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Method of compensation of errors in measurement of roundness and cylindricity deviations caused by eccentric position of measured element in relation to the axis of rotation of FMM table

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Abstract- Typical algorithms used in Form Measurement Machines are sensitive to the position of the measured object with respect to the axis of rotation. In order to get high accuracy the operator should be very precise in positioning the measuring object and that is time–consuming. The paper presents a conception of a new method which gives results more resistive on the position of the object under measurement.

I. Introduction

Accurate measurements of shape deviations of mechanical elements, especially the measurements of roundness and cylindricity deviations are usually performed with radial method, using specialized stations described by an acronym FMM (Form Measuring Machines). Owing to small measuring range and high resolution of used displacement sensors they guarantee high accuracy. However, one disadvantage remains – long measuring cycle. Obtaining high accuracy requires precise positioning of the element [1, 2, 3], so that the eccentricity of its axis in relation to axis of rotation of the measuring table (or axis of rotation of the measuring head) was insignificant with regard to the radius of the measured section:

$$\frac{e}{R} \ll 1 \qquad (1)$$

where:
R – average radius of the element's measured section,
e – distance of the centre of measured profile from the axis of rotation of FMM table.

Although modern machines ensure automatic centering of the element, coaxial positioning of all measured sections is not always possible. It particularly pertains to the measurement of elements of structurally assumed mutual eccentricity of particular sections and to mechanical units composed of several assembled parts.
Since the measuring range of gages used in most of currently produced FMMs amounts to at least 1000 µm, it is technically possible to scan the surface with axes shifted in regard to the axis of rotation by even half a millimeter, without the need of precise positioning of the elements. To make the gathered data useful, other than commonly used method of processing the measuring signal is needed, such that would provide robust results, i.e insusceptible to position of the element relative to the axis of rotation.
Employing one of such methods, based of using computational algorithms applied in coordinate measuring machines is presented in this paper. The results of practical application of the developed method on the example of elements with constant and variable curvature are presented as well. The purpose of the following research was the comparison of profiles of cross sections obtained by computations of reference profile by currently used method and new herein described method.

II. Errors in calculating roundness deviation in measurements by radial method

Radial method is used to measure variations of element's radius ΔR as a function of rotation angle φ. Absolute dimensions of the element are not measured. In the typical algorithm instantaneous values of the reference circle are calculated as the sum of mean value of measuring signal and its first harmonic. It is the approximate mapping of instantaneous radiuses of the associated circle according to the least squares criterion. The errors resulting from the applied approximation increase with the distance e between the centre of measured section and the centre of rotation.
Measurements of elements ideally round but positioned eccentrically provides profiles that are not circles. It was shown [2] that the error in calculating of local radius of such profile $\Delta R(\varphi)$ equals:

$$\Delta R(\varphi) = -\frac{(e_x \sin\varphi - e_y \cos\varphi)^2}{2R_z} \qquad (2)$$

where: e_x, e_y – eccentricity respectively in direction x and y, R_z – substitute radius, wherein:

$$R_z = \frac{d}{2} + r_k \qquad (3a)$$

for external surfaces and

$$R_z = \frac{d}{2} - r_k \qquad (3b)$$

for internal surfaces
where: d – mean diameter of the element, r_k – radius of the probe tip.

From the formula it follows that the obtained profile is distorted in the following way – it is lengthened in the direction of vector linking the centre of the profile with the centre of rotation.

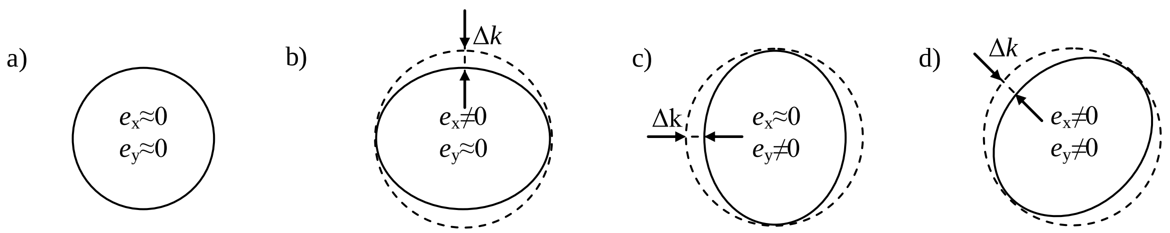

Fig. 1. Distortion of roundness profile caused by eccentric position of the centre of element's section in relation to the axis of rotation: a) coaxial positioning $e_x \approx 0$, $e_y \approx 0$; b) eccentric positioning $e_x \neq 0$, $e_y \approx 0$; c) eccentric positioning $e_x \approx 0$, $e_y \neq 0$; d) eccentric positioning $e_x \neq 0$, $e_y \neq 0$

Maximum error value of profile radius equals:

$$\Delta k = \frac{e^2}{2R_z} \qquad (4)$$

wherein:

$$e = \sqrt{e_x^2 + e_y^2} \qquad (5)$$

As demonstrated by formulas (4) and (3b), this error increases when measuring elements of small diameter, especially holes. For instance while measuring a hole of 10 mm in diameter which axis is shifted relative to the axis of rotation by e = 200 μm, using probe tip radius of 1 mm, the error Δk amounts to 5 μm.

III. Method of measurement resistant to eccentric position of the element under examination

This paper presents the results of applying the calculation method, which allows limiting the influence of element's position in the measuring space on the result of roundness and cylindricity deviations measurement. Applying this method requires the knowledge of approximate value of diameter d of element's measured section. It can be determined by measurement with other device or by assuming nominal value given in the specification of measured element. The proposed method consists of the following steps:

a) measurement by radial method n signal values r_i, corresponding to evenly spread angles $\varphi_{i,}$
b) calculation of signal mean value $\overline{r_i}$,
c) calculation of signal deviations from mean value $\Delta r_i = r_i - \overline{r_i}$,
d) calculation of local radiuses $R_i = R_z + \Delta r_i$,

e) transformation of polar coordinate system R_i, φ_i to Cartesian coordinate system,
f) applying one of CMM algorithms to determine the parameters of reference circle (Least Square Circle - LSC),
g) determining local roundness deviations,
h) determining roundness parameters like RONt, RONp, RONv, RONq.

At point d, from the values usually oscillating around zero, total (so positive) values of local radiuses are obtained. Owing to that operation the set of data from FMM is expressed in polar coordinate system or cylindrical coordinate system if axis Z is taken into account. Such a way it can be simply transformed to Cartesian system that allows applying CMM algorithms.

IV. Simulation research

The performed simulation research aimed to monitoring the results of new computational method. We assumed that the measured element is ideally round. It was also assumed that maximum error of estimating the mean diameter d of a given measured section is g. During simulation d value as well as section eccentricity e were changed and different values of error g were assumed. In the first phase of simulation the measuring signal was not quantized (the simulated measurement data were taken without rounding). Next simulations also accounted for the resolution of analog-to-digital converter.

Fig. 2 presents sample results of simulation research for the element of nominal diameter d = 20 mm, estimated with error g = 0,25 mm. Value of eccentricity e was modified in 0 – 250 μm range and the influence of errors caused by signal quantization was accounted for. Errors $\Delta k(e)$ resulting from applying the traditional algorithm are shown by solid line. Errors $\Delta w(e)$ associated with applying new algorithm are illustrated by dotted line. In both cases to avoid plotting two very closely situated curves corresponding to the measurement of external and internal surface, the influence of tip radius was neglected (it was assumed r_k = 0).

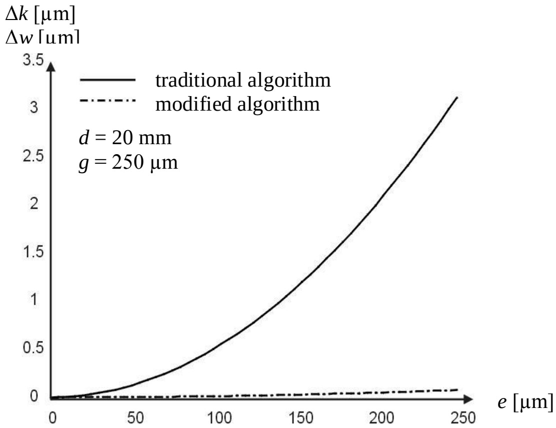

Fig. 2. Comparison of errors in determining roundness deviation by using typical and new algorithms

The comparison of errors Δw and Δk warrant the conclusion that proposed algorithm very strongly reduces the influence of element's eccentricity on measurement results.

V. Experimental studies

In order to verify the efficiency of proposed method in practice, some experiments were performed using a cylindrical roundness master with 19 mm diameter and two other workpieces: the first one with 64 mm diameter and the second one with 90 mm diameter. The measurements were performed with computerized measuring instrument Talyrond 200 that included inductive probe with spherical tip 2,5 mm in diameter. The measuring range of probe was 1000 μm, while the number of sampling points at perimeter was 1024. For calculating with the improved method self-developed software in Matlab was used. The examined elements were placed on the measuring table at different positions in relation to the axis of rotation, beginning with coaxial positioning and ending with eccentricity reaching e = 0,5 mm along x-axis or y-axis.

Fig. 3 presents sample results of measurement obtained at various locations of roundness master Φ19. The plots in figures 3a and 3b illustrate the measurement results obtained directly from Talyrond 200 device, software which uses typical algorithm for reference circle (LSC) calculation. The plots in figures 3c and 3d were obtained with new algorithm. Two plots on the left side (3a and 3c) present a profile of the master placed coaxially with the axis of the Talyrond table ($e \approx 0$ µm). It can be seen that in such a case both methods give identical results.

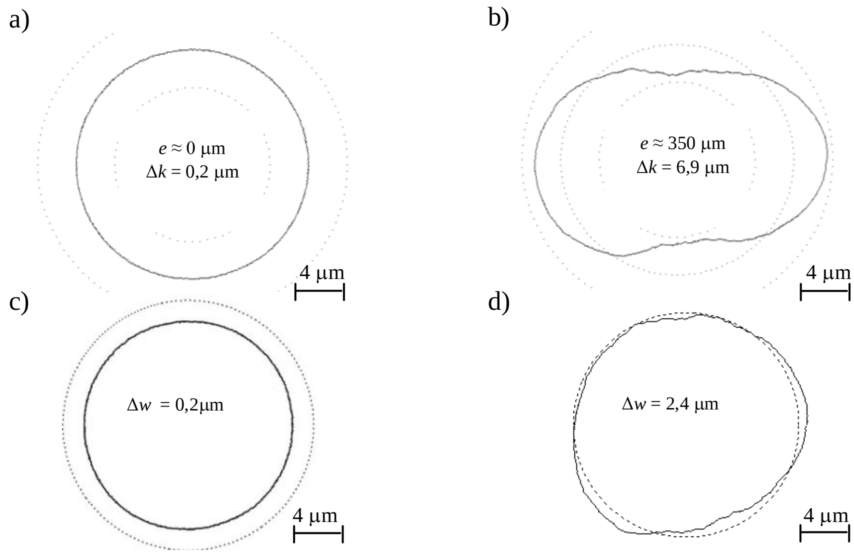

Fig. 3. Polar plots of form errors of cylindrical master obtained by typical (a, b) and modified algorithm (c, d)

The pair of plots on the right side show the measurement results of the same cross-section but when eccentricity was $e \approx 350$ µm. Both obtained profiles are deformed. In the first case (3b), due to the shortcoming of classical algorithm, the plot is oval in shape as the second harmonic became significant in accordance with the theory. In the second case (3d) the plot is irregular and more similar to a circle. The observed deviations from roundness are mainly caused by non-linear characteristic of inductive probe, which was found out during probe calibration. Despite probe nonlinearity, the roundness deviation Δw received using the modified algorithm is more than twice lower than the roundness deviation Δk obtained with traditional algorithm.

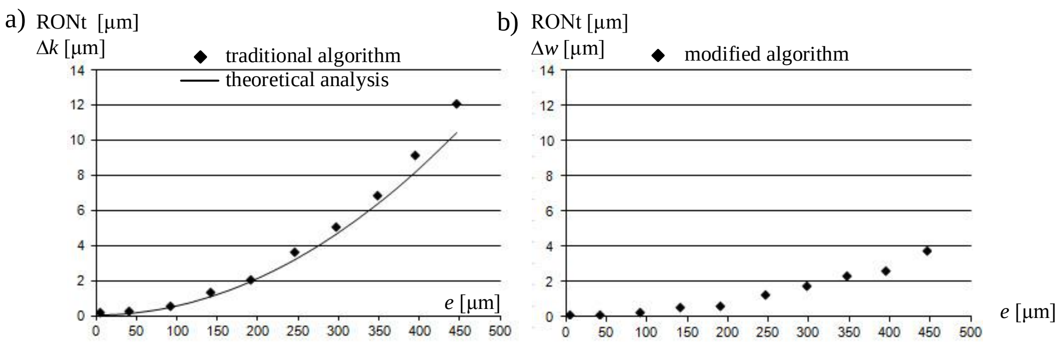

Fig. 4. The influence of eccentricity on the measurement of roundness error: a) traditional, b) modified algorithm

Fig. 4 presents values of roundness deviation RONt obtained from measurements of the master Φ19 which was placed at different distance e from the axis of rotation. The plots demonstrate that at low values of eccentricity e (i.e. $e < 100$ µm) the results obtained with both algorithms are similar. However, for eccentricity $e > 100$ µm the modified algorithm gives considerably better results.

Similar conclusions can be drawn from the plots of amplitude of the second harmonic C_2 (fig. 5), which is the measure of ovality. Rise of C_2 due to increase in e is considerably greater in case of traditional method.

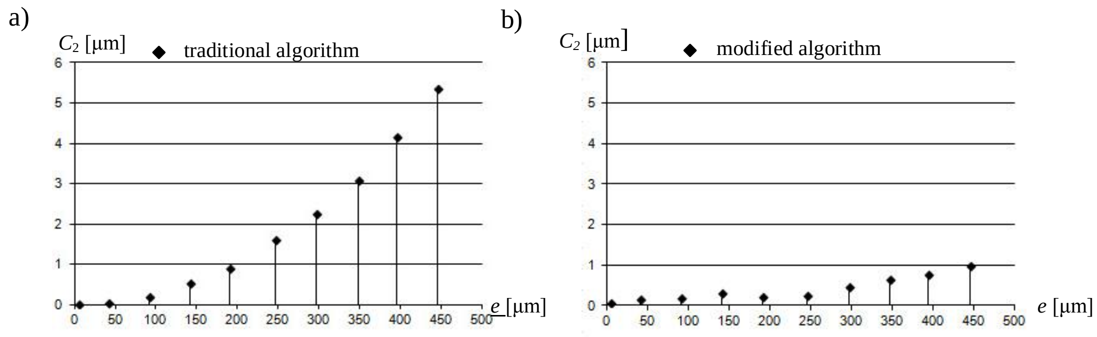

Fig. 5. The influence of eccentricity on the amplitude of 2nd harmonic while measuring roundness master Φ19: a) traditional algorithm, b) modified algorithm

Further experiments were aimed to verify if applying the new computation method for elements of lower precision and other shape will also improve measurement accuracy. For this purpose the measurement of two elements Φ64 and Φ90 were performed. Fig. 6 presents the profiles of examined sections. The first one is of irregular shape similar to a circle, the second one is oval (in accordance with technical specification).

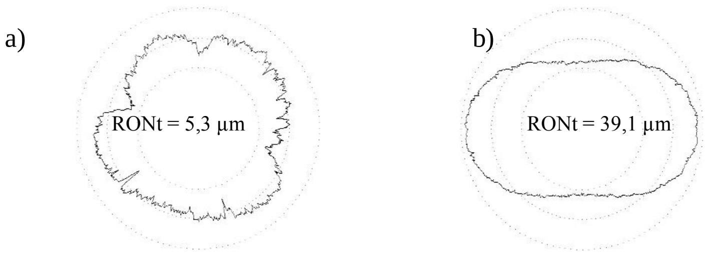

Fig. 6. Form errors of examined cross sections a) Φ64, b) Φ90

The diameters of both sections are several times larger than diameter of the master discussed before. Thus, according to the theory, the influence of eccentricity of these elements on results obtained with traditional algorithm should be proportionally smaller.

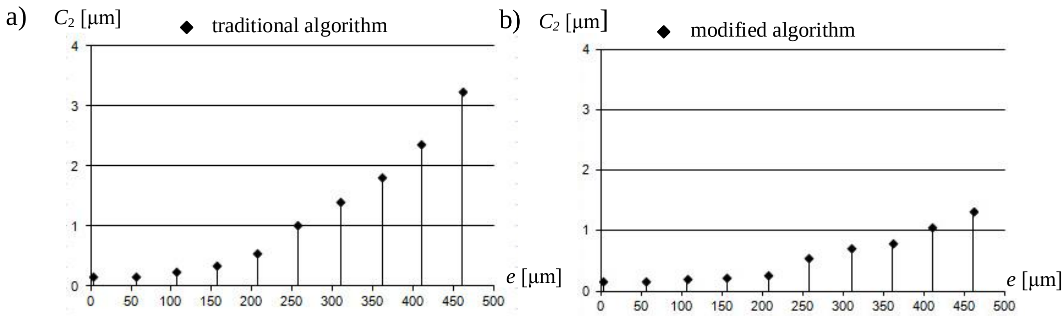

Fig. 7. The influence of eccentricity on the 2nd harmonic (element Φ64): a) traditional, b) modified algorithm

Measurement of element Φ64 were performed in the same way as for the master. The traditional method was compared with the improved one, and the changes in the amplitude of the second harmonic C_2 (fig. 7a and 7b) were analyzed. The obtained results confirm greater resistance of modified algorithm to the eccentricity. Furthermore, by comparing pairs of charts in fig. 5 and fig. 7 it can be confirmed that the errors caused by applying the typical algorithm depend on the diameter (fig. 5a and fig. 7a), while the efficiency of improved algorithm does not depend on the section size (fig. 5b and fig. 7b). Similarly, as shown in fig. 5b, the increase of C_2 observed in figure 7b along with increase of e is the result of non-linearity of the probe, not by calculation method.

Measurements of the third element (Φ90, oval) were performed a bit differently as it was expected that the second harmonic causing by eccentricity would suppress or enhance true out-of- roundness of examined oval section. Therefore, the element were displaced from the axis of rotation in two directions respectively – along longest diameter (parallel to the X axis), next along shortest diameter (parallel to the Y axis).

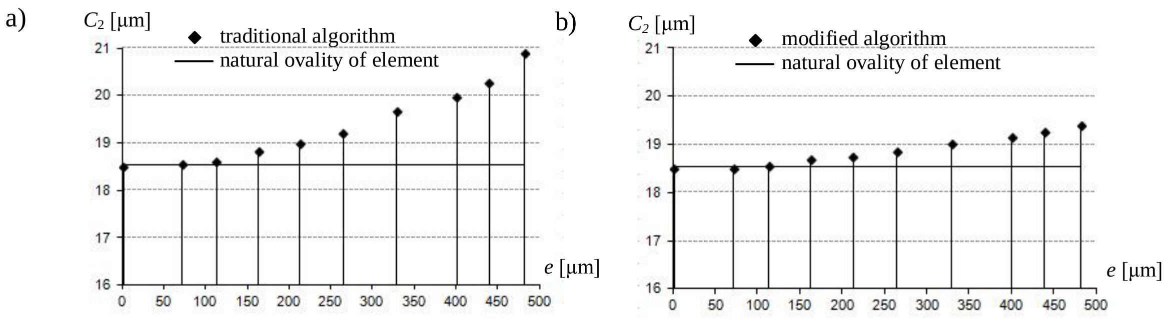

Fig. 8. The influence of eccentricity of cross section Φ90 along X axis on the 2nd harmonic a) traditional, b) modified algorithm

The results shown in figures 8 and 9 confirm the predictions. They demonstrate that in case of ovality, eccentricity can cause both an increase and a decrease of results of roundness deviation measurement. Therefore, the measurement error can take both positive (fig. 8) and negative (fig. 9) values, depending on the angle of eccentricity. In case of applying traditional algorithm the absolute value of C_2 measurement error reached 2,5 µm (fig. 8a), while by applying new algorithm it did not exceed 0,9 µm. As in the previously described measurements, changes in C_2 observed in fig. 8b are mainly caused by non-linearity of the probe.

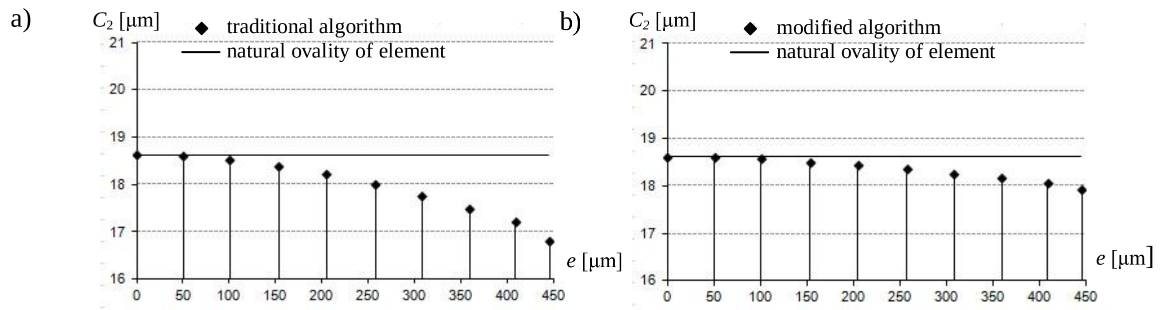

Fig. 9. The influence of eccentricity of element Φ90 along Y axis on the 2nd harmonic: a) traditional, b) modified algorithm

VI. Conclusions

Results of roundness measurement with standard Form Measuring Machines depend on examined element position in relation to the axis of rotation. The computational algorithm proposed by authors eliminates this drawback so results become resistant to the eccentricity. The simulations proved the efficiency of this algorithm even in occurrence of very large eccentricity (500 µm). Several empirical experiments confirmed the theory. The benefits resulting from applying the proposed algorithm are greater, the smaller the diameter of measured object and larger eccentricity. Performed experiments revealed that the probe non-linearity is the major source of errors but this issue is easy to solve numerically. However, to assure very high resistance on eccentricity, FMM machine should provide an adequate signal resolution and ensure imperceptible stick-slip vibration during all scanning process.

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