OPTOELECTRONIC METHODS OF GEOMETRICAL PARAMETERS MEASUREMENTS WITH MICRO- AND NANOMETRIC RESOLUTION

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Many tasks of non-destructive testing and technical diagnostics come to measurements of different geometrical parameters of tested objects [1]. The report concerns high-precision optoelectronic methods featuring digital processing of measuring information, providing micro- and nanometric resolution. The methods concerned are the following: 1) computer microscopy; 2) homodyne white light interferometry; 3) laser heterodyne interferometry with acoustooptical light frequency transformation.

1. Computer microscopy.

Classical microscopy of dimensional measurements comes to pointing the microscope sight to the points of the edge of object's geometrical image and determination of distance between the points by means of reading devices [2]. Computer microscopy digitally processes the image using CCD-matrix and performs software determination of distance between the points [3]. CCD-matrices provide high precision coordinate measurements both for geometrical images [4] and interference fringes [5], as described in a number of works. In particular, positional precision of CCD-matrices is considered in detail in [5] and low values of measurement errors distributed among different directions CCD-matrix receiving plane are proven. These results prove the correctness of usage of CCD-matrices in measuring microscopes as well.

Measuring microscopes errors having geometrical character (caused by Abbe error, guide straightness variation, measuring scales or displacement encoders position errors, and other) can be revealed during device calibration and can be compensated by device adjustment or software algorithms correction for concrete measuring tasks solution.

The most essential and practically irreducible part of error is the error of pointing the microscope's sight to the points of the edge of object's image. It's main reason is wave nature of light and is based on Fresnel object's knife-edge diffraction [6]. Fresnel diffraction's influence is especially high on measurement of objects with edges, spatially spreaded along the optical axis, as well as cylindrical, conical, helicoidal surfaces and parts with non-flat, curved edges.

Special tools – measuring knives – are used in metrological practice in order to reduce the influence of diffraction image blurring on object's geometrical parameters measurement errors. The knives' blades are put in contact with the measured object's edge. Then microscope's sight lines are pointed at knife's hairline in order to point the microscope's sight to the point of the edge of object's image precisely. However, measuring knives are precision tools with standard parameters and fine straightness of edges, and field of their usage is limited to measurements of, mainly, cylindrical, conical surfaces and threads with high pitch. Application of measuring knives to other surfaces involves difficulties or is impossible. Measuring knives setting during measurement is individual and labour-intensive, limits productivity and requires highly skilled operator, while knives themselves are wearing quickly.

Computerization and intellectualization of measuring microscopes based on digital image processing of sight zone provides essential reduction of diffraction error and allows to do without knives. The essence of this processing is as follows.

The image of measured part and microscope's sight is formed at the monitor screen (fig. 1). Actually the image in the left window at fig. 1 corresponds to the image seen by an operator through microscope's ocular during pointing the microscope's sight to the point of the object's edge.

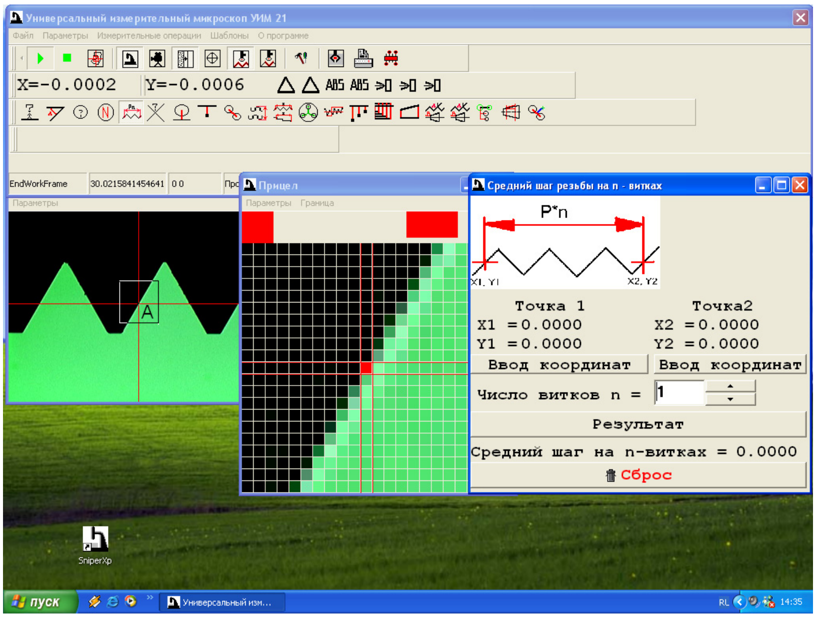

Fig. 1 On-screen image of measured part and microscope's sight

Then the following problem is being solved by software. A little square with a side sized *a* around the center of the sight (crosshair) (point A) is picked up. Usually, *a* is assigned a value between 20 and 30 pixels of digital measuring zone image. The picked up piece, zoomed in 500-600 times, is displayed in a separate window (middle window, fig 1). In order to do this a "electronic magnifier" mode is used, performing digital zoom during video image processing. Thus in the middle window a blurred image is displayed, representing Fresnel knife-edge diffraction. Special algorithm analyzes this image and light intensity distribution within Fresnel diffraction image (fig. 2). Next, inverse problem of mathematical optics is solved, consisting in determination of object's edge position by distribution caused by this position. The microscope's sight should be superposed with indicated elements of object's edge.

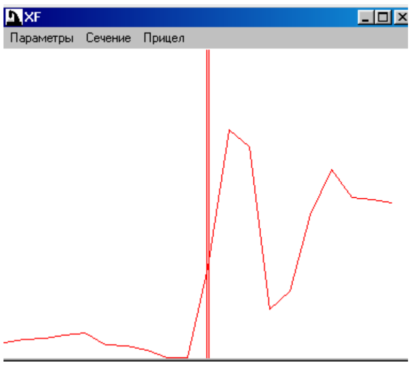

Fig. 2 Light intensity distribution of Fresnel diffraction pattern by real object's edge

The results of Fresnel diffraction pattern analysis are presented in the figure 2. This light intensity distribution is similar to the known theoretical distribution of Fresnel diffraction [6].

The inverse problem of mathematical optics solution provides exact determination of object's edge position causing Fresnel image intensity distribution. The solution is indicated in the window with blurred sight zone image by a special mark, for example, a red square. The operator's task comes to superposing the red mark with the microscope's sight crosshair center (middle window, fig 1). Thus uncertainty of edge's position caused by Fresnel diffraction is essentially decreased. Experiments proved the uncertainty is at least 2-3 times decreased.

Fig. 3 shows an example of Fresnel diffraction by cutting edge of tool.

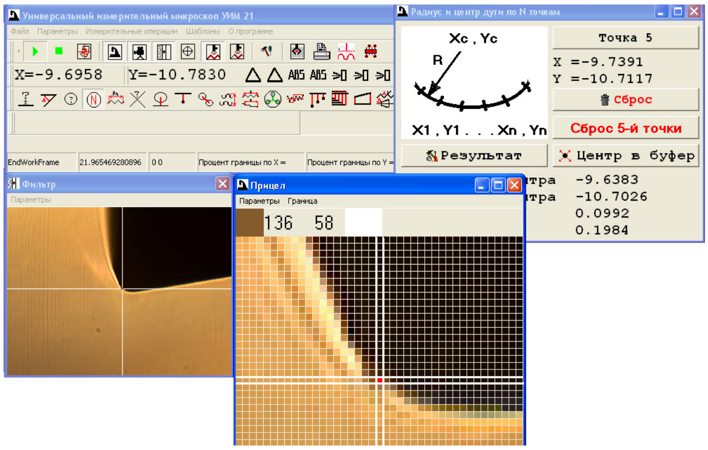

Fig. 3 An example of Fresnel diffraction by cutting edge of tool.

Generally, concerning wide variety of measured objects with different edge shapes and spread along microscope's optical axis, this problem is ill-posed and requires special solution regarding edge's features. Still exact solution of this problem is known, for example, for the case of an object with infinitesimally thick edge and monochromatically lit. The solution of this problem is given in [6], determining intensity of Fresnel diffraction pattern in the point, corresponding to the edge of the object, is equal to 0,25 of incident light intensity.

Experimental study of developed automated measuring system with digital image processing, involving measurements of cylindrical surfaces diameters between 0.5 and 90 mm and dimensions of prismatic objects with edge spreaded along the optical axis within 0.02 – 100 mm, proved the distribution of light intensity similar to the theoretical Fresnel diffraction pattern distribution, agreeing with theoretical Fresnel diffraction pattern distribution given in [6]. The dimensions measurement error did not exceed $\Delta = \pm[(2,5\ldots3)+L/100]$ microns (95% probability).

In general, having the edge's spread and shape are outside the mentioned above values, the edge's position determination may not correspond to the Huygens-Kirchhoff's theory and may require involving more strict diffraction theories [6]. In this case the object's edge position determination corrections bank is required. Developing such bank for objects with different shapes is a subject of further study.

Inverse problem of mathematical optics solution provides quite exact determination of object's edge position. Thus intellectualization of spatial measurements takes place, used by MSTU "Stankin" in order to upgrade industrial measuring microscopes [7]. Hence, two guidelines for industrial measuring microscopes upgrade are provided: on the one hand, development of new computerized measuring systems with extended functionality and increased precision, on the other hand – modernization of existing measuring microscopes pool. For example, a measuring computerized system featuring measured parts image output, and real-time computer image processing is developed based on a commercial universal industrial measuring microscope. The system is provided with coordinate measurements means with 0,1 micron resolution with digital indication and automatic readout input and computer processing. The system features custom software performing efficient automated processing of complex objects measurement results.

The software features the following functions:

forming measured parts elements video image using CCD-cameras featuring controlled optical and digital zoom;

digital image computer input;

coordinate displacement readout of microscope's stage by means of optoelectronic encoders with automatic computer information input;

on-screen measured zone visualization, crosshair or marks forming for coordinate measurements:

semi-automatic optical system focusing on measured objects;

zoomed crosshair area image output with controlled zoom ("electronic magnifier" mode) for accurate superposing the object's edge points with the crosshair center;

digital image processing with using of different algorithms (image differencing, selection of separate geometrical shapes, digital image filtering e.t.c.);

software simulation of complex geometrical shapes used as normal gauges (standards) during complex objects measurement;

deviation of measured contours of complex or small parts from simulated standards evaluation using different approximations methods (least-squares method, minimal deviation, spline methods);

automated computer processing of measuring information during measurement of small elements of part's surface involving digital image processing;

efficient recordation of measurement results and printing (hard-copy output) of enlarged images of complex elements of measured parts.

Measuring options consist of about 30 different routines for linear and angular dimensions measurements, determination of complex positioning and shape errors, including: measuring of flat formers and master formers, measuring of surfaces specified by tables of coordinates or systems of linear equations, formers control using master formers; control of thread gauges, measuring distance between points, angle between lines, circle or arc radius and center coordinates after N points coordinates, coordinates of the point of two lines intersection, distance between the center of a circle and a line, average thread pitch measurement, distance between points along X and Y axes, linear and angular dimensions between centers of circle systems (positioning errors of circle systems), straightness variations based on N measured points, non-parallelerism and non-perpendicularity, distance between a base line and other points, distances within dimensional chains from the base point, distances in a system of surfaces with different specification of bases and other measuring tasks.

2. Homodyne white light interferometry.

Homodyne white light interferometry has various metrological applications [6]. One of the most important applications is usage of homodyne white light interferometry in precision measuring tools – end gauge blocks – and other precision parts attestation.

According to the State Accuracy Chart transfer of length unit size from 1^{st} class standards to 2^{nd} – 4^{th} class industrial standards is performed by intercomparison of master standard and controlled standard by contact white light interferometers.

Contact interferometers cover the range of controlled objects sizes of 0 to 1000 mm and greater, and many of controlled classes of end gage blocks are widely used in industrial and high-tech practice.

The principle of measuring transformation of white light interferometers is well known [2]. It is based on two-beam interferometry performed by Michelson interferometer optical scheme with moving mirror. The mirror is rigidly bound to test point contacting the master or tested end gauge block.

The advantage of white light interferometry is forming a special achromatic fringe within the observed spectral – colored interference pattern (fig. 4.a). The achromatic fringe, sensitive to mirror movement, acts in contact interferometers as sight, moving along a fixed scale corresponding to the end gage block's size variation. The interference pattern intensity distribution is represented on fig. 4.b

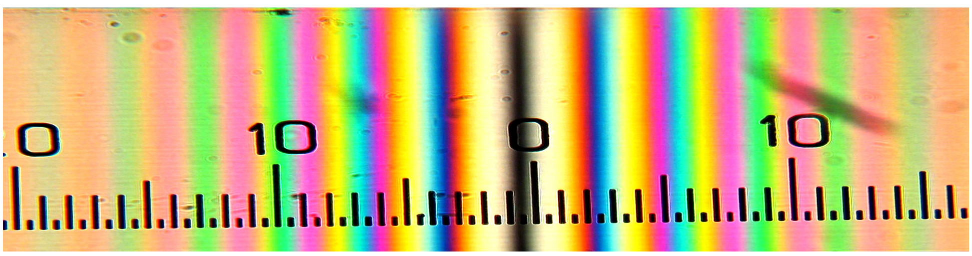

Fig. 4.a Colored interference pattern over the interferometer's scale with achromatic fringe.

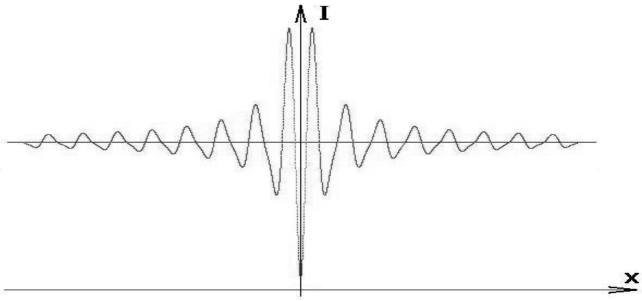

Fig. 4.b White light interference pattern intensity distribution.

The other important feature of contact interferometers is their natural connection to the main physical unit of length, reproduced by light wavelength. In order to provide this interferometers have two operation modes: 1) monochromatic light adjustment mode, 2) white light measurement mode. The first mode is used for optical scale calibration in the light wavelengths. The light from the light source passes through color filter with known wavelength (green line, λ=555±15 nm). Scale calibration comes to fitting of defined number of interference fringes into corresponding number of scale marks (fig. 5). The operation is performed by a mechanical adjustment of fixed mirror pitch, changing the interference fringes width and provides scale interval of 0.05 – 0.2 micron. Thus the unit of length is naturally transferred to the interferometer by optical wavelength.

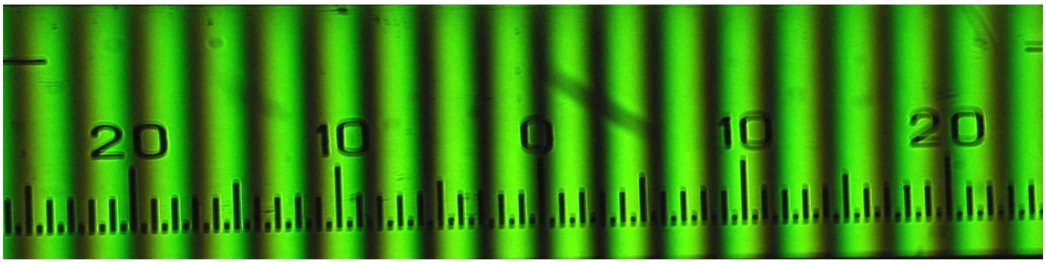

Fig. 5. Adjustment mode with green light interference pattern over the interferometer's scale.

The second – measuring - mode is activated by removing the color filter from the light's path. Thus white light interference pattern appears with central achromatic fringe, moving along the scale, calibrated by light wavelengths (fig. 5).

Computerization and automation of white light interferometers is based on digital optical image processing [8,9], preserving their advantages mentioned above.

In order to do that a CCD-device is placed within the interference pattern forming plane (in the ocular), connected to the computer's video capturing device (framegrabber). As a result, interference pattern is saved in the computer memory and outputted to the monitor screen.

The scheme of optical transformation is shown at fig. 6.

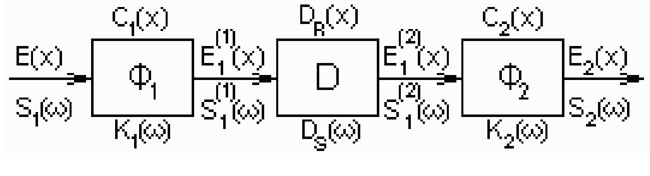

Fig. 6. Scheme of optical information transformation.

According to this scheme the process is divided into 3 stages:

1. Charging filtration Φ_1:

The output signal $E(x)$ is a function of illumination, it's spectrum is - $S_1(\omega)$, weight function of filtration is $C_1(x)$, it's spectrum - $K_1(\omega)$.

Additionally takes place the following:

- aperture CCD filtration and signal transformation with weight function $h_a(x)$ and corresponding spectrum $K_{(1)}(\omega)$;
- diffuse filtration with weight function $h_d(x)$ and corresponding spectrum $K_{(2)}(\omega)$.

As a result $C_1(x) = h_a(x) \otimes h_d(x,\lambda)$, where '$\otimes$' is the integral convolution symbol, and $K_1(\omega) = K_{(1)}(\omega) K_{(2)}(\omega)$.

2. Digitization D:

the input signal is filtered function $E_1^{(1)}(x)$, it's spectrum is $S_1^{(1)}(\omega)$, digitization function is - $D_R(x)$, it's spectrum is $D_S(\omega)$.

3. Charge transfer filtration Φ_2:

The input signal is $E_1^{(2)}(x)$, it's spectrum - $S_1^{(2)}(\omega)$, weight function of filtration is, $C_2(x)$, it's spectrum $K_2(\omega)$.

Thus the system's output signal is as follows:

$$E_2(x) = R^P E(x) \otimes C_1(x) \cdot D_R(x) \otimes C_2(x),$$

where $R^P = I(x)/E(x)$ - is the photosensitivity factor.

The corresponding modulation-transfer characteristic is as follows:

$$S_2(\omega) = R^P S_1(\omega) K_1(\omega) \otimes D_S(\omega) K_2(\omega).$$

The influence of different system parameters on the output signal was studied using the convolution theorem and Fast Fourier Transform, considering the number of CCD matrix pixels, interference fringes number and charge transfer loss factor. The achromatic fringe center locating error analysis has proven the relative error to be less then 0,01 fringe pitch. In order to increase the achromatic fringe center locating accuracy using CCD-matrix with high pixel count (high resolution) and low charge transfer loss factor.

Based on analysis mentioned above, CCD-matrix is proposed to be used as a controlled high-resolution electronic scale with per-pixel dial resolution. The scale interval is set by electronic scale calibration by light wavelengths. Readout is performed on the basis of digital interference pattern processing according to the pixels as electronic scale intervals. The interference pattern itself is filtered, leaving almost only the achromatic fringe in the field of view (fig. 7).

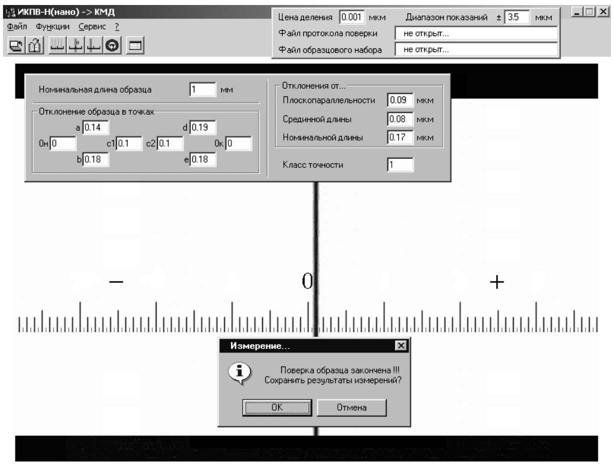

Fig. 7. User interface window with the scale and achromatic fringe.

The obtained results prove that the convergence of interference signal center position measurement results is characterized with a constant value of 0,1 of sampling increment, corresponding to relative error of $\approx 3\cdot 10^{-3}$ of fringe pitch. For comparison, convergence of visual method of interference fringe displacement determination is 0,1 of fringe pitch.

Theoretical and practical results of this work were used for development of computerized interferometer based on commercial contact interferometers for automated calibration of end gauge blocks of 2^{nd}, 3^{rd} and 4^{th} classes. Thus the white light interference pattern digital processing method provides:

subjective operator's errors elimination;

1,5-2 times absolute error and readout variation reducing (up to 0,02 micron and 0,01 micron for correspondingly 2^{nd} and 3^{rd} class standards);

100 times measurement resolution increase (up to 0,001 micron);

operator's conditions of work improvement and 3-4 times productivity of end gauge blocks calibration increase due to:

distant observation of the interference pattern on the monitor screen;

automatic nominal sizes and basic errors of master end gauge blocks input from database;

automated readout input;

automated measurement results processing;

computer-aided documentation and archiving of calibration results featuring automated protocol issue and forwarding calibration results to the company's network.

3. Laser heterodyne interferometry with acoustooptic light frequency transformation.

One of the possible non-contact methods of object's dimension measurement and it's non-transparent edge location is usage of laser beam. The laser beam in this case acts as a non-contact optical "caliper jaw", functionally same to the jaw of usual mechanical caliper. Known laser optoelectronic measuring systems realizing this measuring method are based on detected laser beam intensity change caused by object's edge displacement overlapping the beam. Thus amplitude transformation of measured value takes place. Another known method of electromechanical scanning of the object by laser beam, transforming the measured dimension, in condition of constant scanning speed, into time interval between two light impulses appearing when laser beam oversteps the object's boundaries. In this case, time-pulse transformation of dimension takes place.

The method of optical "caliper jaw" realization concerned is fundamentally new. It involves phase or frequency object's edge displacement transformation [10]. The essence of the method is positioning the non-transparent object's edge in the Fresnel zone of laser beam diffraction on acousto-optic modulator with ultrasonic wave propagating in it. As a result of diffraction of light by traveling harmonic ultrasonic wave, a set of plane waves in the spectrum of scattering optical radiation is formed – a set of diffraction maximums with different optical frequencies and directions. In the near (Fresnel) zone diffraction maximums overlap forming a complicated traveling interference field, the period of which is equal or a multiple of ultrasonic wavelength, propagating through the modulator. Displacement of object's edge within the Fresnel zone causes phase shift of photoelectric measuring signal, frequency of which is equal to the frequency of ultrasonic wave. Thus phase transformation of object's edge displacement with high frequency carrier takes place.

The functional scheme of the phase measuring system is presented at the fig. 8. Laser beam 1 with aperture h passes through acoustooptic modulator 2 being an optically transparent object with ultrasonic wave propagating in it. The ultrasonic wave at frequency f is generated by electronic generator 3 with the aid of a piezooscillator. As a result of acoustooptic interaction between light beam and propagating ultrasonic wave the optic interference pattern is formed in the Fresnel zone at the modulator output.

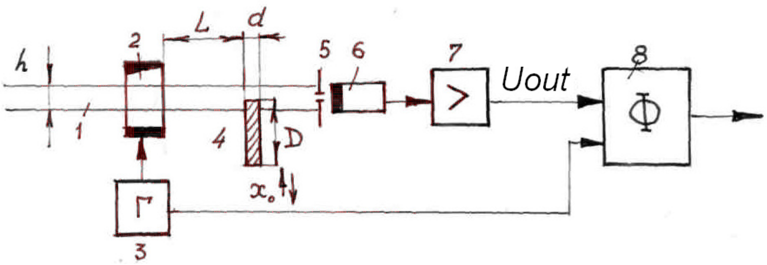

Fig. 8. Scheme of phase heterodyne measuring system with acoustooptical transformation of light frequency.

At a certain distance *d* from modulator outflow surface within the Fresnel zone a non-transparent object 4 is placed. It's edge's position changes with the x_0 value change. In general the object is volumetric with edge having width *d* in the direction of light propagation and can have different shapes. Experiments show that volumetric effects of optical diffraction are insignificant.

Behind the object 4 at fixed distance *L* from it receiving stop 5 and photoreciever 6 are placed. The photoreciever's output signal contains information on object's edge displacement x_0. Photoelectric measuring signal $U_{вых}(t)$ carring this information is formed after selective amplification in normalizing amplifier 7. The simulation of measuring transformation is quite sophisticated in general, but as a first approximation comes to the following. The modulator's transmission function is $T(x,t) = [-a \cdot cos(K \cdot x - \omega \cdot t)]$, where a is phase light modulation amplitude within the modulator 2, $K = 2 \cdot \pi / \Lambda$ - the ultrasonic wavenumber, Λ - ultrasonic wavelength, $\Omega = 2 \cdot \pi \cdot f$, f - ultrasonic frequency, x - sound propagation direction. Supposing light beam 1 to be a plane monochromatic wave $E_1 = E_0 \cdot exp(-j \cdot \omega \cdot t)$, where E_0 is the amplitude, $\omega = 2 \cdot \pi \cdot \nu$, ν is optical frequency, the modulator output light field $E_2(x,t) = E_0 \cdot T(x,t)$. Resulting field $E_3(x,t)$ in the plane of object 4 is determined by succession of spatial transformations. The spatial spectrum of light field $E_2(x,t)$ as modulator 2 output is $A_2(u) = F\{E_2(x,t)\}$, where $u = \sin(\alpha / \lambda)$ - spatial frequency, α – diffraction angle, F – Fourier transform symbol: $F\{E_2(x,t)\} = \int E_2(x,t) \cdot \exp(-j \cdot 2 \cdot \pi \cdot x) dx$. Spatial spectrum $A_3(u)$ of light feeld $E_3(x,t)$, formed in the plane of measured object 4 at distance *L* from modulator 2, is determined by multiplication $A_3(u) = A_2(u) \cdot H(u)$, where $H(u) = exp(i \cdot k \cdot L)\sqrt{1-(\lambda \cdot u)^2}$ - optical transfer function of free space, $k = 2 \cdot \pi / \lambda$ - light wave number, λ - light wavelength. Light field $E_3(x,t)$ in plane of object is calculated as inverse spatial Fourier Transform of spectrum $A_3(u)$. Under the assumption of knife-edge it's function can be expressed by spatial Heaviside step function $T_o = T(x - x_0)$. The light field $E_4(x,t)$, coming to the photoreciever, is, evidently, $E_4(x,t) = E_3(x,t) \cdot T(x - x_0)$. Applying known mathematical apparatus of acoustooptics [11], limiting our concern to diffraction maximums of 0 and ±1 orders, after filtration of photoelectrical signal with filter frequency *f* by selective amplifier 7 form as result output measuring signal $U_{out} = U_0 \cdot sin(K \cdot x_0 - \Omega \cdot t)$. The latter is a harmonic signal with carrier frequency *f*, the phase of which changes proportionally to displacement of object's edge x_0. Thus measuring of object's 4 edge displacement x_0 comes to measuring the phase shift of $U_{вых}(t)$. Phase shift measurement is performed by digital phasometer 8 (fig. 8.a) having reference signal from electronic generator 4 as second input. The method and schemes of photometry for this case are described in [12]. Fig. 9 shows experimental measuring transformation function of phase measuring system for *f* = 8 MHz, Λ= 143 micron, *L*=23 mm. The results correspond to the theoretical measuring transformation function with sensitivity of 2,5 electrical degrees per micron of displacement. Usage of high frequency modulators (*f*=25-30 MHz, Λ=20-30 micron) provides sensitivity of about 20-30 electrical degrees per micron of displacement.

Thus resolution of about 0,1 micron is provided, within the measuring range equal to aperture *h* of beam (*h*≈1 mm).

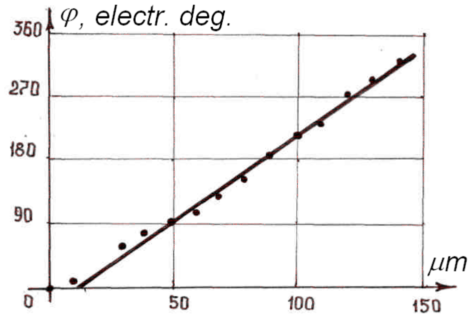

Fig. 9. Experimental measuring transformation function of phase measuring system

The other way of increasing the resolution is frequency transformation of the measuring information. The method comes to forming measuring system with acoustooptoelectronic feedback (fig. 10). The optical scheme is kept without change, but the photoreciever output signal is fed back to generate acoustic wave within the modulator 2. Thus single positive feedback 3 is formed, essentially changing measuring transformation function.

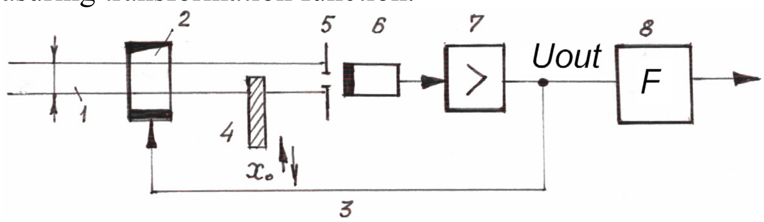

Fig 10. Scheme of frequency heterodyne measuring system with acoustooptical transformation of light frequency.

Object's 4 edge displacement x_0 is performed at speed $v(t)$, i.e. $x_0(t) = \int v(t)dt$. This displacement causes Doppler light field $E_3(x,t)$ frequency shift, equal to $v(t)/\lambda$. This causes output signal frequency shift $\Delta f(t)$. As a result the new frequency of harmonic output signal *f* is established. The output signal frequency shift $\Delta f(t) = \frac{1}{\tau}\cdot\int \Delta v(t)dt = x_0(t)/\lambda\tau$, where *τ* – is acoustic wave delay time, determined by light point coordinate, is the integral of Doppler frequency shift $\Delta v(t)$ and is proportional to measured displacement $x_0(t)$. Fig. 11 shows experimental measuring transformation function of frequency measuring system with flat objects thickness *d*=1,06 – 5,5 mm. Within this thickness range the character is almost invariable and almost independent of thickness *d*. The sensitivity was over 260 Hz per micron of displacement. The frequency counter 8 measures value of Δ*f*. The transformation function steepness can be adjusted by control of time *τ* or forming more complicated positive feedback structure.

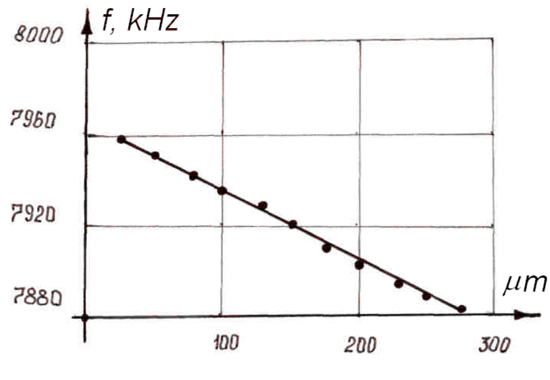

Fig. 11. Experimental measuring transformation function of frequency measuring system

Thus phase and frequency laser heterodyne measuring systems can be basis for object's edge displacement measurement systems with up to 0,01 micron resolution on carrier frequency up to several dozens MHz, that allows the usage of the non-contact method for measurement of objects, moving at speed of about several hundreds meters per minute. The method can be used for non-contact measurement of objects having the dimension D greater then the beam aperture h (provided with two heterodyne channels at nominal distance D from each other) and having the dimension D less then the beam aperture h (measuring the dimensions of defects of optical fiber, wire and other radioelectronic parts).

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