

DEVELOPMENT OF A TECHNIQUE FOR THE DETERMINATION OF METROLOGICAL PARAMETERS OF TECHNOLOGICAL SYSTEM CLWS-300/C FOR SYNTHESIS OF HIGH PRECISION ANGULAR MEASURING STRUCTURES

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1. INTRODUCTION

Over many years, the development of an independent technology and equipment to produce high-precision encoders of linear and angular quantities has remained an important problem for Russian optomechanical industry. It is well-known that in the USSR there were attempts to create a technology similar to a popular technology named Diadur (the Heidenhain firm, Germany) [1]. These attempts were made by a branch of ENIIMS (Vilnius) jointly with the Research Institute of Applied Mechanics (Moscow). A fundamentally new technology and equipment to manufacture photomasks and master-discs of high-precision (of the order of $\pm 1,0''$) angular sensors is proposed. It is based on investigations performed by the Institute of Automatics and Electrometry (IAE) of the Siberian Branch of the Russian Academy of Sciences (SB RAS) and the Technological Design Institute of Scientific Instrument Engineering (TDI SIE). In this paper, some problems that emerged when this technology was introduced at the Ural Optical Mechanical Plant (UOMP, Ekaterinburg) are analyzed.

2. COMPARISON OF METROLOGICAL PARAMETERS OF TWO ALTERNATIVE TECHNOLOGIES FOR SYNTHESIS OF ANGULAR MEASURING STRUCTURES

At present, a technology of projection photolithography, which is well-known as the Diadur technology, is widely used in the manufacturing of high-precision angular transformers. An alternative technology to manufacture angular measuring

structures, such as scale-plates, limbs, or rasters, was proposed at the Siberian Branch of USSR Academy of Sciences. This technology is based on laser thermochemical recording of hidden images on chromium films in conditions of circular scanning [2]. In 1997, UOMP's specialists compared the two alternative technologies: the projection lithography technology and the circular scanning one. For this purpose, an AS-700 unit was used. The unit was created at the plant to inspect limbs. The errors of rasters with 36 000 graduations were determined. One raster was manufactured for a ROD-800 encoder by the Heidenhain firm, and another one at a CLWS-300 station at TDISIE SB RAS. The results are presented in Fig. 1.

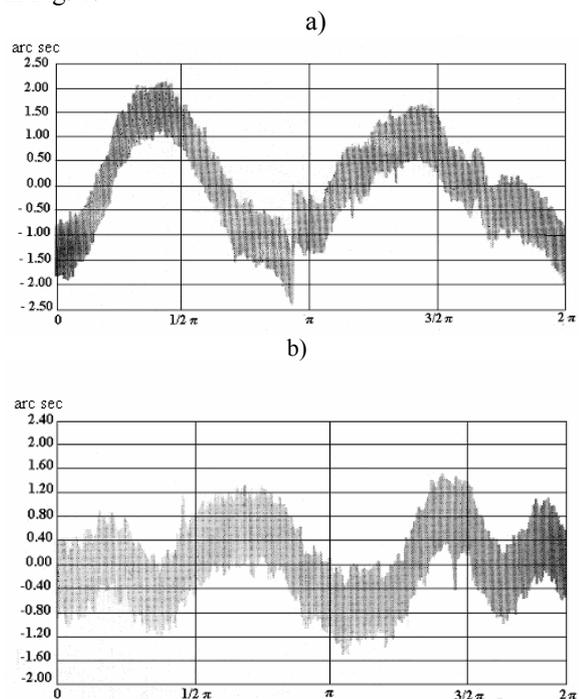


Fig. 1. Errors of rasters manufactured by using the alternative technologies

It has been shown that for the raster manufactured using the Diadur technology the accumulated error is by a factor of 1,5 greater than that for the raster produced on the basis of the alternative technology. The former error amounts to $\pm 2,2''$ (Fig.1, a). Besides, an error type that is specific for this technology has been recorded. Specifically, there is a discontinuity at the interface between the scale beginning and end, which amounts to $2,2''$. For the raster made using the raster scanning technology (see Fig.1, b), the accumulated error does not exceed $\pm 1,5''$, and no discontinuities are recorded.

3. PECULIARITIES OF PRECISION INSPECTION OF CIRCULAR STRUCTURE SYNTHESIS USING AS-700 STATION

3.1. Schematic diagram of limb inspection AS-700 station

To obtain an objective estimate of potentialities of the new technology, one should analyze the peculiarities of the process of measuring the error of angular measuring structures (scale-plates, limbs, and rasters) by the AS-700 station and eliminate the factors that distort the results of measurements. Figure 2 shows a simplified schematic diagram of the station.

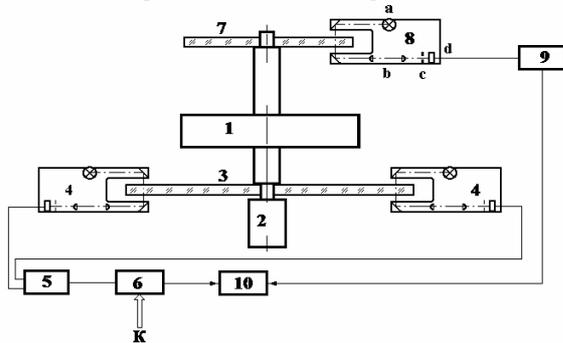


Fig. 2. Schematic diagram of AS-700 station.

1- spindle, 2- motor, 3- reference limb, 4- limb 3 data sensing system, 5- reference grid formation block, 6- virtual scale formation block, 7- limb under inspection, 8- optical data sensing system, 9- count pulse formation block, 10- control computer

Limb surface 3 has a rotation start mark and a regular raster with 28 800 graduations. System 4 has five sensing heads. Four of these heads are designed for data reading from the raster, and one of them for reading from the mark. Limb 7 error measurement takes place at continuous rotation of spindle 1. A priori information about the limb under inspection is entered into block 6. Control computer 10 forms two data files, F_1 and F_2 , about the mutual shift of even and odd pulses at the outputs of blocks 6 and 9:

$$F_1 = \{\Delta\Phi_1 \dots \Delta\Phi_{2i-1} \dots \Delta\Phi_{2n-1}\}, \quad (1)$$

$$F_2 = \{\Delta\Phi_2 \dots \Delta\Phi_{2i} \dots \Delta\Phi_{2n}\}$$

The phase shift $\Delta\Phi_i$ between two corresponding pulses is represented by the following three terms:

$$\Delta\Phi_i = \Delta\phi_0 + \delta\phi_1 + \delta\phi_2, \quad (2)$$

where $\Delta\phi_0$ is a constant shift, $\delta\phi_1$ and $\delta\phi_2$ are random phase variations of formed pulses of the virtual and inspected scales, respectively.

3.2. Systematic error of AS-700 reference scale

The reading conditions of data of the AS-700 reference scale are constant. Therefore, the component $\delta\phi_1$ can be regarded as a systematic error of the AS-700 station. It can be revealed using either a phase-statistical measurement technique or a special test stand.

3.3. Random error components of data reading out from inspection limb

The component $\delta\phi_2$ includes the inspected scale error being measured Δ_{mes} and some random components. The random components appear when count pulses are formed in block 8, which distort the result of error measurement Δ_{mes} .

A considerable random component of the error $\delta\phi_2$ is the error $\delta\phi_{ecc}$ of deviation of the scale center from the spindle rotation axis (the so-called eccentricity error). It changes periodically, once in every scale rotation. It is considered that it does not characterize the precision of scale manufacturing. It can be removed in the final product if the scale is adjusted properly. Therefore, the eccentricity error is excluded from further analysis using a special program.

Nonorthogonality of the limb to the rotation axis leads to face run outs of the limb working surface during its rotation, and causes errors of two types. One error is produced by the change in the trajectory of a reading beam as it is transformed from a circular to an elliptical one. The amplitude of this component is estimated as follows:

$$\Delta R_1 = \frac{(\Delta H)^2}{R}, \quad (3)$$

where ΔH is the stroke of the product surface in the forward direction as the spindle rotates. The frequency of changes in this component is twice as great as that of the limb being inspected (the second error harmonic). For limbs that are most widely used at UOMP ($R \cong 45$ mm) at $\Delta H = 10$ μ m the contribution of this error does not exceed $0,01''$.

The second error component occurs as a reading beam passes through the glass limb base. If the limb base is plane-parallel and its thickness is d , the incident beam goes out of the glass shifted by ΔR_2 , where

$$\Delta R_2 = \frac{d_{n,l}}{R \cdot n_{cm}} \cdot \Delta H. \quad (4)$$

When the plate rotates, the beam goes out and makes a circle of radius ΔR_2 about its nondistorted location. The tangential projection of the rotating vector gives an error component that is synchronous with the rotational speed.

At $d = 5$ mm and $\Delta H = 10 \mu\text{m}$, ΔR_2 reaches $0,7 \mu\text{m}$, which causes an angular error of about $3,2''$.

In the manufacturing of high-precision limbs, wedge-shape of the bases up to $2'$ is allowed. Wedge-shape causes a change in the orientation of the beam as it goes out of the base. When the base rotates, the beam makes a cone as it goes out of the base. The cone base is in the plane of the front lens of the reading objective *b in block 8* (Fig. 2). This cone is a circle whose diameter is proportional to the wedge angle β and the distance from the base to the photodetector objective H :

$$\Delta r_1 = H \cdot \text{tg} \beta \quad (5)$$

The tangential projection of the rotating vector gives an error component that is synchronous with the rotational speed. At $H = 40$ mm, Δr can reach $24 \mu\text{m}$. At radii of 45 mm, this corresponds to an angular error of $\approx 96''$.

In practice, base surfaces are manufactured with a limited precision. Admissible deviations from an ideal plane are given by the number of interference bands N on the entire surface (global non-flatness) or ΔN in a limited domain (local non-flatness). Non-flatness of the base surface as it makes one revolution about the spindle rotation axis causes changes in the direction of the normal to the base surface. At each point of the base surface, non-flatness reveals itself as local wedge-shape, whose contribution to the total measurement error can be estimated by a formula similar to (5). In this formula, the wedge-shape parameter β is represented as the angle between the normal to the surface and the vertical. When the angle β changes its sign only twice during a revolution, the distortion of results can reach

$$\Delta r_2 = \frac{H}{R} \Delta h, \quad (6)$$

where $\Delta h = N \cdot \lambda/2$, $\lambda = 0,55 \mu\text{m}$. The specific contribution of the component being analyzed is $0,11 \mu\text{m}/\text{band}$ or $0,5''/\text{band}$ at a frequency that is twice as great as the rotational speed (the second error harmonic).

The relation for the beam shift in the plane of the front lens of the reading objective with inoperative surface irregularities (in the simplest case) is as follows:

$$\Delta r_3 = -H/R \cdot n_{gl} \Delta h, \quad (7)$$

where n_{gl} is the refraction index for glass. The amplitude of the shift is greater than in the previous case, and has the opposite sign. The increase is proportional to n_{gl} .

As in the three previous cases, the contribution of local non-flatness ΔN is determined by the wedge-shape parameter β . Its absolute value is inversely proportional to the size L of the zone with distortion being analyzed. In the simplest case, the beam displacement caused by this surface defect can be represented in the following form:

$$\Delta r_4 = 2H/L \cdot \Delta h = H/L \cdot \Delta n \cdot \lambda. \quad (8)$$

The changes in the noise spectrum contributed by local distortions have higher frequencies than those produced by global distortions.

4. METHOD OF STATISTICAL SEPARATION OF ACCOMPANYING ERRORS FOR DETERMINATION THE METROLOGICAL PARAMETERS OF PROCESSES

It was shown above that in the process of measurement of the errors of angular measuring structures by the AS-700 station there occur numerous accompanying errors. These errors are different in character and behavior. For instance, the error in manufacturing of the AS-700 reference scale is mainly caused by the spindle rotor of the unit. It can be considered as a systematic error, whose contribution can be compensated using a phase-statistical method (PSM) of measurement.

The PSM compensation of the reference scale systematic error is based on the following well-known principle: the sum of errors of graduations of a circular scale, $\Delta \varphi$, is zero:

$$\sum_1^n \Delta \varphi_i = 0. \quad (9)$$

To realize the PSM, one should take a series of data files about the mutual location of marks in the inspected and reference scales with various orientations of the scales. The data obtained must be referenced to the origin of one of the scales. If the data are referenced to the start of AS-700 rotation, the following result, which characterizes the deviation of the i -th graduation of the reference scale from its actual position, is formed at each i -th line of the total file:

$$\begin{aligned} \Delta \varphi_i &= \frac{1}{m} \sum_{j=0}^{m-1} (\Delta_{ref_i} + \Delta_{mes_{i+j}}) = \\ &= \frac{1}{m} (m \cdot \Delta_{ref_i}) + \frac{1}{m} \sum_{j=0}^{m-1} \Delta_{mes_i} = \Delta_{ref_i} \end{aligned} \quad (10)$$

Here $i=(1...n)$ is the current graduation number of the inspected and reference scales, and $j=(0...m-1)$ is the number of the current phase shift in the mutual location of the scales.

Operation (10) results in the formation of a new file, which characterizes non-uniformity in the graduations of the AS-700 reference scale.

If the data are referenced to a certain graduation of the inspected scale, the following result of measuring the error in the location of the corresponding graduation of the inspected scale is formed in each line of the total file:

$$\begin{aligned} \Delta\varphi_i &= \frac{1}{m} \sum_{j=0}^{m-1} (\Delta_{ref_i} + \Delta_{mes_{i+j}}) = \\ &= \frac{1}{m} \sum_{j=0}^{m-1} \Delta_{ref_i} + \frac{1}{m} (m \cdot \Delta_{mes_i}) = \Delta_{mes_i} \end{aligned} \quad (11)$$

This result is not affected by the systematic error in the reference scale. However, the obtained value of Δ_{mes_i} is not free from the above-mentioned errors caused by defects in the base. This is explained by the fact that the base defects rotate about the reference scale, in synchronism with the marks of the inspected scale, and their contribution does not vary as the mutual location of the scales changes.

To estimate potentialities of the new technology, the contribution of the base should be differentiated from the changes introduced by inaccuracy in the location of the inspected scale graduations. Here, one can again use a statistical approach to solving the problem.

For this, one should take a set of K scale-plates of the same type manufactured using the same program and, if possible, in a short period of time. In this case, one can assume that the error in applying the scale topology will be practically the same for all products of this set, and this error can be taken as a systematic one. At the same time, the accompanying errors caused by the peculiarities of manufacturing the bases can be considered as individual and random.

If we add the files with the results of measurements for all K products of the set and then average the summation result, the random components become weaker by a factor of \sqrt{K} . This makes it possible to identify the sought-for error of the raster scanning method, which manifests itself as distortions of the topology of high-precision angular measuring structures.

5. EXPERIMENTAL RESULTS OF THE METHOD OF MULTILEVEL STATISTICAL SEPARATION OF ERRORS

A set of 16 chromium-blanks was produced to determine the potentialities of the raster scanning

technology at synthesis of angular measuring structures. Both sides of these blanks were prepared with surface finish class 0 ($N = 0,5$ and $\Delta N = 0,1$). Structures of the same type were recorded on all chromium-blanks: a scale with a number of graduations of 360; the graduation width was $2\mu\text{m}$; the length was 2,0 mm; the graduation that coincided with the CLWS-300 origin was broadened by $5''$. The main results of the investigation are presented in Fig. 3.

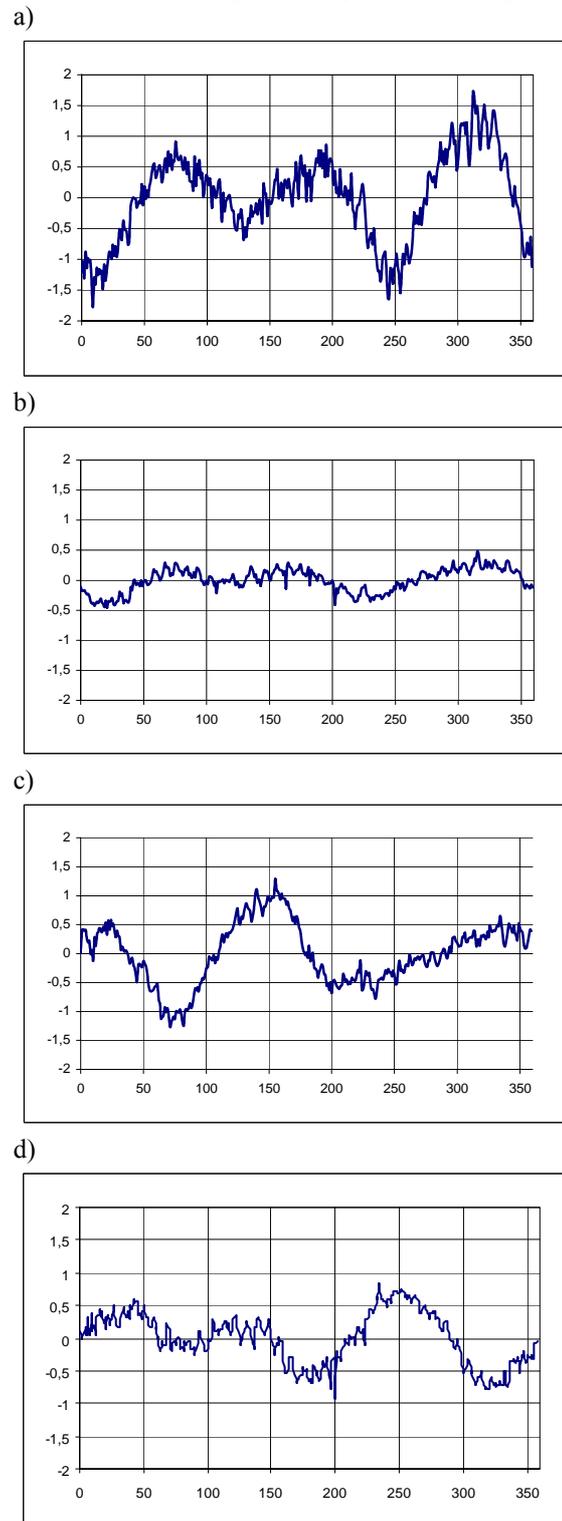


Fig. 3. Results of measurements and error separation

A typical result of an individual measurement of the accumulated error of a scale synthesized at the CLWS – 300 station is shown in Fig. 9,a. As discussed above, this file contains the contributions of at least three sources of error: the reference scale, the recording unit and the base, on which the inspected scale was recorded.

It has been found that for individual measurements the maximum value of the scale error reaches $\pm 1,6''$. In accordance with the measurement method proposed, files for 18 relative positions spaced uniformly with a step of 20° were recorded for each scale. A total file, \overline{F}_r , was formed from these files. This file characterized the accumulated error of the AS-700 reference limb (Fig. 3,b). The maximum error of the reference scale reaches $\pm 0,4''$.

To determine the angular error of structures synthesized on the CLWS – 300 station, a special equalization procedure was applied to all initial files. This was done using the cyclic permutation method, to «reference» the data to the CLWS – 300 rotation start. The graduation that served as a reference to determine the CLWS – 300 rotation start was artificially broadened by $5''$ on each recorded scale. After the data equalization, a total file, \overline{F}_{mes} , was again formed for each scale. It was obtained by averaging of the files processed for each of the 18 locations. Then a new total file, \hat{F}_{mes} , was formed from the total files \overline{F}_{mes} obtained. It was produced by averaging of the files \overline{F}_{mes} for all formed scales. This file characterizes the sought-for scale error synthesized on the CLWS – 300 station using the raster scanning method (Fig. 3,c). It has been shown that the maximum error of the raster scanning method does not exceed $\pm 1,1''$ at a root-mean-square deviation of $0,52''$.

It has also been found that the distortions caused by the base reach $\pm 0,7''$ (Fig. 3,d). The result was obtained by subtracting the data in the file \hat{F}_{mes} from the data in the file \overline{F}_{mes} .

6. CONCLUSION

A method to measure the error of topology formation of angular measuring structures has been proposed. This method makes it possible to identify the components that distort the results of measurement.

It has been shown that the destabilizing factors that accompany the process of measuring the errors of topology formation of high-precision ($\approx 1''$) angular measuring structures introduce distortions comparable to the parameter value being inspected.

It has been proved, by manufacturing a small set of products of the same type, that the raster scanning technology provides the stable and reproducible formation of angular measuring structures with a topology error of about $\pm 1''$.

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