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The Centerless Measurement of Roundness with Optimal Adjustment

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Abstract. A new metering and data-processing method for the centerless roundness measuring, using corrective adjustment, is scientifically developed. In this paper, a mathematical model based on numerical (iterative) method and harmonic analysis, which additionally considers the reposition of the prism planes contact points with the component part by rotation, is proposed. In accordance with practical measurements and modeling, a possibility of consistent error minimization and improving accuracy of the centerless roundness measuring is found.

1. Introduction
The form testing of the machine or mechanism components surface is an important task today which has always attracted the attention of the specialists. Rotary bodies form accuracy in the cross-section is normalized by a special index “roundness” which indicates to what extent actual profile of the product differs from the reference circle. Standard ISO 12181-1:2011 recommends Minimum Zone Tolerance Circle as a basic variant of the measurement reference, but the usage of the identified derived elements in the form of superimposed external and inner circles (Maximum and Minimum Inscribed Circles) or central Circle Least Squares Estimate (LSE) is also considered acceptable. The choice of the specified reference circles depends on the functional purpose of the machine or mechanism components.

Different accuracy, efficiency and control condition requirements caused the development of a wide range of measurement methods and instruments each of which cannot be universal [1]. Methods of radius, coordinate and differential roundness measuring are well-known. Each of these methods has its own peculiarities and involves the use of different measuring instruments and results processing algorithms. The following is a short review of the methods from the point of view of their application to the specific control conditions.

The radius method means the usage of the precise rotation of roundness measurement instrument spindle with the small linear displacement sensor which contacts with the measurable component. Currently, high accuracy of roundness measuring is promoted by the roundness measurement instruments produced by Taylor Hobson (UK) under a trademark «Talyrond». If there is a misfit of spindle and workpiece axes of rotation then systematic inaccuracy appears and it is corrected with pre-centering and statistical analysis of the results based on harmonic analysis [2, 3]. The characteristic of the precise roundness measuring instruments is special placement and highly qualified staff necessity; there are also size and weight restrictions for the measured parts; and the high cost of the equipment of this type.

The coordinate measuring method is performed by Coordinate Measuring Machines (CMM) using special mathematical apparatus for result processing. Typically, the geometric image of the ideal...
components is created, then this image is corresponds to the real coordinates and the firm deviations are calculated. The important feature of the coordinate measuring method involves the irregularity of measured points position at the roundness chart, as it was mentioned in the research paper [4]. Using contact measuring method, accuracy and efficiency of CMM is considerably inferior to roundness measurement instrument with precise rotation.

When using the differential method, not absolute values of the investigated variable are defined but the difference between its consecutive values pulled apart with the definite interval. Moreover, analytic dependence between measured and desired quantities is unknown. Under the factory conditions for roundness measuring the devices with two-point contact (micrometers and gages) and three-point contact (different combinations of the prisms and small linear displacements sensors) are mainly used. It is the latter type of measuring that the centerless method under review is relevant to.

Instruments for the centerless measuring are generally like different combinations of prisms and small linear displacements sensors. The instruments with prism angle of 60, 90 or 120 degrees or the measurement direction of which is the same as prism bisectrix of angle are most common. The prisms with regulated expansion angle and sensor change position are also known. Such devices have a simple construction, high reliability and small size.

The main point of the centerless measuring method is that the product rotates and locates on the prism planes actually with the measured surface, and the small linear displacements detector fixes the roundness. The main disadvantage of this scheme is the systematic measurement inaccuracy which is up to 100 percent according to the different estimates [5]. Despite of the obvious advantages of this device – the simplicity and high efficiency – it is this reason that limits its operation.

The certain attempts to minimize the systematic measurement inaccuracy in terms of device construction solutions and the development of special measurement result processing procedures only partially solved this problem [6]. The main difficulty involves development of a mathematical model for measuring with high degree of adequacy. Therefore, a new centerless measuring model using numerical techniques and harmonic analysis is proposed in this paper. Due to this model the modeling for the actually measured details is done and the opportunity for systematic measuring inaccuracy minimizing is proved.

2. Argumentation and development of the mathematical model of the roundness centerless measuring.

The main feature of the centerless measuring is that the device sensor reading data and actual circular deviation value are non-linearly related, that is, there is a systematic inaccuracy. This inaccuracy is due to the measuring scheme itself and therefore it cannot be entirely precluded by the constructive solution or mathematical data processing. The principle of the measuring process is that the item locates on the prism planes actually with the measured surface. Consequently, the error of locating leads to repositioning of detail profile center and thus, changes the distance to the measuring sensor. The device detects these changes as well as surface form deviation. A specific device with the fixed prism angle value and sensor position has a different measurement error for different harmonic components in the profile. Since the product profile is described by superposition of harmonicas with different amplitudes and initial phases, systematic measuring inaccuracy minimizing is a complex mathematical problem.

The known mathematical model of centerless measuring presented in the paper [7] means invariability of the detail contact points with prism planes in the course of control. These dependences are true only for individual harmonicas since they do not consider their initial phases and that prevents from superposition principle proper using. The results obtained from this model are special and that makes their application challenging.

A new roundness centerless measuring model which is more adequate to a real process and focused on numerical methods and harmonic analysis is developed. Mathematical description of a measuring process is considered in three stages: detection of the profile center circle center after locating (for
each detail current position); definition of the radii of the profile points measured by the sensor; resulting roundness estimation by the measured points.

In the paper [8] it is shown that the detail crossing profile is most accurately described by a trigonometric polynomial. Values of amplitudes and harmonics initial phases are obtained with harmonic analysis of real parts profiles. Thus, it is possible to model both a specific part profiles and profiles of specific kit of parts. In polar coordinates the profile is defined in the following way:

\[ r = R + \sum_{n=2}^{p} a_n \cos(n\varphi - \varphi_n), \]

where, \( R \) is central circle radius; \( a_n, \varphi_n \) is the \( n \)-harmonic’s amplitude and initial phase; \( p \) is a maximum number of relevant harmonics; \( \varphi \) is a vectorial angle.

At the first stage locating inaccuracy is defined, which makes for departure of actually achieved part location from nominally cylindrical part of radius \( R \) without form deviation. In such a case, in a part cross-section the required center position (point 0) is uniquely determined by the radius \( R \) and the prism angle \( \alpha \) (figure 1).

![Figure 1. Measurement calculating model.](image)

At the second stage we define radii \( r_2 \) of the measured profile points after locating. The initial values are coordinates of the profile central circle centre \((\Delta, \nu)\), obtained at the first stage, and the radius \( r_1 \) of the part profile points.

The third stage concerns with the roundness deviation determination – it is the maximal distance from profile points to the reference circle. The easiest is to find the roundness deviation for the Least Squares Circle (LSC) [8]. If the center of the LSC of the out-of-roundness coincides with the origin of the coordinate system, the roundness deviation is the difference between the maximum and minimum radii. Otherwise, it is required to determine additionally the coordinates of the LSC center and then the roundness deviation. To find the roundness deviations of the Minimum Zone Tolerance Circle or Maximum Inscribed Circle and Minimum Circumscribed Circle, it is possible to apply the techniques stated in works [9, 10].

3. The measuring and simulating of the centerless roundness measuring.

The proposed strategy for the centerless roundness measuring of the product with corrective adjustment assumes repeated measurement of one product. The first measurement allows revealing harmonic structure of the profile to a first approximation. These data are used for simulation by the developed model, which result becomes a new device setting. After re-measuring to the accepted
setting the received values of the harmonic structure and roundness are comparing to the original ones. If the roundness does not decrease, it is considered that setting parameters are optimal. Otherwise, the process of simulating and corrective setting repeats. Generally, in practice, the process of the corrective setting is limited by two or three measurements.

On the basis of mathematical simulation of the centerless measuring is developed the algorithm and the program in C++. The algorithm includes two cycles: to set a profile by the angle \( \varphi \) with the variable \( j \) distributing from 1 to \( m \) (\( m \) – number of points on the profile); product rotation by measurement by the angle with the variable \( j \) distributing from 0 to \( 2\pi \). During the first cycle the cross-section profile of the product is formed as a set of radius-vectors \( r_i \) based on the original data \((n, a_n, \varphi_n)\) concerning the roundness harmonic structure. The second cycle calculates basing error and measures radii \( r_2 \) of the profile. At that the number of initially set points of a profile and number of the measured points may not coincide. According to the simulating results it is possible to find in an interactive mode the optimum device settings on \( \alpha \) and \( \beta \) angles. The harmonic analysis, centering of the out-of-roundness and calculation of the roundness deviation by various techniques are considered to be known and the scheme shows them conditionally.

Made numerical experiments demonstrate that by using of the single prism with a constant angle and the angular position of the sensor it is not possible to provide both an acceptable measurement error for all harmonics and a constant measurement error for the first 20 harmonics. This result corresponds with similar data presented in the study [6]. The systematic error is about 5% for the 9th harmonic and up to 105% for the 8th harmonic. The received results can be used by the device setting only by the single dominant harmonic in the profile but this is rare state in the contemporary manufacturing technology. The superposition principle by the centerless measurement simulating is not observed due to system nonlinearity. Therefore the recommendations for the certain harmonics do not allow reducing the measurement error in the real production.

The measurement and simulating for 50 external racers with a diameter of 30 mm were made with the tolerance roundness of 0.002 mm with the purpose to research the systematic error and its reduction methods. Sample measurements which set the valid profile, were carried out on a micrometric out-of-round gage Talyrond 30. Prism angle varied of \( \alpha = 60, 90, 120^\circ \) and the sensor angle varied of \( \beta = 0, 15, 30, 45, 60, 75^\circ \). Figure 2 presents an average ratio error and figure 3 reflects results for a standard measurement error deviation.

The graphs show that the prism angle and the sensor angle affect the measurement error. For individual product and device settings ratio error reached 120%. For party of product the worst ratio error is 62 % and corresponds to the parameters \( \alpha = 120^\circ, \beta = 75^\circ \), the best ratio error is 17.5% for the parameters \( \alpha = 90^\circ, \beta = 15^\circ \). The standard deviation for these setting variants was 26% and 14.5% correspondingly. Thus, the optimal setting for the product kit can simultaneously reduce the average systematic error and its range. The minimum value of the standard deviation does not always correspond to the minimum average error. However, this is important only by the optimal device setting for the specific product kit.

The above presented measurements were performed for precise ball bearing product of the small roundness compared to its diameter. Additional measurements for the less precise product with a higher roundness deviation established that for them the systematic measurement error increases slightly. However, the general pattern of the optimal setting for measurement process stays correct.

Not only device setting for product kit was carried out for the data, but the setting for every product separately was made accordingly to the reasonable strategy for corrective setting. Optimal setting provided an average error about 4.11% and the standard deviation about 4.12% for 50 components. The choice of the prism angle was also limited only by three values of \( \alpha= 60, 90, 120^\circ \). Obviously, the finer device setting according to the prism angle and the sensor angle will allow reducing the systematic measurement error more effectively. The complexity by such measurements increases, but the simulation by the modeling program develops much faster than the device measurement itself.
Therefore, centerless measurement in its efficiency will hold on to the Rotational datum method and the Coordinate Measuring Method.

4. Abstract
The analysis showed that the measured roundness value in most cases exceeds the actual value. When monitoring the probability of making $\alpha$-error increases. At the same time, if the measured roundness value is placed in the tolerance, we can guarantee a minimum probability of $\beta$-error. This is particularly true when monitoring mass-produced product, e.g., in car and ball bearing industry.

Our research suggests that the centerless roundness measurement of the prism with small linear motion sensor has a systematic error. It depends on the harmonic content of the product form deviations. The superposition principle for the harmonics is not observed due to system nonlinearity.

Ratio error in the experiments reached the maximum 120%. On the other side the device settings such as the prism angle and the sensor position also contribute to the systematic error. The optimal device setting helps to reduce the measurement error which will not exceed the amount of 5%. It is
reasonable to complete settings on the basis of simulating by the proposed algorithm in several stages. Optimal setting parameters can be determined for a separate product and for the product kit.

5. Conclusion
The new method of the centerless roundness measuring with corrective adjustment using a new mathematical model can effectively reduce systematic error. In this case, centerless measurement is a good alternative to the precise roundness measuring indicators or to the Coordinate Measuring Machines due to its accessibility to the users. Being inferior to a certain degree to these methods in precision, centerless measuring has high efficiency, low cost and does not require highly qualified staff. It is recommended for the control of the mass-produced product with the high and medium accuracy, both in labs and at factories.

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