NEW APPROACH TO PRECISION ANGLE CALIBRATION MEANS AND METHODS

Mindaugas Rybokas [1], *Lauryna Siaudinyte* [2], *Vytautas Giniotis* [3]

[1] Dept. of Information Technologies, Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius, Lithuania, E-mail: mjonasr@hotmail.com
[2] Dept. of Geodesy and Cadastre, Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius, Lithuania, E-mail: lauryna@inbox.lt,
[3] Institute of Geodesy, Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius, Lithuania, E-mail: vg@ai.vgtu.lt

Abstract:
The paper deals with the methods and means of precision angle calibration with new development of methods for raster scales measuring and vertical angle measurement of geodetic instruments. The calibration of angle information measuring is discussed including rotary encoders, precision circular raster and coded scales. The new development of mechatronic test bench and the results of measurement are described.

Key words: angle, measurement, circular scales.

1. INTRODUCTION

Circular raster and coded scales are used in most measurement and technological equipment as the reference measure. They are implemented into the rotary encoders as the main standards for light beam modulation and angle displacement indication. Accuracy calibration of these scales is the first step of information for the accuracy improvement of the final measurement systems of the machines. Standard and reference measures used for the most precise measurements are described in the article [1]. The main methods and means for precision angle measurement including the mostly used classic methods, recent developed ones with application of high precision angle standards are presented [2] and newly developed Moire fringe, π rad standard angle method and method for vertical angle calibration of geodetic instruments.

2. METHODS OF ANGLE MEASUREMENT

There is a great variety of methods for accuracy calibration of the circular scales and rotary encoders.
Angle measurements are based using multi-angle prisms – polygons with autocollimators, rotary encoders for high accuracy and circular scales as the standards of the flat angle. Traceability of angle measurements is based on the standard of the plane angle – prism (polygon) calibrated at an appropriate accuracy. Some metrological institutions have established their special test benches (comparators) equipped with circular scales or rotary encoders of high accuracy and polygons with autocollimators for angle calibration purposes [2, 3]. Nevertheless, the standard (etalon) of plane angle – polygon has many restrictions for the transfer of angle unit – radian (rad) and other units of angle. It depends on the number of angles formed by the flat sides of the polygon that is restricted by technological and metrological difficulties connected with the production and accuracy determination of the polygon.
The errors of circular scales are determined by some methods approved in written standards, such as:

- the method of approximation;
- the method of opposite matrix;
- the method of Heuvelink (Yeliseyev),
- the method of Wild.

The methods for circular scale calibration are applied in machine engineering and instrumentation:

- the comparison of the angular values of the scale strokes with the values of the reference scale or other reference measure of angle (polygon);
- the comparison of the angular position of strokes of the scale with the reference angle created by the strokes of the same scale. This method also is called the calibration with the constant angle setting in the full circumference.

Table 1. Accuracy specifications of angle measuring devices and standards

No	Angle standards of measure	Discretion	Standard deviation
1.	Polygon – autocollimator	10°; 15°; 30°	0.15″
2.	Moore’s 1440 Precision Index	15’	0.04″
3.	Circular scale-microscope	3°, 4°,5°	0.2 μm
4.	Photoelectric rotary encoders	1″; 0.1″	~ 0.3″
5.	Laser gyro	0.1″	0.05″

The pitch of measurement (discretion) of circular scale is not small enough, so the discretion of the stroke errors is big; it is determined at quite large intervals of the scale. Furthermore, the errors of “diameters” are determined, not the angular position of the strokes of the scale. It is the reason why the comparative scales measurements are performed in machine and instruments engineering by using for the calibration the other angle standards with much higher discretion of reference angle measure. The angle standards of measure as the polygon – autocollimator has the number of angles (flat sides or angles) equal to 10°; 15°; 30°,…and systematic error of angles about 0.15″… 0.30″, uncertainty of calibration (u = 2) approximately 0.05″. Next widely used flat angle standard is Moore's 1440 Precision Index table with fixed angle positions equal to 15', systematic error ~ ±0.1″, uncertainty 0.04". Using the circular scale- microscope ensures step of measurements 3°, 4°, 5° with systematic error ~ ±0.2″, uncertainty ~±0.1″. Photoelectric rotary encoders have the discretion of measurement 1"; 0.1", accuracy parameters ~ 0.3" and uncertainty of measurements ~ 0.05".

The methods of circular scales calibration were created and developed by such famous scientists as H. Bruns, G. Schreiber, A.Perard, H. Wild, Heuvelink, S. Yeliseyev, etc. [1, 4]. The "diameters" errors are determined by using those methods at angle intervals applying the control angles equal, for example, to 10°, 20°, 30°. Some accurtacy characteristics of angle measurement are presented in Table 1.

2.1. Method of π angle

A possibility to create the standard of the angle equal to $\boldsymbol{\pi}$ rad or half the circle or the full angle is proposed. It can be created by the circular scale with the rotation axis of very high accuracy and two precision reading instruments, usually, photoelectric microscopes (PM), placed on opposite sides of the circular scale using the special alignment steps [4]. A great variety of angle units and values can be measured and its traceability ensured by applying the third PM on the scale. Calibration of the circular scale itself and other scale or rotary encoder as well is possible using the proposed method with an implementation of $\boldsymbol{\pi}$ rad as the primary standard angle.

The metrology of circular scales was mostly developed in geodesy and astronomy; and there such terminology is used as "error of the scale's diameter". The expression "diameter" means the line going through the strokes lying at the opposite side according to the centre of the scale. In most geodetic measurements the errors of "diameters" or the errors between the "diameters" are determined. It helps to avoid the errors due to the eccentricity of the scale to be measured and the trajectory of axis rotation [6].

Photoelectric microscopes M1 and M2 are placed on the opposite strokes ("diameter") of the circular scale every stroke of which features of the stroke's angular position error $\partial\varphi_i$. Let the angular position of the first stroke is without error, so $\partial\varphi_0=0$. The opposite stroke's angle position error is $\partial\varphi_{\pi.}$ The next step is the rotation of the scale under the microscopes to 180° exactly into the position when the stroke "π" is placed into the optical axis of the first microscope and the stroke No "0" will take place on the position equal to its angular error $\partial\varphi_\pi$ from the optical axis of the microscope M2. The third step will be tangential displacement of M2 microscope to the position equal to $\partial\varphi_\pi$ /2 and in this position both microscopes occupy an angular distance between them equal to π rad. So, the angle standard of π rad is set for the subsequent circular scale measurement. It must be noted that this angle position will be valid for every opposite pair of the strokes of the scale. This standard of measure can be set with high accuracy in case of using precision axis of the scale rotation and photoelectric microscopes. The angle standard created serves as standard measure for measurement of every stroke of the circular scale that usually is impossible using conventional angle standards. An important feature of the standard created is that the error determined from the standard angle of π rad is not connected between the separate strokes of the scale. It must be determined using the third microscope placed on the position M3 at the chosen angular pitch of φ_t. A great number of calibrated discrete angular values can be measured against this angle standard, and other kinds of angle positions, as the output signals of rotary encoder, geodetic or other optical instruments could be measured. This method of angle calibration permits to measure and calculate practically all systematic errors of the angular position of the strokes on the scale. The method proposed enables to assure a traceability of angle measurements at every laboratory having appropriate environment and reading instruments of appropriate accuracy together with a rotary table with the rotation axis of high accuracy – rotation trajectory (run-out) being in the range of 0.1 - 0.05 μm.

The raster circular scale can include from several hundred to several tens of thousands of strokes. It is evident that there is no easy means for creating the standard angle for the measurement of each stroke and thus the errors of the "short period" are not determined. Some methods developed for solving the problems of such kind use the phase shift in measurement. The problem is getting more complicated by a wide variety of scales used in modern automated engineering. Raster scales of wide range of accuracy and dimensions, system of graduation: 360°, 2^n, 10^n number of strokes in the circle, various coded scales, etc. are used for special tasks of instrumentation and automatisation.

2.2. Method of the Moiré fringes

The diameters of raster scales are considerably small, so many of the angle calibration methods are difficult or rather impossible to apply for these scales. For this purpose Moiré fringes' form features can be used. A case of a pattern consisting from two scales with different pitch values is known as a Vernier pattern (Fig. 1).

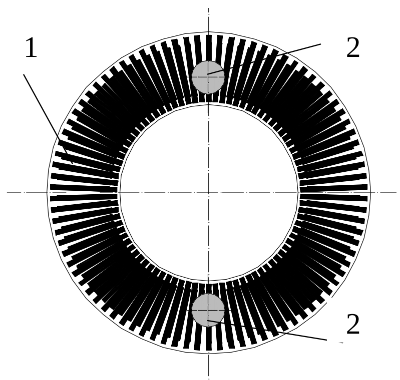

Fig. 1. Vernier fringe pattern formed by two circular raster scale. 1 – Vernier conjunction of two raster scales; 2 – photocells placed at opposite sides of the conjunction.

Simplified expressions for two raster Vernier patterns were developed [5], as a function of i, $\varsigma\omega$ - the coefficient of optical reduction i and of the difference $\Delta\omega$ between the pitches of the two raster scales that make a Moiré conjunction. The equations thus derived, coupled with the results of several experiments performed allow to come to the conclusion that Moiré fringe patterns could be used for the assessment of the accuracy of the raster scales. If one of the raster scales is chosen as the reference (etalon) scale, then another, in conjunction with the first, will show any change from the regular form of the pattern. A displacement of one of the raster scales gives the movement of the period of the pattern multiplied by the value of the optical coefficient i. The same occurs with the error of the raster strokes; it will be magnified by the optical coefficient as well. This optical effect can be used for the determination of raster scale accuracy, taking one as a reference [5]. Scales without errors would form a regular circle or a straight line for a circular or linear pattern of the scale. An assessment of the accuracy of the circular scale can be performed using a concentric circles template, as it is used in roundness measurements. The method is assumed to apply for systematic error assessments in the range of 1’...10’ (min. of arc) and for about 10 μm for the linear scales.

Two analyzing photocells are located at a distance equal to the Vernier pattern period (Fig. 1) or located on the spacing, equal to 0.5$\boldsymbol{W}$ or $\boldsymbol{W}(k+0.5)$; where k = 1,2,3. $\boldsymbol{W}$ – distance between the extreme points (period) of Moiré (Vernier) conjunction; $\boldsymbol{w}_{\mathbf{i}}$ – pitch of the raster scales. The output voltage from the photocells is amplified, transferred to the summing unit and then passed further to the recording device. It is obvious that in the case of a high accuracy raster scale, the output voltage in the recording device shows no change and the graph will be a straight line (or a sine wave) during a constant rotation of the raster conjunction according to the two photocells. When the raster pitch error occurs, the fringe pattern moves by a distance equal to the pitch error multiplied by i. The output voltage changes accordingly, providing a clear indication of the raster scale pitch error. The sensitivity of the index device can be tuned, enabling a measurement of a wide range of errors to occur. Precise roundness measuring devices and templates are very relevant for such a purpose. The results can be represented in a digital or graphical form. On this basis a new type of measuring devices for raster scales measurement can be developed.

The values of the systematic error of the scale strokes’ position are shown in Fig 2.

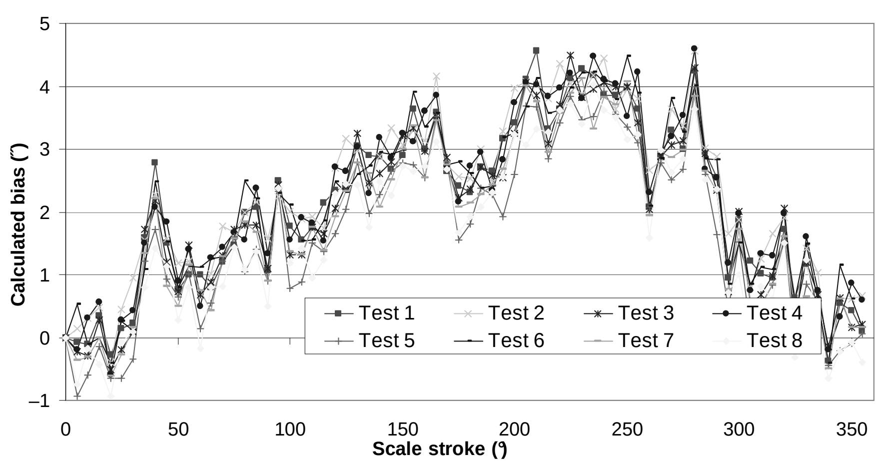

Fig 2. Systematic error of the circular scale recorded during the multiply measurement

Systematic error of the scale is determined by comparing this scale with the reference one (using the test rig described bellow). Mean value from the several measurements can be used for the correction of accuracy of the scale and consequently, the rotary encoder or the rotary table of machine tool.

3. TEST RIG FOR PRECISION ANGLE MEASUREMENTS

The multipurpose test rig for angle measurements was developed on the basis of circular dividing machine [6]. General view of the test bench is shown in Fig. 3.

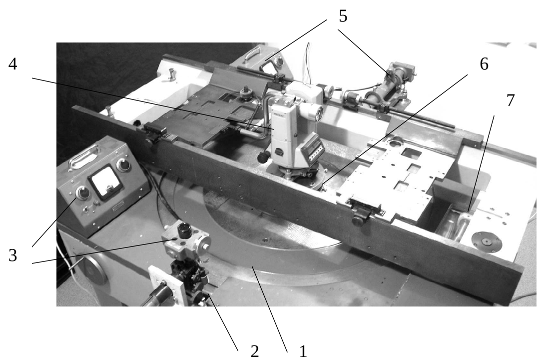

Fig. 3. View of the test rig for an angular measurements: 1 – worm wheel; 2 – circular scale on the wheel; 3 – photoelectric microscope with the display unit; 4 – geodetic instrument to be calibrated; 5 – autocollimator with the display unit; 6 – polygon; 7 – drive unit (step motor).

All the items shown in Fig. 3 are mounted on the sturdy base of the test bench. On the disc surface of the worm gear 1 there is a circular scale to which the photoelectric microscopes 3 are pointed. The light beam from the autocollimator 5 is directed via the display unit into the side of the multi-angle prism (polygon) 6. The measuring information from the autocollimator is input into the computer. For automating the monitoring process the rotary encoder is coaxially fixed to the worm gear, the output from which is fed via the control unit into the computer and to the step motor for the table rotation. Also the instrument under calibration is fixed to the axis of the rig with the possibility of axial adjustment and levelling. The test bench is used for calibration of circular scales, rotary encoders or angle measuring instruments, such as theodolites, tacheometers, total stations.

The autocollimator and polygon, the rotary encoder and the circular scale with the microscopes – one of these standards can be chosen as the standard measure for angular displacement control. When using the circular scale as the standard of measure, two photoelectric microscopes are used to avoid the influence of eccentricity for angular measurements.

A rotary table of ultrahigh precision is developed using mechatronic means for the spindle rotation. It is shown in Fig. 4.

The rotary table is controlled from the computer. Piezoelectric drive is fed from the generator of high frequency [7]. Use of the piezoelectricdrive facilitates a very high rotation accuracy of the aerostatic spindle. The object to be measured is placed and leveled on the table.

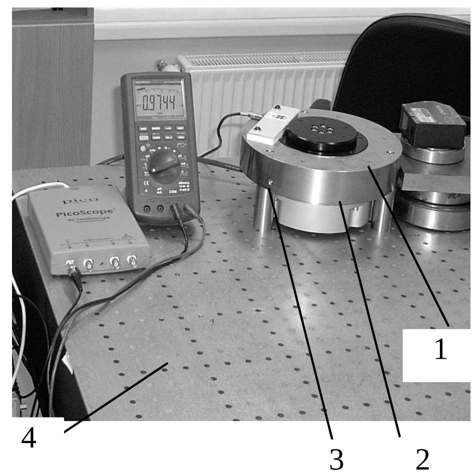

Fig. 4. Mechatronic rotary table for high precision angle measurements: 1 – the basis of the table, 2 – aerostatic bearing, 3 – piezoelectric drive.

Another newly developed arrangement for the vertical angle calibration of angle measuring instruments is shown in Fig. 5.

3.1. Arrangement for vertical angle calibration

The proposed arrangement for vertical angle calibration is based on the trigonometric angle determination using the reference scale of the length for vertical readings by the tacheometer and another reference measure of length – for distance from the tacheometer's axis to the vertical scale determination [8].

The designations in Fig. 5 are: I^1 – initial instrument's position with the axis of rotation of the spyglass O_1; I^2 – auxiliary instrument's position with the axis of rotation of the spyglass O_2 This position is achieved by moving the instrument along the slide rails of the test bench for geodetic instruments testing [7, 8]. At the distance *l* from the axis of the instrument the linear scale *S* is fixed in vertical position to the instrument's horizontal axis. The distance from the instrument's both positions l_e is fixed by using reference measure of length, for example, end length gauge (length standard). The linear photoelectrical transducer, laser interferometer or even precise linear optical scale (with microscope) can be used for this purpose. For the precise vertical angle measurements the distance from instrument to be calibrated (tacheometer) and the reference measure (linear scale) l_m has to be determined quite precisely (down to 0.01 mm). The accuracy of distance determination influences the results of measurements considerably giving a bias of reference data.

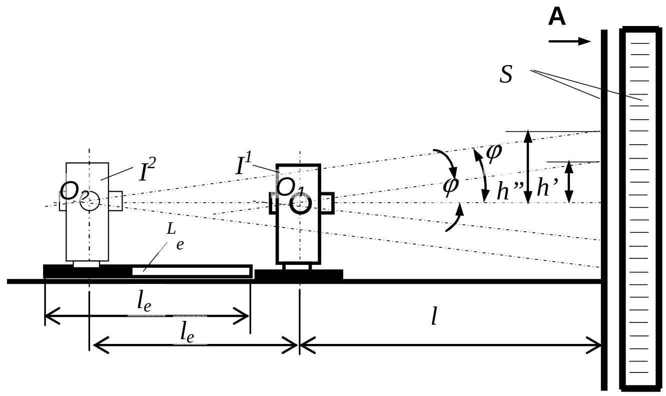

Fig. 5. Arrangement for vertical angle calibration of geodetic instruments

At the position I^1 of the instrument the reading *h'* from the scale is taken at the angle φ of the axis of telescope of the instrument and horizontal line.

The reading *h'* from the scale is taken. The angle of interest is expressed

$$\varphi = arctg\frac{h'}{l} \qquad (1)$$

After displacement of the instrument linearly to the subsidiary positions I^2 keeping the same vertical angle φ, the next reading h'' is taken and the distance *l* can be determined

$$\varphi = arctg\left(\frac{h''}{l} + l_e\right) \qquad (2)$$

and substituting the equations (1) and (2) will yield to

$$l = \frac{h' l_e}{h'' - h'} \text{ or}$$

$$l = \frac{l_e}{\frac{h''}{h''} - 1} \qquad (3$$

After taking the readings h' and h'' from the scale *S*, the true value of the distance *l* will be determined. Further measurements can be performed determining every tested vertical angle of the instrument operating with known distance and using the readings h_i from the scale. A full range of vertical angles of the geodetic instrument can be tested at laboratory environment in such way improving the accuracy of calibration and with a possibility to perform this at every desired time in spite of meteorological conditions.

Only a small part of the information about accuracy of angle measuring systems can be determined during calibration process. For example, for the raster scale with a pitch Δ of the raster strokes, $k\Delta$ - a pitch of the accuracy calibration, $m\Delta$ - the total number of strokes in the scale there is only small number of strokes which accuracy can be determined using standards of measure. For the circular scale, the calibration of angular accuracy by using the polygon can be performed for only 8 positions of the strokes in the scale [9, 10]. Conventional measurement formulas will show the measurand after the calibration without indication which part of the scale is measured. This disadvantage can be lessened using the information entropy expressions. The results developed give some value of information entropy restricted by the finite number of measurands registered in one-, two- or three-directional measurement.

This evaluation is widely used in signal processing, communications, economics and financial operations, evaluation of stock exchange operations, etc. For expression of mutual information such mathematical expression is used [8,9]:

$$I(X,Y) = H(X) - H(X/Y) = \sum_{x,y} p(x,y)\log\frac{p(x,y)}{p(x)p(y)} \qquad (4)$$

Mutual entropy shows a measure of dependency between two variables. Therefore, it can be used to join the assessment of systematic error expression, uncertainty and information entropy, showing at which extent the variable is evaluated in all the data available. For an analogue function it means that there must be shown the interval of evaluation (*a*, *b*) in which such an evaluation is present.

4. CONCLUSIONS

- Review of angle calibration methods that permits to determine the error of great number of strokes of circular scale are described. They are supplemented by ones newly developed measuring methods that are convenient to apply for the raster scales of small diameters.
- A multipurpose test rig has been created for accuracy testing of geodetic angle measuring instruments. Using a piezoelectric drive the high precision angle measuring table was created using the high accuracy rotary encoder as the angle standard.

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