

Informative 2D Scales of Measurement Systems Design and Metrological Characteristics

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Abstract

The report briefly reviews the linear displacement measuring systems and the information that they provide in terms of quantity. It also provides an overview of the features of their scales. The report analyzes the scales used in measuring systems, which give information not only about the main motion, but also about the two straight motion errors in the plane, functional and accuracy parameters. These scales are called the 2D scales.

The report gives the analysis of formation methods of such scales and their accuracy, shows the methods and results of the precision experimental research of this process, presents the conclusions about the effectiveness and viability of the methods of separate scale formation. This report presents 2D scale calibration features and new requirements for equipment calibration.

KEY WORDS: *2D scales, metrology, precision measurements.*

Introduction

Photoelectric displacements measurement systems are developing in the direction of precision, resolution and information content increase. In such a way the object is to obtain the maximal amount of information about the displacement parameters. In this respect special attention is given to so-called 2D measurement systems which provide information not only about the displacement along the axis of encoder scale, but also the information about small linear displacements transversely to the axis of encoder scale and angular oscillations on the plane of the scale of a measurement encoder.

Such encoders need complex raster scale with some information tracks that should be precisely related to each other. Technological processes and equipment, used for the measurement of scales, designed for 1D, i.e. movement in one direction, are inappropriate for the production of 2D scales originals [1, 2]. Besides, calibration equipment, used for 1D scales calibration [3-10], is inappropriate for the calibration of 2D scales.

This article examines the peculiarities of the raster image of 2D scales comparing them with 1D scales, the methods of the formation of the originals of these scales, the possibilities of the achievement of their precision. Besides, the results of experimental researches are given; the peculiarities of the calibration of 2D scales and new requirements for calibration equipment are examined.

1. The analysis of the peculiarities and information content of the scales of measurement encoders

1D scales

The simplest and the least informative are incremental measurement encoders having one raster track with periodic structure (refer to Fig.1, a), which enables to form in the encoder quasi-sinusoidal signals having different phases. According to these signals the size and direction of encoders displacement from home position are found.

More informative are incremental measurement encoders having above mentioned raster track with periodic structure and code marks track. Information content changes depending on the number of code marks and their arrangement.

When there is one code mark (Fig.1, b), system readings show information about the size and direction of the displacement with regard to code mark. To make it easier and more operative to find the home position of movement there are formed not one, but several code marks (Fig.1, c), which are ranged at fixed or variable intervals. In the first case, code mark is not recognizable and its position is found using additional information. In the latter case code mark is identified according to the distance between this mark and neighboring marks.

Scales which have raster tracks with periodic and code structure (Fig.1, d) provide information about absolute position of the measurement encoder along the scale. Code structure is made so that depending on the "word", which codes the position, having taken N bit code at any place of the scale, it is not repeated throughout the whole length of

the scale. Every “word” of the position has its fixed position value. Having read N bar, the position of the encoder is found within the accuracy of code track resolution. More precise position is found using periodic structure.

The structure of the periodic raster of precision scales is formed so that single-step error would not exceed $\pm 0,05\mu\text{m}$, the error of the position of bar symmetry axis would be not higher than $\pm 0,5\mu\text{m}$, and the cumulative error of periodic structure would not exceed $\pm 2,5\mu\text{m/m}$.

The following requirements are raised for code marks. Position error with regard to periodic structure should not exceed $\pm 0,25\mu\text{m}$, the error of the interposition of code bars should not be more than $\pm 0,5\mu\text{m}$, the error of the bar width of the code structure - up to $\pm 0,5\mu\text{m}$.

Allowable deviations of the form of all raster structures elements are up to $1\mu\text{m}$.

Absolute scales and periodic scales with code track provide information absolute position of the reading head of the encoder in regard to the scale. The number of tracks coding the position depends on the length of code word and desirable resolution. If the word that codes position is made of 12 bits, the scale will have code forming 12 tracks and a track with periodic structure, whereby precision displacements is found.

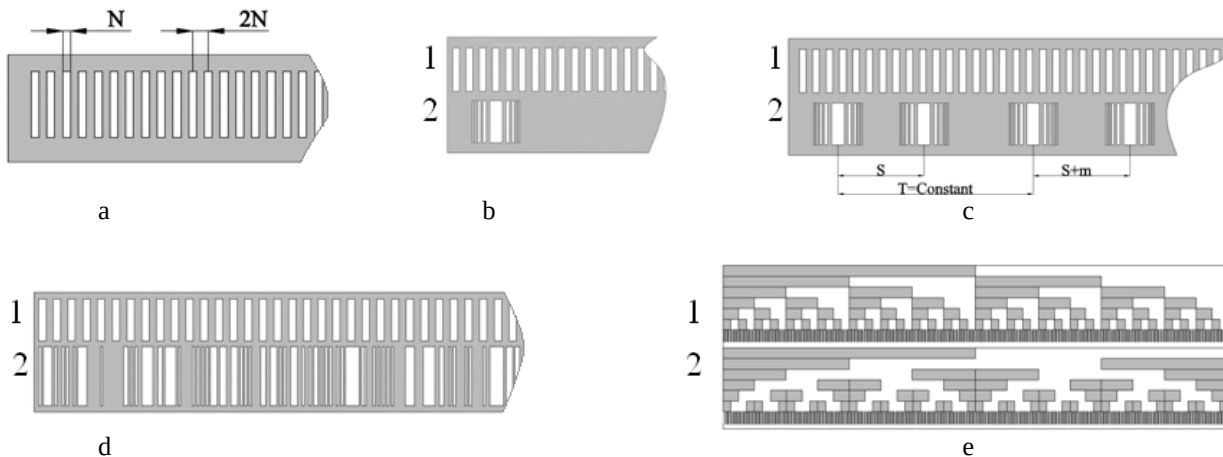


Fig. 1 The examples of 1D scales a) a scale with one periodic raster track, b) a scale with periodic raster track 1 and a code mark 2, c) a scale with periodic raster track and several code marks, d) a scale with periodic 1 and code raster tracks 2, e) absolute 1 Grey's code and 2 binary codes scales.

2D scales

Let's examine two versions of these scales.

Scales which have two periodic informative tracks (Fig. 2, a). The first periodic structure is ranged along the axis of the scale, and the second one transversely to this axis. With a help of such scale encoders, which have three photon-coupled initial signals formation groups, it is possible to measure linear displacements along the axis of the scale, and linear and angular errors of direct motion on the scale's plane [11-13].

Scales with raster angle-wise oriented elements in regard to its axis (Fig. 2, b) also provide information about system position in regard to the scale along its axis and linear displacements perpendicularly to this axis, and turns on the scale's plane. These scales have 2 code tracks and 2 tracks with periodic structure whose raster are oriented angle-wise in regard to scale's axis. Using a special optical system can be obtained information about the shift in the direction perpendicular to the plane of the scale.

The precision requirements for the formation of the structure of 2D scales are the same as the requirements for 1D scales.

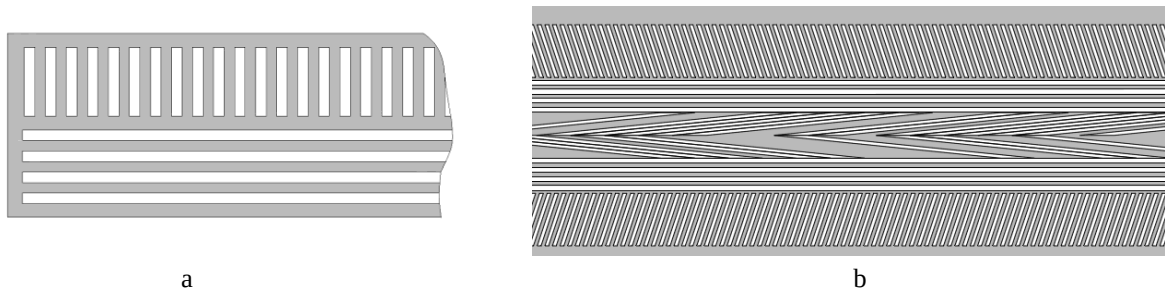


Fig. 2 The examples of 2D scales: a) 2D scale with periodic raster structures, b) 2D scale with code structures which have angle-wise oriented raster elements

2. The methods of the formation of linear scales, their precision research

The production process of 2D scales is similar to the production process of 1D scales. The different is the originals formation process and the equipment used for its implementation. The point is that the equipment of the formation of 1D scales' originals does not permit to form angle-wise and along the scale axis oriented raster elements with necessary accuracy.

2D scales' originals could be formed in accordance with the following methods:

- junction of fragments.
- continuous method.

We are going to examine the peculiarities of these processes more comprehensively.

The formation of long scales originals with a help of junction of fragment

When a raster image is formed with a help of this method first of all separate scales' fragments are formed. After that they are jointed according to established procedure. To this effect they are precisely positioned and set out on the blank of scale's original. The length of the blanks of scales' fragments depends on the available originals' formation equipment and raster image. It does not usually exceed 200 mm.

The precision of scale's original depends on the precision of fragment formation and its position in regard to the blank of scale's original during the exposure. The junction of scales' fragments is executed either precisely positioning scale's fragment on the blank or according to in advance formed marks on the fragment and original's blank.

The method of the precise positioning of a blank and original's fragment.

The method is founded on the exposure of the fragment based on the edges of its blank. A fragment is grasped by a grab at the edges and carried from the fragments accumulator to a necessary place on the blank, then it is precisely put and exhibited. This method does not need additional setout processes.

When forming a scale with a help of this method high requirements are put forward fragments in regard to raster image position fragment bases and fragment bases precision. This interconnection of an image with the edges of a fragments highly influences the precision of a forming scale.

On purpose to implement this method it is necessary to have a manipulator capable to move in three directions. Its motions should be very precise. The grab of the equipment should be fitted for precise, gentle grasp of a fragment so that when grasping a fragment it would not damage its edges.

The example of the equipment designed for the formation of the originals of long scales by precise positioning of a blank and original's fragment is given on the Fig. 3.

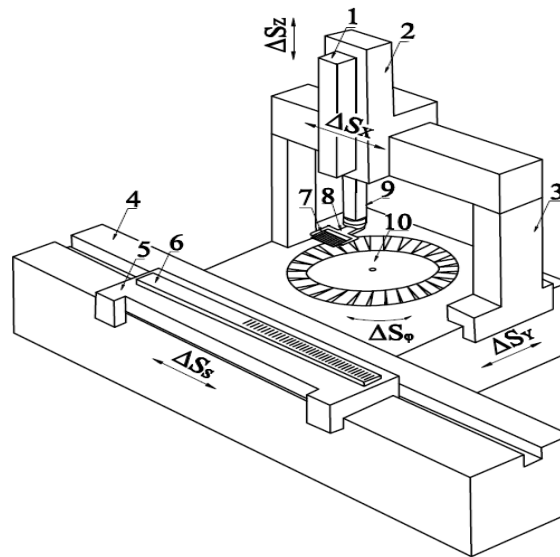


Fig. 3 The equipment designed for the formation of scales by the precise positioning of a blank and original's fragment.

1 – illuminator, 2 – carriage, 3 – portal, 4 – support, 5 – table, 6 – blank, 7 – fragment, 8 – grab, 9 – poppet sleeve, 10 – fragments' converter. S_x – carriage's displacement in the direction of x axis, S_y – portal's displacement in the direction of y axis, S_z – poppet sleeve's displacement in the direction of z axis, S_s – table displacement, S_ϕ – fragments converter's angular displacement

The method of the superposition of the marks of an original's fragment and a blank

Forming the originals of scales with a help of this method fragment positioning is made in two stages. It is taken by a manipulator from the fragments accumulator and transported on the precise fragment setout mechanism. The latter sets out the fragment in regard to a blank precisely according to the marks which were in advance formed on the original's blank and fragments.

For a precise positioning of fragments there is created a positioning mechanism with a help of which original's fragment is positioned to a necessary place, lifted and lowered on the blank. With a help of three piezoelectric elements a fragment is supported on fixed height above the blank. When necessary a fragment is smoothly lowered with a help of piezoelectric elements on it. Other three piezoelectric elements are meant for the positioning of a fragment on the scale's plane. With a help of them the system can be scrolled in x-y directions and turned. Piezoelectric elements enable us to set out the system with an accuracy of $0,05\ \mu\text{m}$. The scheme of the precise setout mechanism is given on the Fig. 4.

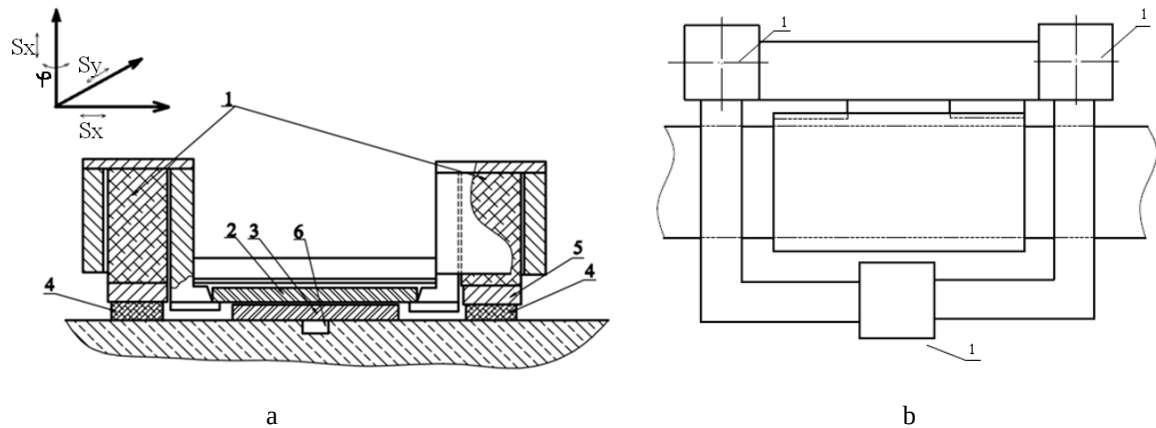


Fig. 4 Precise setout mechanism and precise movements implemented by it a side-view, b turned top-view, 1 – piezoelectric elements for the system's lifting and lowering, 2 – original, 3 – blank, 4 - piezoelectric elements for navigation (movement) on the scale's plane, 5 – sub frame, 6 – groove for the vacuum fixation of a blank

There were conducted experimental researches with a help of which according to minimal marks superposition error the configuration of superposition marks, their number and position with regard to the raster image of fragments were optimized. Researched marks are shown on the Fig. 5. Executing the superposition by PSD sensors the best superposition results were obtained using the marks shown on the Fig. 5, g.

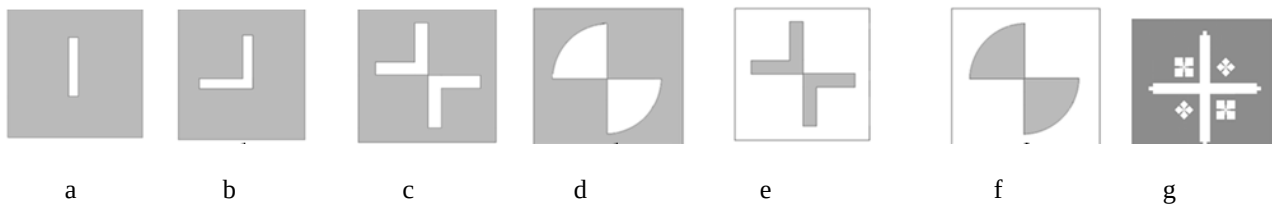


Fig. 5 Alignment marks

The formation of the originals of long scales by continuous method

With a help of this method the raster image of a scale is formed not from separate structure fragments joining them one after another, but directly by photolithographic or laser-based method.

Photolithographic method

A scale is formed from separate scale's fragments positioning them in proper places and exhibiting them. On purpose to make 2D code ruler 3 meters in length, there can be up to 80000 elements forming part of code structure. If there is no the drawing of a scale on electronic media coordinate values are typed in by hand. During the forming of the raster image of a scale there is a big possibility of coordinate error. If you type in an incorrect coordinate during the process it is impossible to notice this mistake until the whole 2D code structure is formed and all photolithographic operations are made. If there is a mistake or defect which demand to discard the scale, production process should be newly executed.

The researches are conducted using longitudinal division machine with additional optic exhibition system, laser displacement measurement system, process management software.

The advantages of this process:

- the process is easily adjusted,
- very good bar quality is obtained,
- bars can be formed at any angle.

Laser-based method

Code structure is formed by laser ray which affects the blank.

The main advantages of the production of 2D scale with a help of continuous laser-based method are the following:

- the process is very quick and ensures high productivity;
- code structure is formed in dynamic mode.

However, this process ensures worse quality than the quality of photolithographic raster image.

An accuracy analysis of the linear scales formation methods

Economically rational and the most reliable method is the probabilistic method of the total error calculation is applied. Total error $\Delta\Sigma$ is calculated by the formulas [14]:

$$\Delta_{\Sigma} = \sum_{j=1}^k \Delta_j \zeta_j \pm t \sqrt{\sum_{i=1}^n \sigma_i^2 \xi_i^2} \quad (1)$$

where Δ_j is j systematic component of total error; $j = 1, 2, \dots, k$; ζ_j is the influence coefficient of j systematic error; t is multiplier, evaluating confidence interval; σ_i is an average square deviation of accidental component of i is error; ξ_i is an influence coefficient of accidental component of i is error.

This method was applied for the assessment of all scales formation methods. These are the results of the calculation of total scales formation errors for 1m long scale.

For the method of precise original's fragment positioning. $\Delta_{\Sigma p} = \pm 4,09 \mu\text{m}$. The components of this error are: the error of the position of the raster image of original's fragment in regard to its basic surfaces; the error of the grasp of original's fragment, the error of manipulator's positioning.

For the method of the superposition of the marks of original's fragment and a blank $\Delta_{\Sigma zj} = \pm 1,40 \mu\text{m}$. The main component of this error is the error of the arrangement location of the marks on the blank.

For the continuous photolithographic method $\Delta_{\Sigma fc} = \pm 1,03 \mu\text{m}$. The main components of this error are: the linear error of the direct motion of original's formation equipment on the raster formation plane perpendicularly to the main movement; mechanical and thermal drift along the forming scale, occurring between the separate raster tracks exposure starts; the error of the measurement of comparative displacement of raster's forming system and a blank.

For the continuous laser-based method $\Delta_{\Sigma li} = \pm 0,84 \mu\text{m}$. The main components of this error are: mechanical and thermal drift along forming scale, occurring between the separate raster tracks exposure starts; the linear error of the direct motion of original's formation equipment on the raster formation plane perpendicularly to the main movement; the error of the measurement of comparative displacement of raster's forming system and a blank.

When calculating total errors the following presumptions are accepted:

- a) there is fulfilled the compensation and correction of all systematic errors and the errors, which are assessed within calculations, are randomly distributed in accordance with normal (gauss) probability distribution;
- b) the errors of all methods are calculated for conditionally equal equipment accuracy (precision) 95 % (+/- 2 S) for confidence interval. The cumulative error of the raster image of original's fragment is supposed to be zero;
- c) all technical processes are executed in thermo stuck-at environment (temperature and its stability in the checkpoint of the laboratory 20 +/- 0,2 C°; temperature gradient in space– vertical 0,05°C/m, horizontal 0,2 °C/m; temperature gradient depending on time 0,05°C/h).

3. Experimental researches of junction errors

Whereas modern-day technologies of the formation of continuous 2D raster scales' originals and equipment preparedness do not ensure necessary raster quality, the main method is the formation of raster with a help of junction.

In order to make sure what is the real influence of junction process towards cumulative scale's error, with a help of junction method according to the marks there was formed 3150mm long original of a raster scale. Fig. 6, c shows the diagram of errors throughout the length of a scale. The junction occurs beside 1250 mm mark. Here we can see higher error jump. Scale's error in this area was calibrated additionally at 1mm step. The results of these measurements are given on the Fig. 5, a.

These measurement results show that at the junction of segments appears an error up to +1,3 μm . It also can be seen on the Fig.5 b, which shows the fragment of a scale at the junction area. It also shows alignment errors and for scale's axis in perpendicular direction, as well as the differences of separate scale segments raster, occurring because of the instability of the photolithographic processes of their fragments production.

The reason for the jump of errors at this junction is explained on the Fig. 5, d – f which shows the superposition of the marks of scale's blank and segment. There you can see an obvious insufficient matching of marks. The reason of this is the errors of the arrangement of the marks on the segment and the blank and the errors of marks formation.

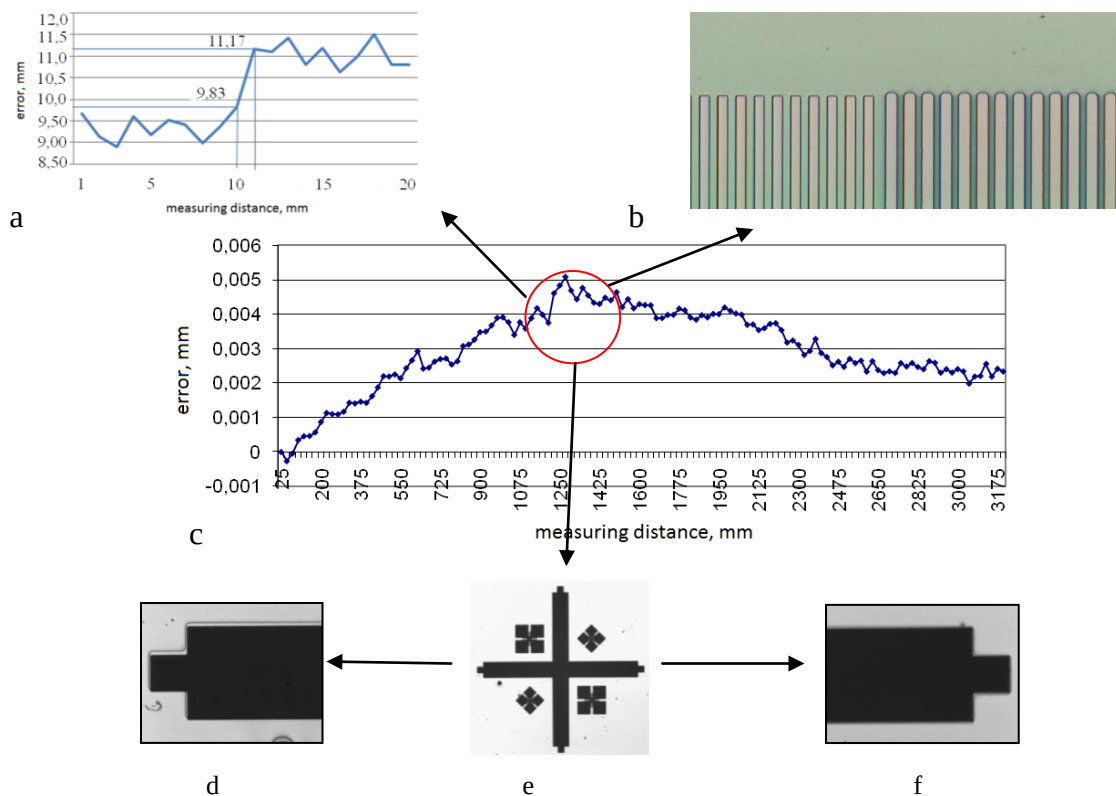


Fig. 6 The errors of a scale's original made by junction method

4. The analysis of the peculiarities of 2D scales calibration

The peculiarities of 2D scales calibration, new requirements for calibration equipment.

For the scales with periodic structure (Fig.1, a), the deviations of bars position, their width, in specific cases – the deviations of their edges' directness and parallelism are regulated and calibrated. Calibrators [3, 5, 8, 9] have direct motion node, which transports a microscope designed for the establishment of bar position and for the assessment of its form errors, and direct motion measurement system, as well as software designed for the assessment of above mentioned deviations.

For the scales with periodic structure and zero indexes (Fig.1, b), additionally as compared to above mentioned scales, there is regulated and calibrated the position of zero indexes in regard to the first or other preset bar of periodical structure. For the measurement of this parameter calibrators should have a microscope with precise linear movement device in the perpendicular direction of scale's axis. The error of movement directness up to 10 millimeters for process does not exceed 0,1-0,2 μm .

For 2D scales which have periodic raster structures positioned along and perpendicularly to the scale's axis (Fig. 2, a), in comparison with the scales having zero indexes, it is necessary additionally calibrate the errors of raster elements position and width perpendicularly to the scale's axis and the deviations of these elements directness throughout the length of the scale.

For the implementation of these new calibration requirements, microscope with a device for precise linear movement in the perpendicular direction of scale's axis should have precise linear displacements measurement system, whose measurement error does not exceed 0,2-0,3 μm . By these means it is also possible to assess bars mismatching errors at the junction of raster when the originals of scales are produced joining their separate segments.

Besides, it is necessary to ensure that the influence of linear direct motion error towards the measurement of the deviation of the directness of raster elements positioned along the scale's axis does not exceed 0,5-1,0 μm . It can be achieved by technical means or calculating the compensation of motions errors [11].

For 2D scales which have periodic raster structures positioned along and perpendicularly to the scale's axis (Fig. 2, a) and periodic raster structures positioned angle-wise with regard to the scale's axis (Fig. 2, b), it is necessary additionally calibrate the errors of the position of raster elements positioned angle-wise with regard to the scale's axis and width errors perpendicularly to these raster elements, the error of the angle of raster elements with regard to the scale's axis.

If the originals of such scales are formed by the method of junction of separate segments, it is also necessary to measure the errors of the directness of raster elements at the junction of segments, and the angle deviations of separate segments of forms raster structures with regard to the scale's axis.

For the implementation of these new calibration requirements a microscope with its linear movement system should be based on precise turn spindle with precise angle measuring system. The radial error of spindle rotation should not exceed 0,5 μm , the error of rotational angle measurement– up to 3 angle sec.

Conclusions

1. The highest accuracy of the formation of 2D scales' originals is reached using the continuous laser-based method. To achieve the calculated accuracy it is necessary to implement mathematical compensation or correction of systematic errors, and for the implementation of this method it is necessary to solve the problem of the quality of raster element formation.
2. The originals of scales formed with a help of continuous raster formation method will be distinguished by their monotonically changing errors depending on the length of a scale. When forming raster from segments by junction methods, formed originals of scales will be distinguished by their saltatory changing errors, repeating throughout the length of raster segment.
3. When forming raster from segments by junction methods, for formed scales' originals the errors on perpendicular scale's axis will saltatory distort the forma of raster elements for a step, repeating throughout the length of raster segment.
4. The main component of the total error of 2D long (up to 3,4 m) scales forming the originals with a help of all above mentioned methods are errors related to the linear errors of the direct motion of original formation equipment on the raster formation plane perpendicularly to the axis of forming raster.

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