# Estimation of the uncertainty of the roundness measurement with a rotary sensor instrument 

# Szacowanie niepewności pomiaru zarysu okrągłości z wykorzystaniem przyrządu z obrotowym wrzecionem 

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#### Abstract

The paper presents the estimation of uncertainty of roundness measurement using the Talyrond 73 by analyzing the sources of measurement errors such as measuring noise, signal drift, radial spindle error, repeatability, signal amplification error and uncertainty of measurement standards. The study included the following measurements: roller bearing, glass hemisphere and flick standard. KEYWORDS: roundness profile, uncertainty


In evaluating the quality of machine parts, apart from the dimensions, it is fundamental to control quality of its surface. The quality of the surface are evaluated with the use of parameters describing so-called geometrical structure of the surface. One of the components of this structure are form profiles. In the case of cylindrical elements following form deviations can be distinguished: roundness, cylindricity, straightness of the cylinder generatrix and flatness of the cylinder face. Usually, the the accuracy of cylindrical elements is evaluated with the use of roundness deviation.

## Methods of measurement of roundness profiles

Considering laboratory and industrial conditions, two main groups of methods of roundness measurements can be distinguished: a radius-change method and a multipoint one. It is also possible to determine roundness deviation with the use of coordinate measuring machines.

The simplest way to measure the roundness deviation is to measure it in the claw device. In this technique, a rotary cylinder is measured, which is fixed in the fangs and the sensor is perpendicular to the axis of the element. Another way is to measure the roundness deviation with using the radius-change instrument. Radius change instruments can be divided into two groups: rotary sensor and rotary table instruments.

The multipoint methods can be divided by the number of measurement points and support points into: 2-point, 3 -point and $n$-point [1-2].

An important advantage of the application of the coordinate measuring technique to measure the roundness deviation is the ability to conduct comprehensive analysis of dimensions and form tolerances of the element.

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## Uncertainty as a component of the measurement result necessary to assess compliance with the specification

Measurement uncertainty in accordance with PKNISO/IEC Guide 99: 2010: International Metrology Dictionary - Basic and General Terms and Terms Related to Them (VIM) is a non-negative parameter characterizing the dispersion of the magnitude values assigned to the measurand, which is calculated on the basis of the obtained information [3]. The GUM Guide defines the uncertainty of measurement as a parameter associated with the measurement result, characterizing the dispersion of values that can reasonably be attributed to the measured value.

According to the guidelines of the GUM guide, uncertainty components are calculated using two methods:

- A - uncertainty components are calculated using statistical methods,
- B - components are estimated by other methods.

Unlike the A-type method, based on the distribution of measurement results, the B-type method is based on the calculation of uncertainty components based on a priori data distributions by analysis based on all available data with possible input variations such as previous measurements, the data obtained during the calibration, experience metrologist based on the knowledge of the measurement process and the characteristics of devices and standards used in practice [4].

Uncertainty of measurement is a component of the measurement result necessary to assess conformity with the specifications of manufactured products. The design technical documentation of the product uniquely identifies the limits of tolerance. Measurements of the object produced are uncertain, which results in a division into a specification zone, a nonconformity zone, and a uncertainty zone for which conformity or its absence cannot be determined [5-6].

## Measuring instrument and standards

The uncertainty budget for roundness profiles measurement presented in the article refers to the results of measurements performed on the instrument Talyrond 73 by Taylor Hobson with a rotary spindle with a length of 64 mm . The instrument is located in the Laboratory of Computer-Aided Measurements of Geometrical Quantities of the Kielce University of Technology. Analysis of the measured profile with the appointment of the parameters is carried out using software ROFORM. For calibration of the instrument was used:

- standard in the form of a glass hemisphere,
- flick standard


## Analysis of basic error sources

The structure of the sources of errors in the measurement process of roundness with the radius change method by using a rotary sensor instrument consists of the following basic categories:

The measurement noise consists of the noise of the electronics connected to the measuring instrument and the noise resulting from the vibrations occurring in the spindle drive system. The measured noise value of the electronic components is only a small percentage of the total measurement noise that can be determined by measuring the glass hemisphere standard after correcting the spindle error (fig. 1).


Fig. 1. Noise of: a) electronic circuit, b) total measurement
Signal drift is that there is a significant difference between the initial contour point and the end point. This error is the sum of the sensor signal drift and the unstable attachment of the measured object on the measuring table of the instrument (fig. 2).


Fig. 2. Signal drift
Radial spindle error determined during the calibration process using a glass hemisphere standard using a multi-step method based on multiple measurements rotated every $30^{\circ}$ on the measuring table of the instrument. The roundness profile is a combination of spindle rotation errors and standard roundness profile. The measurement result of the glass hemisphere
standard with spindle error correction and without correction is shown in fig. 3 [7].


Fig. 3. Roundness profiles of the hemisphere glass a) without correction, RONt $=41 \mathrm{~nm}$, b) with spindle error correction, $R O N t=8 \mathrm{~nm}$

Repeatability based on 30 part measurements (cylindrical bearing roller). A series of measurements is performed in such a way that before each measurement the measured element is attached to the worktable of the instrument. The standard deviation of the measurement series thus made is approximately 10 times greater than the standard deviation of the measurement series without removing the measured element from the worktable. In the first method of determining repeatability, the dispersion component resulting from the fixing of the measured element is taken into account.


Fig. 4. Histogram of the repeatability of the measurement results obtained with each element attachment on the measuring table


Fig. 5. Roundness profile of the flick standard
Measurement of the signal amplification error determined during dynamic calibration using a flick standard. Using this method allows setting high frequency responses (fig. 5).

Uncertainty of a standard associated with the calibration process of a flick standard and standard in the form of a glass hemisphere.

## Measurement uncertainty budget

The measurement equation for the correction resulting from the measurement conditions is:

$$
R O N t=\overline{R O N t_{p}}+\delta_{n}+\delta_{c}+\delta_{s}+\delta_{m}
$$

where:
RONt - roundness deviation,
$\overline{\text { RONt }_{p}}$ - average results of measurement of deviation of roundness,
$\delta_{n}$ - correction due to measurement noise,
$\delta_{c}$ - correction resulting from signal drift,
$\delta_{s}$ - correction due to spindle error,
$\delta_{m}$-correction resulting from calibration of the gain.
The standard uncertainties of the individual components were determined as follows:

- Uncertainty due to limited repeatability measured on the basis of a series 30 measurement of an element with roundess deviation value comparable to the value of elements for which the uncertainty of measurement will be estimated. The calculated standard deviation will be a component of uncertainty resulting from lack of repeatability.
- Uncertainty resulting from measurement noise based on measurements of the glass hemisphere, after filtering the component representing spindle error and standard error with a filter of $15 \div 500$ upr.
- Uncertainty due to signal drift, determined on the basis of the research conducted. Maximum closing error does not exceed 100 nm . The $U$ type distribution is assumed.
- Uncertainty resulting from the spindle error determined by measurements. The maximum spindle error does not exceed 30 nm . A normal distribution of the interaction of this error with the outline of the measured element is assumed.
- Uncertainty due to calibration error of the sensor amplifier determined on the basis of uncertainty of flick standard calibration. According to calibration certificate data, the calibration uncertainty is $1 \%$ of the calibrated flick standard.

TABLE. Measurement uncertainty budget of roundness deviation

| Component <br> name | Metodh | Distribution <br> type | Limit <br> of <br> variation, <br> nm | Uncertainty <br> component, <br> nm |
| :--- | :---: | :---: | :---: | :---: |
| Repeatability | A | Normal | - | 15,9 |
| Noise | A | Normal | 25 | 8,3 |
| Drift error | B | U | 45 | 31,5 |
| Spindle error | B | Uniform | 30 | 18,0 |
| Signal <br> amplification <br> error | B | Uniform | 5 | 3,0 |
| Standard complex uncertainty, $U_{c}$ |  | 40,6 |  |  |
| Extended uncertainty $(k=2), U$ |  |  |  | 81 |

Based on these assumptions, the budget for the uncertainty measure of the deviation of the roundness was drawn up as shown in the table. It concerns measuring elements, the roundness deviation value of which does not exceed $1 \mu \mathrm{~m}$, i.e. products with high dimensional requirements.

Standard complex uncertainty was calculated from the formula:

$$
u_{c}=\sqrt{u^{2}\left(\overline{R O N t_{p}}\right)+u^{2}\left(\delta_{n}\right)+u^{2}\left(\delta_{c}\right)+u^{2}\left(\delta_{s}\right)+u^{2}\left(\delta_{m}\right)}
$$

In contrast, the expanded uncertainty was determined for $k=2$ with a probability of $95 \%$.

The uncertainty of the budget presented shows that the dominant components of uncertainty are signal drift error and spindle error. In the case of measurement of elements with greater deviation, the value of the component resulting from the calibration error of the sensor will increase in proportion to the value of this deviation and will be the dominant component of the uncertainty balance.

The use of programmable spindle error correction, signal drift and the removal of dominant components associated with the spindle drive transfer can be used to measure uncertainty in the measurement of roundness deviation. These capabilities are included into ROFORM software, spindle error correction, signal drift correction, and the removal of the harmonic components associated with the spindle drive from the amplitude spectrum. In the case of applying of these corrections the main uncertainty component will be the one that results from the lack of repeatability.

## Conclusions

Rotary sensor instruments using the radius change method for measurements of roundness profiles are a group of reference devices due to the low values of measurement uncertainty achieved.

It is recommended to use these instruments for measuring the components that should meet highest demands relating to their accuracy.

An important element of metrological monitoring of this type of instrument is the periodic checking of the spindle error by the multistage method. This allows for the introduction of the program correction of this error and dynamic calibration using the flick standard.

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