq. (5) one can obtain the following expression for the intensity distribution in the plane P_2:

$$I_{out}(x_2) = I_0 \left| \begin{array}{l} \tilde{Y}(x_2) + 0.5\alpha e^{-iz\omega^2/2k}[e^{i(\varphi+\omega x_2)} \times \\ \times \tilde{Y}(x_2 - \beta) + e^{-i(\varphi+\omega x_2)}\tilde{Y}(x_2+\beta)] \end{array} \right|^2 \quad (6)$$

Here, $\beta = z\omega/k = \lambda z/T$. It is evident that non-uniform illumination of the object leads to a half-plane edge displacement Δ_{xnonun}, which under T>> $\sqrt{\lambda z}$ according to Eq.(6) is equal to:

$$\Delta x_{nonun} = -\frac{\sqrt{2\lambda z}\alpha \cos\varphi \cos(\pi/N^2) - \sqrt{2}\alpha N^{-1}}{1+\alpha(1+\cos\varphi) - 2\sqrt{2\pi}\alpha N^{-1}\sin\varphi} \times \quad (7)$$
$$\times \sin\varphi\cos(\pi/N^2) + 0.5\alpha^2\cos^2\varphi$$

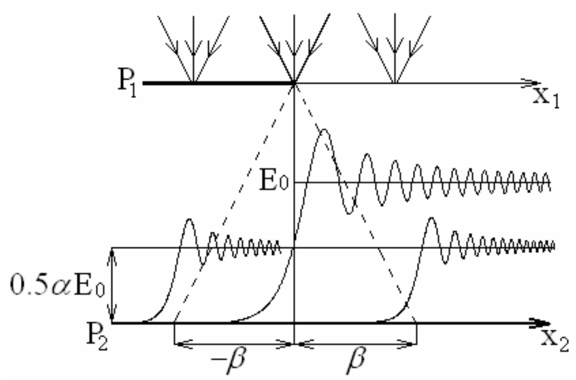

Fig. 3. Edge Fresnel image under non-uniform illumination.

One can expect that the displacement Δ_{xnonun} can be decreased significantly by appropriate threshold correcting. and, for instance, in case of weak non-uniform (B/T<<1):

$$I_{thr} = 0.25 I_{in}(0)[1 + \Delta i/\sqrt{2\pi} I_{in}(0)], \quad (8)$$

where $\Delta i = I'(0)\sqrt{\lambda z}$, and $I'(0) = I_{\max} 4\pi^2 B/T^2$, B is distance between edge location and maximum field intensity I_{max} (Fig. 4). One can see that the influence of non-uniformity on the structure of the edge Fresnel image is local. Moreover, this effect is determined by the degree of non-uniformity of the beam illuminating the object within the Fresnel zone size. According to algorithm (8) value Δx nonum can be decreased by a factor of more than 40.

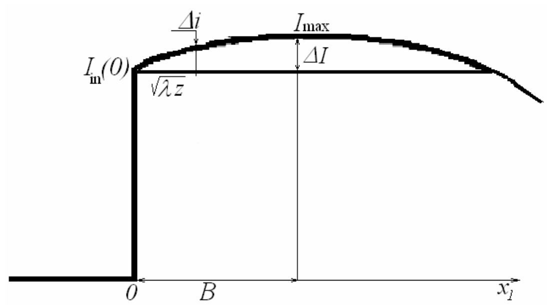

Fig. 4. Threshold choosing for weak non-uniform illumination.

It has been found that the influence of nonuniformity illumination on structure of Fresnel image has local character, i.e. the edge position mainly is determined by field behavior and its derivative on dimensions of Frenzel zone vicinity. In case of weak nonuniformity the real threshold determination is reduced to finding two parameters of this field, namely, field intensity at edge position place as well as degree of its nonuniformity within the Fresnel zone limits. The proposed algorithm to account for illumination nonuniformity allows us to decrease in ten times the indicated error for object edge position determination.

4. INTERFERENCE EFFECTS ESTIMATION

Analyzing a model of an optical signal that corresponds to the Fresnel pattern of an object as a slit, one should take into account the interference phenomenon of its diffraction edges of the object. This effect leads to an edge displacement of Δx_{in}t (Fig. 2). Under estimation of the displacement of the location, for instance, of the object left edge with coordinates x_2=-0.5D, we use the approximation for the Fresnel image of an edge at D>> $\sqrt{\lambda z}$ [4]:

$$\tilde{Y}(x) = Y(x) - 0.5 p\, sign(x) \frac{e^{ikx^2/2z}}{|x| + p}, \quad (9)$$

where $p = e^{i\pi/4}\sqrt{\lambda z}/\gamma$, the value $\gamma = \pi$ at x>> $\sqrt{\lambda z}$ and $\gamma = 2$ at x<< $\sqrt{\lambda z}$.

Let us change the variables as follows x_2+0.5D=y. Then, in accordance with Eq. (9), the field in the vicinity of x_2=0 from the slit left edge is

$$g_1(y) = E_0[0.5 + e^{-i\pi/4} y/\sqrt{\lambda z}] \quad (9a)$$

As for the diffraction image of the second edge, it is described by the following equation:

$$g_2(y) = E_0 p \frac{\exp(ik(y-D)^2/2z)}{2D} \quad (9b)$$

Using Eq. (9a) and Eq. (9b), we obtain the resulting field *I*(y) in the vicinity y=0:

$$I(y) \approx I_0[0.25 + \frac{y}{\sqrt{2\lambda z}} - \frac{\sqrt{\lambda z}}{2\pi D}\cos(\frac{kD^2}{2z} + \frac{\pi}{4} - \frac{kyD}{z})] \quad (10)$$

Hence, the maximum displacement value Δx_{int} of the geometrical location of the object edge image

$$\Delta x_{\text{int}} = \lambda z/\sqrt{2\pi}D = D/18N_{fr} \quad (11)$$

In this case, the relative error is

$$\delta_{\text{int}} = \Delta x_{\text{int}}/D = (18N_{fr})^{-1} \quad (12)$$

Thus, the value of the parameter Δx_{int} is determined by the number of Fresnel zones at the object size *D*. It is seen, that the influence of interference effect is especially appeared at small N_{fr} or when the size D of the object to be measured is of the order of the Fresnel zone size $\sqrt{\lambda z}$ and, for instance, this error at *D*=1 mm and N_{fr}=100 can reach Δx_{int}=0.5μm. As shown below, the accuracy of measurement can be increased significantly if this effect is taken into account.

5. MEASURING SIGNAL FORMATION BY CCD-LINEAR ARRAY

Let us investigate the process of formation of the output signal $I(x_2)$ at the recording of nonlinear field distribution of Fresnel image by CCD linear array. This distribution in the vicinity x_2=0 according to Eq. (9) and Eq. (9a):

$$I(x_2) = \left|\tilde{Y}(x_2)\right|^2 = I_0 \left| 0.25 + \frac{x_2}{\sqrt{2\lambda z}} + \frac{x_2^2}{\lambda z} \right|^2 \quad (13)$$

Evidently that due to integration properties of multielement photodetector under recording the nonlinear distribution Eq. (13) there is a deviation of the output electric signal $I(x_2)$ from the initial optical one. As a result, a systematic error δ_{dis} under the determination of the object edges position is appeared. The value of this error depends on the pixels number *n* of the CCD linear array within the Fresnel zone: $n = \Delta / d = \sqrt{\lambda z} / d$, where *d* is the pixel size on x_2 coordinate. Let us determine analytically the value of this error, depending on the number of CCD-array pixel number *n* in the Fresnel zone and the location of CCD-array pixel Δ_1 relative to the pattern being recorded. To do this, we use the Fresnel edge expansion $\tilde{Y}(x)$ and the equation for a straight line going through two points: $x_1=-d$ and $x_2=0$ (Fig. 5).

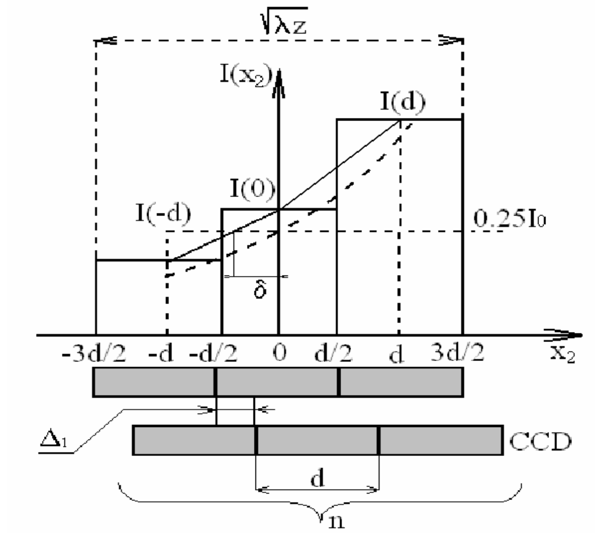

Fig. 5. Determining the displacement δ:
--- signal before the CCD linear array,
— signal after the CCD linear array.

As a result of spatial integration operation, one can obtain the following relation for the error δ_{dis} at $n>>1$:

$$\delta_{dis} = -\frac{d(1 + 6\sqrt{2}mn + 12m^2)}{6\sqrt{2}n(1 + \sqrt{2}/n + 2m/n)} \quad (14)$$

where $m = \Delta_1 / d$. At Δ_1=0 this equation is simplified significantly:

$$\delta_{pd} \approx -\frac{d}{6\sqrt{2n}} \quad (15)$$

This error can reach δ_{pd} = -0.3 mkm at Δ = 0.057 mm, *d* = 14 mkm and can be decreased considerably by suitable choice of the parameter z.

6. PARTIALLY COHERENT ILLUMINATION

By using partially coherent non-point illumination (instead of laser) with angular size $\theta_s = \Delta_s / F$ (Δs is source size, F is objective focal length) one can improve the structure of the output optical signal by suppressing the coherent noise thus increasing the measurement accuracy (Fig. 6).

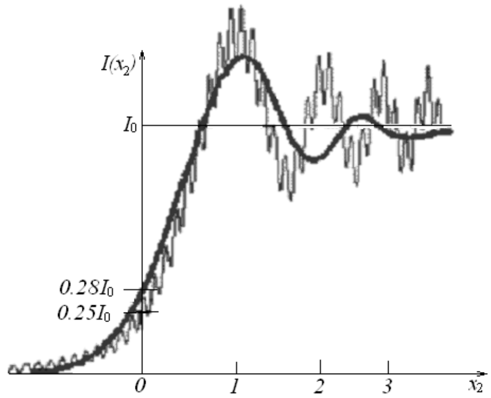

Fig. 6. Edge Fresnel image under coherent (modulated curve) and non-coherent (smoothing curve) illumination.

In this case for intensity distribution $I(x_2)$ we can obtain the following equation:

$$I(x_2) = \frac{I_0}{\Delta_S} \int_{-\Delta s/2}^{\Delta s/2} \left| \tilde{f}(x_2 - \frac{z\varsigma}{F}) \right|^2 d\varsigma \quad (16)$$

However, under partially coherent illumination an object edge displacement Δx_{pc} appears. Using the well-known expansion of the Fresnel edge in the vicinity of point x_2=0: $\tilde{Y}(x_2) = E_0(0.5 + e^{-i\pi/4}(x_2 - \tau\zeta)/\sqrt{\lambda z})$, where $\tau = z / F$ one can obtain:

$$\Delta x_{pc} = -\tau^2 \Delta_s{}^2 / 6\sqrt{2\lambda z} \quad (17)$$

It is evident that this error can be decreased considerably by the threshold choice:

$$I_{thr}(0) / I_0 = 0.25 + \tau^2 \Delta_s^2 / 12\lambda z \quad (18)$$

Thus, for instance, at Δs=50 mkm, λ=0.63 mkm, and z=F=10 mm, the threshold is $I_{thr}(0) / I_0 = 0.28$.

7. INCREASING THE MEASUREMENTS PRECISION FOR SMALL OBJECTS

Let us now investigate Fresnel method characterization for a lower limit D_{low} of measuring range. It is determined by the number of Fresnel zones N_{Fr} within the object size D. Obviously that for $N_{Fr} = D^2 / 4\lambda z = 0.25$ the parameter D_{low} is equal to:

$$D_{low} \approx \sqrt{\lambda z} \qquad (19)$$

In this case, interference effect of the diffraction images of object edges is appeared considerably. It leads to a displacement of the threshold level under determination the object boundaries. For example, the experimental relative error $\Delta D / D$ is equal to 18% under determination the parameter D=0.15 mm by the level 0.25I0 ($\sqrt{\lambda z} = 0.114 mm$, N_{fr}=0.43).

We have proposed a new algorithm for Fresnel image processing that ensures significantly the measurement accuracy increase. It takes into account the character of the field in the vicinity of the edge. In this case the threshold $\tilde{I}_{thr}$ for edge location determination at point x_2=0 at D~$\sqrt{\lambda z}$, according to Eq. (8), can be the following:

$$\tilde{I}_{thr} / I_0 = 0.25 - \frac{1}{2\pi}\sqrt{\frac{\tilde{T}}{\tilde{D}}}\cos(\pi\frac{\tilde{D}}{\tilde{T}} + \pi / 4), \qquad (20)$$

where $\tilde{T} = \sum_{i=1}^{N} T_i / N = \lambda z / \tilde{D}$ is the average period of modulation and $\tilde{D}$ is the object size estimation determined by the level 0.25I_0 (Fig. 7). Using this algorithm the experimental relative error $\Delta D / D$ for above shown parameters can be decreased up to 10 times.

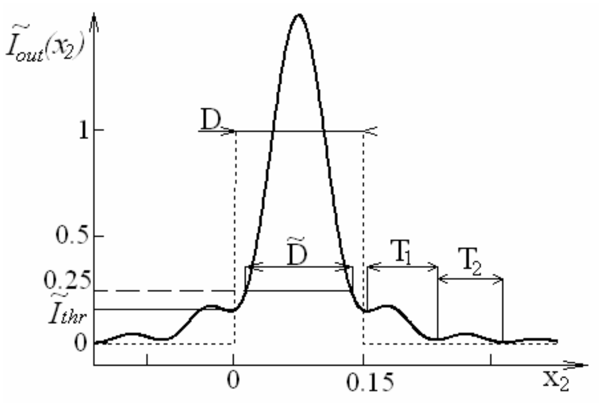

Fig. 7. Finding a threshold in the lower measurement range: D=0.15 mm, $\sqrt{\lambda z} = 0.114 mm$, z=20 mm, N=0.43.

8. EXPERIMENTAL RESULTS

A schematic diagram of the experimental setup is shown in Fig. 1. A light-emitting diode with a wavelength λ_{max}=0,628 mkm and a photodetector, a CCD-line ILX511, with an element size of 14 × 200 mkm (2048 elements), were used in the investigation. The length of the source was 50-100 mkm, and the parameter $z \leq 40$ mm. The light beam was collimated by a condenser lens with a focal length of 145 mm. In the experiment, nontransparent objects of 0.5 mm to 18 mm in diameter were to be inspected. We have investigated the proposed algorithms for account influence of nonuniformity (8) and extended sizes of light source (18) under object displacement in measuring area 5×5 mm^2. The measuring error didn't exceed 1 mkm. The obtained error includes the error of attestation of the objects used in the experiments and error which caused by residual high- frequency nonuniformity of illuminated beam.

9. CONCLUSION

Metrology characteristics of a Fresnel method for dimensional measurement have been investigated.

An effective algorithm for finding the actual threshold I_{thr} in the case of weak nonuniformity is proposed. The Fresnel image microstructure due to the interference effect leads to displacement Δx_{int} which is inversely proportional to the number of Fresnel zones N_{Fr}. Integration properties of photodetector are resulted from systematic error of the edge location, which can be reduced choosing *z*. By using partially coherent illumination one can improve the structure of the output optical signal by suppressing the coherent noise and thus significantly increase the measurement accuracy. The effective algorithm are proposed for finding of the threshold under Fresnel image processing for small object.

The obtained results are confirmed by experiments. The measuring error didn't exceed 1 mkm.

The results obtained can be used under the development of meters based on Fresnel diffraction phenomena.

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