Accuracy enhancement for precision angle measuring structures

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Abstract

Producing high-quality optical limbs, circular scales, rasters, multibit code disks (key metrological elements hereinafter called “angle measuring structures” (AMS) is an important engineering problem for any manufacturer, making angle measuring gauges. The analysis of the precision parameters of the AMS that were made by the method of circular scanning has revealed that the distorted circular trajectory of the recording laser beam moving across the surface of a semimanufactured article to be the main source of errors in the AMS produced. The main reason causing the distortion has been the rotor disbalance in the spindle unit of the laser generator of images. The article offers solutions for accuracy enhancement in manufacturing precision angle measuring structures. It also describes error estimation process in the raster, manufactured upon implementing the solutions offered.

Keywords: Accuracy, laser image generator, circular scanning, angle measuring structures, air spindle

1. Introduction

Usually, industrial manufacturing of an AMS consists of 2 stages: making up a standard specimen of an AMS and its further replication. That is why manufacturing a highly accurate standard specimen with the error as little as possible is crucial moment of the manufacturing process.

Until recently the leading technology to form a precision angle measuring structure was projection photolithography, developed by German company HEIDENHAIN and known as Diadur technology. And now one can observe intensive development of alternative – laser and electron-beam – technologies.

In the beginning of the eighties of the past century researchers of Siberian Branch of the Russian Academy of Sciences (SB RAS) developed the first laser generator of images that worked in polar coordinates using the method of circular scanning. Currently one of such generators developed by the Technological Design Institute of Scientific Instrument Engineering of SB RAS is being successfully used to produce AMS at Ural Optical and Mechanical Plant in Yekaterinburg (UOMP). It has allowed industrial manufacturing of the AMS with error (1 – 2)". Further enhancement of this accuracy still remains an actual problem especially when it comes to angle measuring gauges smaller in size. In the author’s point of view the solution depends on enhancement of the metrological characteristics the technological complexes in use.

2. Analysis of errors in AMS formed by circular scanning

One considers that placing the reference gauge and a semimanufactured article in alignment at one rotating shaft has allowed the reference raster transfer with as few errors as possible.

That is why, willing to enhance the accuracy one tries to decrease the error of the raster itself using all the known methods including the one of track averaging (using a number of
sensing heads in the reference gauge). There are some known precision plants for inspection of angular encoders which reference one has 6 sensing heads, positioned at 0°, 11.25°, 22.5°, 45°, 90° and 180° [1]. According to the theory [2] it allows compensating the effect of all the 2\(^{n-1}\) low harmonics and all the odd harmonics following. As a result, one has the signal almost perfect that corresponds to the angular position and depends slightly on either the errors in the referent raster manufactured or the defects in the shaft’s bearing resulting in the raster movement’s error. However, the independence of the angular position of the impulses of the referent signal from the shaft’s fluctuations results in the breach of the firm connection through the shaft between the reference gauge and the object being formed. As the result the AMS formed may be distorted in an unpredictable way. One can observe this situation in Fig. 1, displaying the similar geodesic rasters, formed by CLWS-300 (UOMP) laser generator in different time.

![Graphs showing error curves](image)

**Fig. 1.** The errors in the similar geodesic rasters, formed by CLWS-300 laser generator (UOMP): accumulated error geodesic, formed by CLWS-300 (a, c); spectral distribution of the raster (b, d).

The graphs displayed show significantly different forms of the error curves. The spectral composition shows the simultaneous presence of the 2\(^{nd}\), 3\(^{rd}\), 4\(^{th}\) and so on harmonics up to the 12\(^{th}\)-16\(^{th}\) when the 2\(^{nd}\) harmonic prevails significantly. In their article [3] the authors pointed out that such a spectral composition of the errors in the articles manufactured with the use of aerostatic or hydrostatic spindles occurred when the shaft’s axis performs complex loop-shaped motions (Fig. 2,a). In that case the error composition of the profile also contained the 2\(^{nd}\), 3\(^{rd}\), 4\(^{th}\) and so on harmonics simultaneously up to the 12\(^{th}\) (Fig. 2,b).

The constriction of the reference gauge suppresses the key harmonic components of the error, caused by the shaft’s bearings and the raster. That is why the error registered in the measurements comes up as a set of accidental distortions of the motions of the rotor shaft (that does motions together with the raster being formed attached to it) relative to the recording head of the generator’s optic channel.
Fig. 2. The loop-shaped motion of the shaft’s axis and the spectral composition of the profile manufactured:
   a) the motions of the rotor shaft; b) spectral distribution.

One of the reasons causing such an effect is the disbalance of the shaft’s mass center acting relative to its axis of rotation. The aerostatic spindle used in CLWS-300 laser generator adopts so-called kinematic arrangement of the aerostatic bearings. The arrangement is characterized by higher rigidity in the edge and in the radial directions and by much smaller one for the angular loads. As a rule, a laser generator has aerostatic spindles with initial error for axis wavering to be about 0.05-0.1 micron. But installation on them additional mechanical and optical components (face plates, faucets for the reference gauge, engine and the semimanufactured article) results in a significant increase of the wavering.

It is accepted for aerostatic bearings that they have similar rigidity index $k_0$ in all the directions for slight deviations from the initial state. But the value of mass center displacement for unbalanced shaft $z$ depends not only on $k_0$ of the aerostatic suspension, but also on the compliance of the bearing’s mount system. In this case the rigidity index can be determined by the following formula:

$$k = \frac{k_0 \cdot k_i}{k_0 + k_i}$$

(1)

where $1/k_i$ is the compliance of the bearing in the direction selected. Thus, one takes into account the anisotropy of the rigidity coefficient ($k_x \neq k_y$) of the flexible bearings, which is the aerostatic suspension as it is. Figure 4 displays the results of the experiments to measure the reaction of a granite slab to the stress exposed by a spindle attached to it and rotating with the speed of 3 revolutions per second.

Fig. 4. The reaction of the granite slab to the stress exposed by the spindle attached to it.
The author used NS-5/P2 Dual Axis Inclinometer produced by HL-Planartechnik GmbH (Germany) as a measuring gauge. The gauge allows measuring angles of inclination in 2 mutually perpendicular directions in $\pm 5^\circ$ diapason with $\pm 0.01^\circ$ error and resolution capability – 0.0005°.

The results of the measurements are placed on the phase plane. For the equal coefficients of the slab-spindle system compliance in space, its hodograph curve on the phase plane should be a circle. But the experiment has determined the difference in the both directions as for the absolute value (hodograph curve’s ellipticity), as for the phase (the ellipse’s inclination at precisely 90° orientation of the inclinometer’s sensors is an evident of a phase lag in slab’s bearings reactions).

If the anisotropic index of the rigidity produced has been small and the mass center of the shaft has had radial displacement $e$ (eccentricity) relative to the shaft’s axis, but remains within the plane of the bearings’ center of symmetry, the laser track on the photosensitive layer is a circle with the center displaced relative to the shaft’s axis.

When the mass center of the shaft has been beyond the dimensions of the spindle of CLWS-300, the misalignment of the center and the rotation axis results in the angle turns of the axis in the vertical plane i.e. dynamic unbalance. So, analyzing motions of the shaft’s axis one should take into account the gyroscopic components: precession and nutation. Their combined effect results in complex, loop–shaped motions of the shaft’s axis, which has been described in detail in this article [3]. To remedy the defects the new construction of the spindle unit has been developed.

3. Experimental investigations and analysis of the experimental data

In the construction developed the mass center has been put as close as possible to the aerostatic bearing’s center of symmetry. For that a counterweight has been attached to the lower flange of the spindle unit. The counterweight’s mass is equal to the total weight of the face-plate and the photoelectric angle gauge with its bearing faucet. To test the effectiveness of the new construction an 85 mm diameter test raster was made with the number of strokes $N = 6000$ and the raster’s error was estimated. The measurements were carried out with angle measuring gauge AC-700 (UOMP) by the method using «$n$» successive shifts in the phase of the two scales [4]. For that purpose the first stroke matching with the reference point of CLWS-300 (TDI SIE) was widened by $5^\circ$. The test consisted of 12 sets of measurements with $30^\circ$ shift for each of the sets. For the error analysis the measurements started from the reference point of the scale observed. The processed results represented a data file on the each stroke’s error on the scale observed remedied of the errors of the referent scale. The test raster’s error and its spectral composition can be seen in Fig. 5.

![Fig. 5. The error of the raster, made on the modernized CLWS-30:](image)

a) accumulated error raster, formed by CLWS-300 (TDI SIE); b) spectral distribution of the raster.
The graph shows that the 85-mm raster has had the total value of the error not more than ±0.7” [5]. The value of the second harmonic has decreased by about 3 times. Through the tests carried out one could estimate the potentials of CLWS-300 laser generators. One is expedient to apply $F$ instability factor method offered in article [6] for that purpose.

Table 1. The instability factor for precision AMS –making technologies for CLWS-300 laser generators.

<table>
<thead>
<tr>
<th>№</th>
<th>Producer, technology</th>
<th>Diameter of Raster $D$ (mm)</th>
<th>Error of Raster $\Delta \varphi$ (seconds of arc)</th>
<th>Instability Factor, $F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CLWS-300(UOMP)</td>
<td>90</td>
<td>1.0</td>
<td>0.218</td>
</tr>
<tr>
<td>2</td>
<td>CLWS-300 (TDI SIE)</td>
<td>85</td>
<td>0.7</td>
<td>0.144</td>
</tr>
</tbody>
</table>

Through reducing the occasional distortions of the motion trajectory of the upper edge of the shaft of the aerostatic bearing one could reduce the instability factor $F$ to the level of 0.144 micron that has resulted in the error reduction for small-scale AMS formations ($\approx 85$ mm diameter) up to less than 1”.

4. Conclusion

Decreasing of the random distortions of the motion trajectory of the top edge of the aerostatic bearing shaft allows us to reduce the small-scale AMS formation errors. For the first time the angle raster with error in less than 1” was produced in domestic industry.

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References