

Software application for testing a data treatment module of an experimental laser round meter

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Abstract. The aim is to develop a software application for testing a data treatment module of our experimental laser roundness meter (Pat. 2019250 Russia). An application is to inspect the form deviations of the inner ring ball bearing tray. Its principle of operation is deflectometric triangulation. The theoretical base is a geometric-optics. We performed a self-testing procedure with modeling a profile by a sinusoid having a range of 0.4 μm and an amount of waves to 20 within a round of 16.68 μm . We compared the work of two modules. The results are follows: the sensitivity of the application to the range of the sinusoid did not exceed $\pm 2.4\%$ from a limit of uncertainty of the roundness deviation measurement; the discrepancies in the out-of-roundness did not exceed 9% that satisfied to the standards; if we overlay two graphics of the radial profile to each other, their counts had the deviations which reached an amount to the peak-to-valley range of profile. Conclusions are follows: the probability of error both in the program and in the algorithm is practically excluded; the modules under test worked with error; experiments those performed with one roundness meter only could not reveal error.

1. Introduction

Units based on interferometric techniques [1] are used to inspect of the tray surface bearing rings by optical methods. The surface under test has a complex shape, and therefore it makes distortions in an input signal. Correction of those aberrations is an expensive cost challenge. The method of deflectometric triangulation [2] permits us to overcome this without any expensive optics and, therefore, to make up our setup more commercially available.

The aim of this research is to develop a software application for testing a data treatment module of our experimental laser roundness meter (Pat. 2019250 Russia).

2. Backgrounds

This software application models a roundness meter built by us earlier. This roundness meter developed at Samara Branch Physical Institute of RAS and used at Samara National Research Institute in educational process. The prototype was optimized to inspect the form deviations of the inner ring ball bearing tray. This device was earlier tested on these parts (GOST 520-2002, ISO 4920-94, ISO 199-97) with a tray having the nominal diameter of 16.68 mm [3]. The results were encouraging, but they showed that to search of revealed discrepancies between output data of different software units when the same input data were there [4] the further testing a data treatment program unit is needed. One of them was a part of the roundness meter, and another was a unit intended to data treatment of a repeated measurements series those were written in files as intermediate results to further treatment.

3. Method of measurement

A narrow light beam focuses on the surface under test and scans it (figure 1) [5]. During scanning a mirrored light beam is grabbed by a matrix detector. The matrix photo detector does not contain any imaging optics. A profile of the surface under test is obtained from the position center of a light beam pattern on the photo-detector and from changes of this named position which become emerge during scanning.

4. Mathematical model of measurement

The scanning light beam is presented as one ray having no cross width. Geometrical optics principles are in the physical base of the roundness meter.

An opto-mechanical diagram [5] is presented in figure 1. The incident ray \vec{a} is perpendicular to YOZ plane, \vec{b} is a reflected ray. The angles are equal between the surface normal \vec{N} and these light rays that follows from the geometrical optics principles. In additional, all three rays lie in the same plane. This is described by a system of the vector equations (explanations are in figure 1):

$$\left\{ \begin{array}{l} \frac{-\vec{a} \times \vec{N}}{|\vec{a}|} = \frac{\vec{N} \times \vec{b}}{|\vec{b}|}, \\ \frac{(-\vec{a}, \vec{N})}{|\vec{a}|} = \frac{(\vec{b}, \vec{N})}{|\vec{b}|}. \end{array} \right. \quad (1)$$

$$\left\{ \begin{array}{l} \frac{(-\vec{a}, \vec{N})}{|\vec{a}|} = \frac{(\vec{b}, \vec{N})}{|\vec{b}|}. \end{array} \right. \quad (2)$$

Informative parameters are measured in a spherical coordinate frame with a center on OZ axis where the horizontal plane intersects this axis, and \vec{a} lies in this plane. Angle ψ is counted from OX axis to OY axis, and the vertical angle θ is counted from the horizontal plane named above. The surface under test is scanned by turning the part along OZ axis and discrete shifting the light source on the step of Δz along AB line in the points $z_k = z_{k-1} + \Delta z$. The displacement along OZ axis was no required.

Let obtain a mathematical model of the roundness meter from the equations system (1), (2):

$$\frac{d\rho}{d\varphi} = \rho \Phi(\rho, \varphi_R, z_R) \quad (3)$$

where z_R – the displacement of the light source 1; $\varphi = \varphi_c - \varphi_R + \text{Const}$; $z = z_c = z_R$ (see figure 1). Equation (3) turned out to be differential (DE) because the vector of the local normal to the controlled surface is described by a gradient in physical coordinates. Function $\Phi(\rho, \varphi_R, z_R)$ has a view of

$$\Phi(\rho, z, \varphi) = \frac{[\cos(\psi - \varphi_c) - A - B \cos \varphi_c] \times (\sin \psi - A \sin \varphi_c) + \text{tg}^2 \theta \times \sin \varphi_c}{[\sin(\psi - \varphi_c) + B \sin \varphi_c] \times (\sin \psi - A \sin \varphi_c) + \text{tg}^2 \theta \times \cos \varphi_c}. \quad (4)$$

The following symbols are used in this expression:

$$A = \frac{\rho_c}{L}; \quad (5)$$

$$\sin \varphi_c = \frac{d}{\rho_c}; \quad (6)$$

$$\text{tg} \theta = \frac{\xi - z_c}{L}; \quad (7)$$

$$B = \sqrt{1 + A^2 - 2 A \cos(\psi - \varphi_c) + \text{tg}^2 \theta} \quad (8)$$

where $B L = |\vec{b}|$ - the mirrored light beam length; ψ , ξ and θ - the functions of variables φ_R and z_R .

By linearization of (4) in its right side (3) in the domain of the average integral values of (3) we turn to DE:

$$\frac{1}{R} \times \left(\frac{dH}{d\varphi} - a H \right) = b \varepsilon + c \gamma, \quad (9)$$

where a, b, c are got from the right side (3); H – high value of the profile relative to \bar{R} ; $\varepsilon = \psi - \bar{\psi}$; $\gamma = \theta - \bar{\theta}$; a line at the top indicates the average integral value of the whole radial profile. Functions H, ε, γ have φ as their argument; φ – azimuth coordinate of the point on the tested surface radial profile. z is not taken into account.

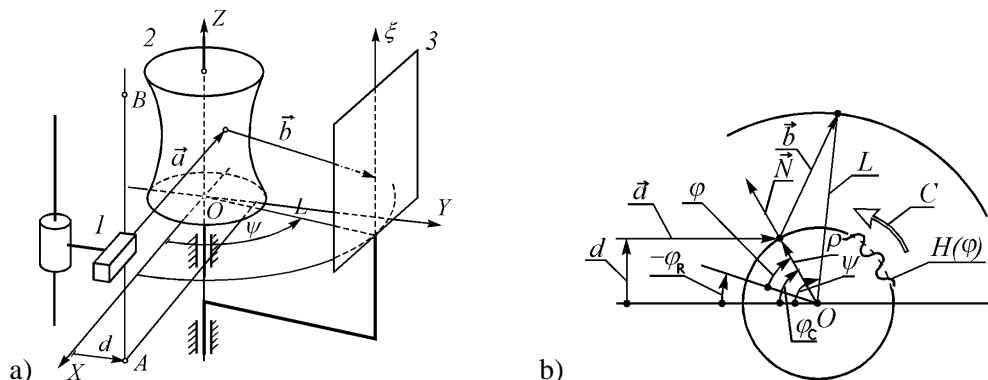


Figure 1. Optomechanical diagram of the device: a) –side view; б) –bottom view; 1 –light source; 2 –surface under test; 3 – video-camera; AB, C – scanning directions; \vec{a} , - incident и \vec{b} - mirrored light rays correspondingly; \vec{N} - normal to surface 2 in the highlighted point; ψ, ξ - coordinates of the mirrored ray on the photo-detector; d – light source shift; L - turning radius of the carriage with a video-camera; φ - azimuth coordinate of the illuminated point on surface 2 in the frame that is rigidly connected to the surface under test; φ_R – turning angle of the part with surface 2; φ_C – azimuth coordinate of the illuminated point on surface 2 in the frame that is rigidly connected to the scanner.

Radius \bar{R} and coefficients a, b, c are calculated from the formulas:

$$\Phi(R, \bar{\psi}, \bar{\theta}) = 0; \tag{10}$$

$$a = \bar{R} \times \frac{d\Phi(\bar{R}, \bar{\psi}, \bar{\theta})}{d\rho}; \tag{11}$$

$$b = \frac{d\Phi(\bar{R}, \bar{\psi}, \bar{\theta})}{d\psi}; \tag{12}$$

$$c = \frac{d\Phi(\bar{R}, \bar{\psi}, \bar{\theta})}{d\theta}, \tag{13}$$

we accept that $R = \bar{R}$ in (10), then we substitute it in (11) – (13).

Thus, DE is presented in expressions (4) – (13). The solution of this DE will be the desired radial profile, provided that the profile is closed.

DE (9) is solved by a Discrete Fourier Transform. The solution is an algebraic connection between the harmonics of the Fourier spectrum of the profile H , on the one hand, and, on the other hand, the right side of DE. We equate harmonics of the same spatial frequency to each other. This solution is used in the tested software modules.

We used another method of solution to develop the model. This is a method of Bernoulli [6]. Let us present the solution of equation (9) as a product of two functions

$$H = u v. \tag{14}$$

Substituting it into equation (9), we obtain

$$\frac{1}{R} \times (u v' - u' v) - a u v = b \varepsilon + c \gamma; \tag{15}$$

$$u \times \left(\frac{v'}{R} - a v \right) + \frac{u'}{R} \times v = b \varepsilon + c \gamma, \tag{16}$$

where stroke means derivative (in this case by variable φ).

Let us choose a function v such that it could satisfy the equation

$$\frac{1}{R} \times v' - a v = 0: \quad (17)$$

$$v(\varphi) = \exp\left[-\frac{a}{(1/R)} \times \varphi\right] = \exp(R a \varphi). \quad (18)$$

Then the equation (15) will have the form:

$$\frac{u'}{R} \times v = b \varepsilon + c \gamma, \quad (19)$$

From this we obtain

$$du = \frac{b \varepsilon + c \gamma}{\frac{v}{R}} d\varphi = \frac{R}{v} \times (b \varepsilon + c \gamma) d\varphi. \quad (20)$$

Now it is easy to get:

$$u(\varphi) = \int_0^{\varphi} \frac{R}{v} \times (b \varepsilon + c \gamma) d\varphi_1 + C_1 = R \times \int_0^{\varphi} (b \varepsilon + c \gamma) \times \exp(-R a \varphi_1) d\varphi_1 + C_1; \quad (21)$$

$$H(\varphi) = C_1 \times \exp(R a \varphi) + R \times \exp(R a \varphi) \times \int_0^{\varphi} (b \varepsilon + c \gamma) \times \exp(-R a \varphi_1) d\varphi_1. \quad (22)$$

We will find the coefficient C from the boundary condition

$$H(\varphi = 0, z = z_B) = H(\varphi = 2\pi, z = z_B), \quad (23)$$

where z_B – some estimated value, it is equal to the coordinate of the radial plane passing through the bottom of the tray of the surface under test. We obtain that

$$C_1 = C_1 \times \exp(R a \times 2\pi) + R \times \exp(R a \times 2\pi) \times \int_0^{2\pi} (b \varepsilon + c \gamma) \times \exp(-R a \varphi_1) d\varphi_1; \quad (24)$$

$$C_1 = \frac{R \times \exp(2\pi R a) \times \int_0^{2\pi} (b \varepsilon + c \gamma) \times \exp(-R a \varphi) d\varphi}{1 - \exp(2\pi R a)}. \quad (25)$$

We get in the end:

$$H(\varphi) = C + R \times \int_0^{\varphi} (b \varepsilon(\varphi_1) + c \gamma(\varphi_1)) \times \exp[-R a \times (\varphi_1 - \varphi)] d\varphi_1; \quad (26)$$

$$C = \frac{R \times \int_0^{2\pi} (b \varepsilon(\varphi_1) + c \gamma(\varphi_1)) \times \exp[-R a \times (\varphi_1 - 2\pi)] d\varphi_1}{\exp(-2\pi R a) - 1}. \quad (27)$$

So, in (4) – (25) we give the output of the transformation function (26) – (27). We used it in the software application, but not for modeling, and to solve the inverse problem – the profile calculation. This function is an alternative to the one used in the round meter, as well as in the program module of the system for processing and statistical analysis of data obtained from the round meter data collection module.

5. The device under research

The destination is an automated quality inspection of tray on inner rings of ball bearings with an outer diameter of 8 to 50 mm with the measurement of quantitative parameters, their processing with the issuance of the results in graphical and textual form. The deviation from the nominal form is inspected, in this case - from the roundness, including its components such as the granularity and waviness.

The optical-mechanical unit of the roundness meter is shown in figure 2.

The input signal of the primary optical converter of the round meter is the dependence of the power distribution of the light beam reflected from the surface under test on the photo detector on time.

Output data of the roundness meter unit intended for collection and processing of data based dependences of informative parameters ε , γ from azimuthal coordinate φ on the tray of the part under test. They are written to an ASCII-encoded character data file (figure 3).

These data are the input data for the two software modules we are testing.

The digits in the 1st column, starting from the 6th row, indicate the radial profile report number. In this case, the radial profile has 600 counts. The figures in the other two columns are the angular coordinates of the center of the light spot on the photodetector from the laser beam reflected from the part under test. In the 2nd column is ψ , in the 3rd column - θ . The angle values are in degrees. The angles are measured in a system of spherical coordinates, rigidly connected with the optical-mechanical unit of the round meter.

The figures at the beginning of the file indicate the following:

- in the 1st line: $L = 35 \text{ мм}; d = 7 \text{ мм};$
- in the 2nd line: the initial position of the light source $(z_R)_0 = 0 \text{ мм};$ the step of moving the light source of radiation $\Delta z_R = 200 \text{ }\mu\text{м};$
- in the 3rd line: service information, not used in the program;
- in the 4th line: the number of counts on the radial profile of the surface under test 600 (they are made by turning the surface under test with the same step); the number of the radial sections 1.

```

35.000    7.000
 0.000    200
 128.000   128.000   0.000
 600      1
  1  106.577   -0.469
  2  106.567   -0.490
  3  106.560   -0.482
.....
599  106.549   -0.502
600  106.538   -0.475

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Figure 3. The structure of the file containing the input data for the program module in the round-gauge, responsible for data processing.

The output data in the roundness meter are the deviation from the roundness, as well as the waviness of the radial profile. This output is presented as an ASCII code. The output is also written to a file.

6. Program module to model of measurement

The program is written on Borland Pascal ver. 7.0. To develop and run the program, an IBM-compatible computer with the NTVDM emulator program was used. Also for comparison, the program was compiled in DOSBox emulator version 0.72. This was caused by problems with russification.

To simplify modeling, the optical scheme of the device was represented as flat. That is, the incident beam and local deviations of the surface under test had no components along OZ axis. This approach is justified by one characteristic feature of the roundness meter transformation function - the factor at an angle θ has a factor proportional to the angle $\bar{\theta}$. And just the average deviation of the reflected beam towards OZ axis was negligible at reflection from the bottom of the tray in our scheme. Then the contribution of the mentioned factor was also negligible.

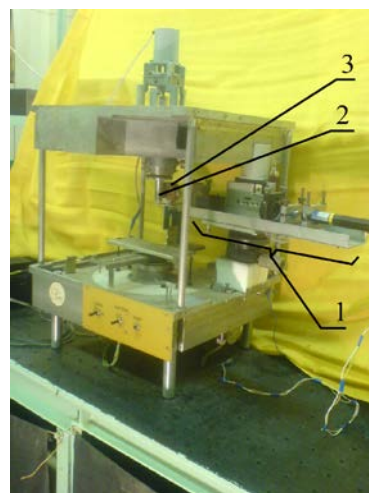


Figure 2. Opto-mechanical unit of the round meter: 1 – light source; 2 – surface under test; 3 – photo-detector.

The functionality of the module included modeling a direct problem, that is, the process of incidence and reflecting a light beam as a single vector on a one-dimensional surface, represented by a circle with a sine wave superimposed on it. The position of the point spot of the reflected light beam on the photo detector was calculated numerically. To do this, the first step was used the method of decachotomy, since the order of the root of the equation to be solved was equal to four, which made it difficult to find the root. In the following steps, we moved on to the secant method. The data obtained, similar to that shown in figure 3, were written to one-dimensional arrays in memory.

Profile recovery we obtained according to the acquired data, we performed according to the formulas obtained by our Bernoulli method. This is an inverse problem in optics. The recovery algorithms differed from those used in the tested modules (discrete Fourier transform). Consequently, the formulas were different. Program codes were also different, as programs were created in different languages and programming support environments, and by different programmers. The practical coincidence of the results would indicate that there are no errors associated with the derivation of the formulas.

To remove the effect of the discrete nature of counts of the radial profile error of the computations, we asked before beginning the procedure of modeling the discontinuity of φ at a rate of 16 intervals on a single period of the model sine. The values of $\psi(\varphi_i)$ and $\theta(\varphi_i)$ contained each count φ_i of the radial profile, which were written in its one-dimensional arrays of data. Also created an array of φ . Then the round-diagram of heights H was calculated, the reports of which were also recorded in their one-dimensional array. Then the program halved the step and repeated the procedure. Its results were compared with the data obtained in the previous step at the same values φ . If the maximum over the whole profile of the modulus of the difference, given the magnitude of the sine wave, became less than a predetermined value (10^{-6}), the loop stopped, the results were displayed on the screen, and, at the request of the user, can be output to a text file. Finally, the restored round-diagram was compared with the samples of a model sinusoid with the same φ coordinate. Based on the results of the comparison, the error was calculated.

Earlier we added in our module the option to retrieve a one-dimensional profile having significant deviations from roundness, comparable to the average radius. The formulas used in this case took into account the non-uniformity of the step, which occurs from the change of heights (depths) with the inclined incidence of the probing beam of light. Since the procedure simulating the direct problem is based on the same approximations as the profile reconstruction formulas, the model and restored graphs had to coincide with the error determined by the error of the calculations of numbers and functions on the computer. The data obtained by restoring the profile of the linearized DE when approaching H to zero should have sought the same result. In this branch of calculations, the division of the step in half did not occur automatically, the decision was made by the user.

Option of this branch of computing has also meant, according to the user selection, instead of specifying the model of the sine wave, reading the data file with the results of the module of data collection and processing of the investigated roundness meter.

For our problem, we introduced an additional branch of calculations on the linearized DE in which the doubling of steps did not occur. The discreteness was set by the user from a set of numbers divisible by four, as was the case in the roundness meter under study. In this branch, the counts of model informative parameters were recorded, in addition to the array in memory, also in an external file on the disk in the format, as in figure 3. In the third column recorded the minimum possible in the computer nonzero values θ of the same magnitude in modulus but with opposite signs when following each other. This was done to ensure that the tested modules did not stop because of the impossible arithmetic operation of division by zero. We used these acquired files in our research by testing the program modules.

7. Tasks of the research

First, we need to perform self-testing of the software package we are developing.

To do this, the following entities and actions must be modeled:

- the surface under test with a typical defect $H(\varphi)$ shape deviations;

- process sensing of the surface being tested along its radial profile by its turn on the angle ($\Delta\varphi_R$);
- writing the data file of the dependences of the informative parameters ψ , θ on the azimuthal coordinate φ of the surface under test;
- calculating the height counts of the circle diagram using the data from this file;
- determination of standard parameters of deviation from roundness by these counts: amplitude (represents the range of the model sine wave) and the number of waves on the radial profile;
- comparison of the obtained data with the model sinusoid.

Secondly, it is necessary to test the software modules of the roundness meter and the system of statistical data processing, for this it is necessary to use the resulting files and dependencies of informative parameters obtained from the model sine wave. It is necessary to compare the results of a single measurement processed by these two programs.

Thirdly, it is necessary to compare the results of measurements of the same part on the same profile – on the bottom of the tray of the inner ring of the ball bearing. This allows us to make the available data obtained at the same initial position of the same controlled parts in the scanner.

The results should be compared with the tolerances for the controlled parameters [7] and the requirements for measurement error [8] in this problem.

The maximum measurement error, according to GOST 17353-89 [8], does not exceed the permissible spindle radial error motion when scanning the radial profile, which is $0.05+0.0005 \times h$ [μm], where h [mm] probe height above the level of the stand for the controlled part.

Tolerances on roundness (the maximum deviation from the smallest circumscribed circle, for spatial harmonics in the Fourier spectrum of the radial profile from the second to the 500th inclusive) and waviness (when in the harmonic spectrum from the 16th to the 500th inclusive, are determined similarly to the parameter Rz roughness), depending on the accuracy class of the part, vary from 0.3 to 1.6 and from 0.05 to 0.2 μm , respectively [7].

8. Realization of research

The amplitudes of deviations from the roundness were modelled by sinusoids with a span of 0.4 μm and the number of waves from 1 to 20 per radial profile.

For comparison, we also used the results of a series of measurements of the researched roundness meter with the ring, which had a typical shape defect (by measurements on the contact round gauge Talyrond 53, performed at the Samara bearing plant SPZ-4, the waviness was from 0.3 to 0.35 microns, non-roundness was from 0.4 to 0.5 microns). More precisely, files in the format, as shown in figure 3, were used from the roundness meter.

The data for radius of the tray was 8.34 mm; laser wavelength 0.78 mm; scan time 1.5 min. Set points in the roundness meter are: 600 steps increments per profile; distance from the axis of rotation of the ring to the photosensitive surface $L=35$ mm; displacement of the light source from the axis of rotation of the ring $d=7.0$ mm (which, according to calculations, corresponded to the angle of incidence of the scanning beam of light on the controlled part 55°).

9. The first results of research

Self-testing of the software application developed by us was performed. Deviations from roundness were modeled by sinusoids with a span of 0.4 μm and the number of waves from 1 to 20 per radial profile. The sensitivity of the program determined in this case was no more than 2.4% of the maximum permissible error of measurement of deviations from the roundness and 0.4% of the minimum amplitude of the waviness, which is recognized for the defect of shape deviations.

The first results of testing of the software module of the data processing the roundness meter and software module for processing single measurements included in the system of statistical data processing. Our software application was used for this purpose. Distortions of the shape of the restored profile were noticeable. If we compare the phase of the sinusoid, then at $\varphi = 180^\circ$ the model and the restored curves in the middle of the coordinate range φ were in the opposite phase, and when approaching φ to 0° and 360° differences gradually disappeared.

For a comparison, figure 4 shows the results of experimental data processing which were obtained from the defective part we used. Waviness graphs with a range of spatial harmonics from 16 to 150

inclusive are presented. The results of the waviness measurements showed for the module A - 0.94 μm , and for the module B – 0.84 μm . The difference between the results was 9% of the radial profile amplitude, or 0.1 μm . This difference was from five to seven times less than the measurement error of the waviness of the investigated round-meter, but twice more than the maximum permissible measurement error in this problem. It was determined by us from comparison with measurements, those were made by the contact roundness meter.

The same profile, retrieved by two software modules under test, in most of its counts of H had clearly visible differences, reaching values comparable to its measured amplitude. At the same time, the characteristic features of the profile shape were restored with much smaller differences, comparable with those for the amplitude. But this is true only if we take into account the shift in φ and the inversion of the sign height H . You can see that this offset is half the step of the restored profile.

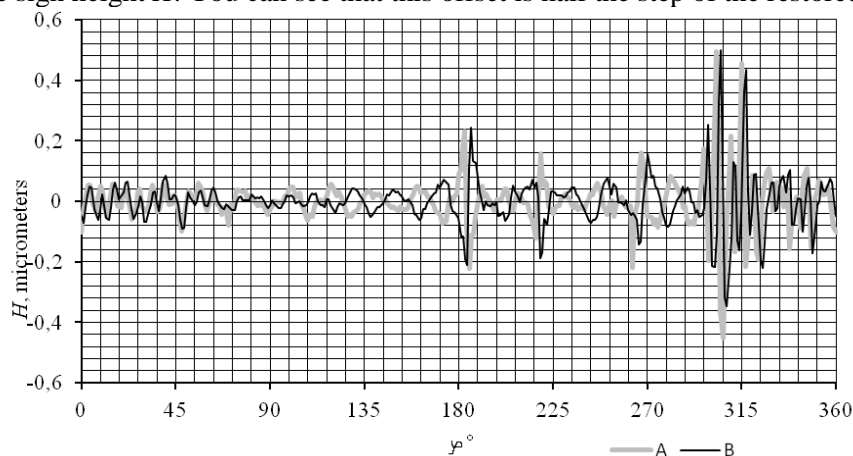


Figure 4. Radial waviness profiles obtained by two different software modules from the same file with experimental results of the data collection and primary processing module in a round-gauge: A-round-gauge; B-statistical data processing system (single measurement used).

10. Discussion

Self-testing was positive. This is evidenced by the fact that the sensitivity of our computer model was 2.4% of the maximum permissible measurement error in the considered practical problem.

In our experiments, the upper limit is less than the required method of 500 because of the technical limitations imposed at this stage of the development of the roundness meter. In the future, they should be removed. However, we note that in a number of practical applications, the upper limit of the waviness of 150 waves is used.

The measurement error of the waviness of our roundness meter was much more demands (up to 10 time greater) to limit the measurement error applicable to roundness meters. At the same time, it was close to the upper limit of the tolerance of undulation for part of the quality of the controlled parts. The components of the optical-mechanical unit of the investigated device can be selected with significantly better technical characteristics. This can reduce the error to the required values, which is in satisfactory agreement with the results obtained by the authors earlier [9], when the data were obtained from a fixed part, the error estimate of the waviness measurement was then 0.05 μm . The radial profile was obtained virtually.

The difference in the magnitude of the waviness obtained from one radial profile, with the same data, but with the help of different programs can be partially explained by the difference in the accuracy of calculations in these programs. The search for causes of distortion in the shape of the profiles requires further research.

11. Conclusion

We describe the software application intended for research of the laser round meter that we develop. Research is performed on the sample of one practical apply that consists in the inspection of form deviation of the tray of inner bearing rings.

Self-testing was performed with a positive result.

The first results of research using our complex of two software modules designed for data processing of the experimental laser roundness meter scanner are presented. One of the modules was part of the studied roundness meter. Another module was the part of the statistical data processing system. In some experiments it was assumed that the data obtained from the scanner of our roundness meter as a result of a series of repeated scans of the part that had a typical defect of the shape deviation. In other experiments, the initial data obtained from the simulation by our software complex were used. The radial profile with deviations in the form of a sinusoid was modeled.

The results of testing of the two modules showed that in both cases the amplitude of deviations from the roundness was determined satisfactorily. However, the shape of the radial profiles was reproduced with distortions.

Conclusions are follows: the probability of error both in the program and in the algorithm is practically excluded; the modules under test worked with error; experiments those performed with one roundness meter only could not reveal error.

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