

The Influence of Machine-Part Measuring Strategies for Coordinate Measuring Devices on the Precision of the Measured Values

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Abstract: This article describes various strategies of measurement and their influence on the accuracy of measured parameters. Maintaining and, in particular, increasing the accuracy of production plays a key role in production companies. Coordinates-based measuring technology enables measuring parameters with a high degree of accuracy, depending on the measuring method used and specific conditions. The scanning system available to the CMM has a significant impact on the result of the measuring. The measuring experiment is executed on a calibration ring of a known size using the PRISMO Ultra coordinate-measuring machine. The goal of the experiment is an analysis of the effect of measuring strategies while measuring a machine-part on the values of roundness and diameter of the calibration ring. This includes a change of measuring method, scanning rate, diameter of the scanning stylus, as well as the evaluation filter. The RONDCOM 60A high-precision measuring device is designed to establish reference values of roundness for the proposed experiment measurement. This paper focuses on the analysis of the impact of conditions of measuring roundness and diameter of the calibration ring on the results of the measurements.

Keywords: coordinate measuring; measurement strategy; accuracy; roundness; diameter

1 Introduction

Production technologies, as well as measuring methods, are currently showing a trend towards increased accuracy. The required geometric and dimensional accuracy of a produced machine-part depends to a large degree on the accuracy of the machine tools and their abilities. It was a subject of the study [1, 2, 3, 4]. The precision of the produced part also determines the conditions of its assemblage and, therefore, the outcome of the assembly process. Along with increased accuracy practical requirements also arose for controlling highly precise dimensions. Coordinate measuring machines (CMM) are often currently used to

cover this need [5]. These machines are highly precise with a low degree of measurement uncertainty. The method of scanning points has a significant effect on measurement accuracy, evaluation methods and measurement conditions [6, 7, 8].

2 Description of Experimental Portion

2.1 The Characteristics of the Measured Part and the Measuring Device

A calibration etalon, a ring of a known diameter of 25 mm (Fig. 1) was used for the execution of the measuring plan. This etalon was awarded a calibration certificate issued by Kontroltech, s.r.o., Dubnica nad Váhom, a calibration company. The calibration center is a calibration laboratory approved by the Slovak National Accreditation Service, according to the STN EN ISO/IEC 17025:200 standard. The calibration ring has a precisely defined internal diameter that was measured in the calibration center at the $h/2$ defined height. The key parameters of the ring are shown in Table 1.

Table 1
Key parameters of the ring declared by the calibration center

Ring	Nominal size D [mm]	Actual size D [mm]	Coordinates
1	Ø25.0000	Ø25.0046	x, y



Figure 1
Inspection calibration ring

The measuring devices used for the execution of this experimental work were:
RONDCOM 60A
CMM ZEISS PRISMO Ultra

These devices are located in Heavy Laboratories of the Faculty of Materials Science and Technology in Trnava of the Slovak University of Technology in Bratislava, Slovakia.

RONDCOM 60A (Fig. 2) is a special device for measuring roundness with high precision. The machine enables high productivity of measurements due to its automated settings. Measuring takes place on a special table of the machine with air-bearings that have a rotational precision up to 20 nm, ($MPEE = 0.015 + 6H/10000 \mu\text{m}$), where H is height from table surface to measuring point. Its granite construction is a sign of the long-term stability of the machine [9].

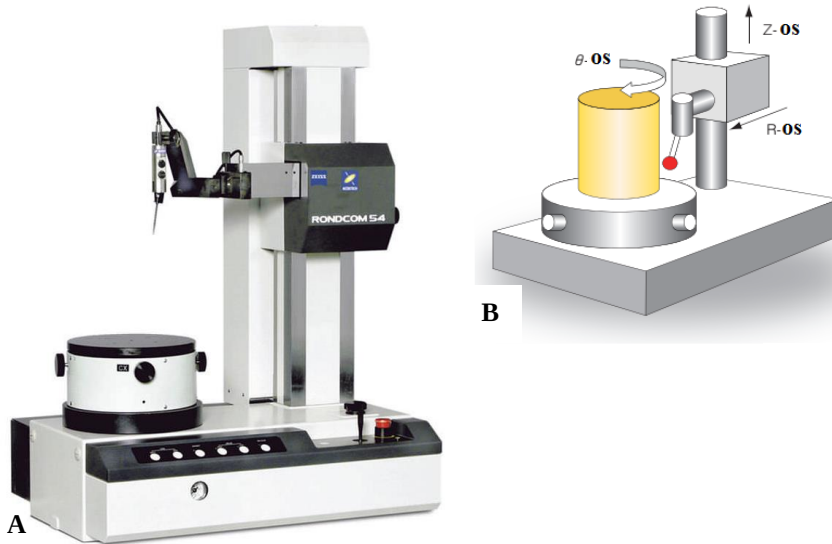


Figure 2

Measuring equipment: A – Roundcom 60A. B – Measurement principle

CMM ZEISS PRISMO Ultra - enables maximum precision at high-speed scanning. The device uses a computer-controlled correction of all dynamic influences on the measuring device.

Device construction [10]:

- A very stiff lightweight portal, thanks to the combination of ceramics and composite materials based on carbon fibres.
- All axes are on air-bearings. Axis X: 8 air-bearings, axis Y: 8 air-bearings, axis Z: 5 air-bearings.
- Elastomer buffering of vibrations and covered conductor paths, including measuring gauges for use in the vicinity of production.

CMM PRISMO Ultra by ZEISS (Fig. 3) is therefore ideal for tasks in the area of research, development and quality control, as well as for calibration of test units

and calibers. The relation (CARL ZEISS, 2015): $MPEE = \pm (0.5 + L/350)$ [mm] establishes the maximum permitted error (MPEE) [11].

A VAST Gold fixed measuring sensor is part of the coordinate measuring device. This measuring sensor is capable of scanning with high precision through a contact method. Coordinate measuring devices may additionally be equipped with rotary tables, particularly for measuring rotating parts such as shafts, bearing rings, gear rings and transmission boxes. The RT-AB rotary table is set on air-bearings, functions quietly, has excellent radial and axial runout values and direct dynamic drive [10, 12].

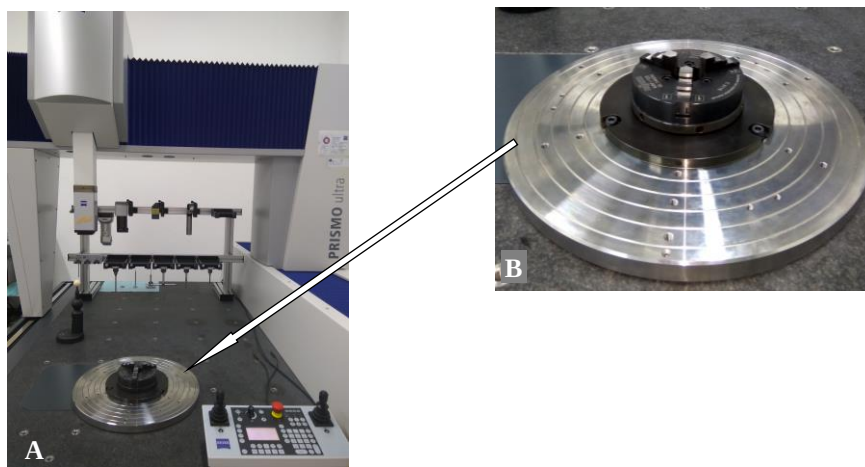


Figure 3

Measuring equipment: A – CMM PRISMO Ultra. B - Rotary table

2.2 Method and Structure of the Measurement

Measuring process using *RONDCOM 60A*:

1. Setup of the scanning system for the Ø1.5 mm sensor.
2. Leveling of the rotation table.
3. Calibration of the scanning system.
4. Setup and fastening of the measured part.
5. Leveling the part.
6. Creating a new measuring plan in the *ACCTee* program.
7. Defining measurement parameters in the *ACCTee* interface.
8. Execution of the measurement.

Measuring parameters for identifying roundness using the *RONDCOM 60A* device:

- Measuring method: semi-automatic.
- Number of scanned points: 3600.

- Measuring rate: 2 mm.s^{-1} , 4 mm.s^{-1} , 6 mm.s^{-1} , 8 mm.s^{-1} , 10 mm.s^{-1} .
- Measuring position: 5.10 mm in the Z axis.
- Evaluation method: Gauss.
- Filter used: Gauss, Spline.

Measuring process using PRISMO Ultra CMM:

1. Scanning strategy – creation of a measuring plan.
2. Setup of the scanning system for $\varnothing 1.5 \text{ mm}$, $\varnothing 3 \text{ mm}$ and $\varnothing 5 \text{ mm}$ sensors.
3. Reference sensor calibration.
4. Scanning system calibration.
5. Rotary table calibration.
6. Fastening the part into the rotary table clamps.
7. Creating a new measuring plan in the CALYPSO program.
8. Defining measuring parameters and evaluation in the CALYPSO interface.
9. Execution of the measurement.
10. Comparative analysis of scanned data against reference values.

A structure of experimental measuring was prepared for better orientation in the experiment (Figure 4). The structure clearly depicts the methods used for scanning: *VAST Gold* sensor / RT; monitored parameters – roundness/diameter; a change of the sensor radius $\varnothing 1.5/ \varnothing 3/ \varnothing 5$; a change of measuring rate; a change of evaluation filter - Spline/Gauss.

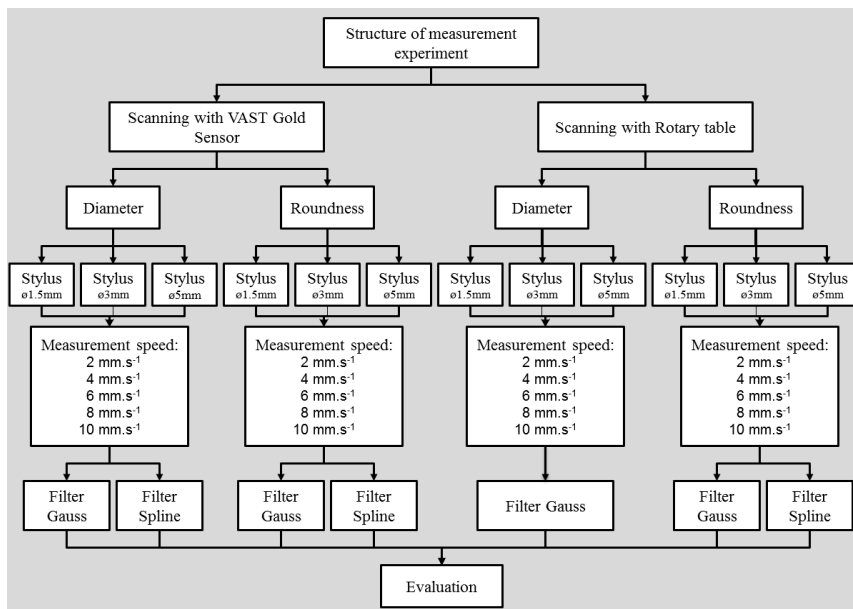


Figure 4
Structure of measuring

2.3 The Execution of the Experimental Portion of the Work experimentálnej časti práce

2.3.1 Preparation and Measuring Conditions

The experimental portion of the work was executed on the *RONDCOM 60A* device and is processed using *ACCTeePro* software. This software uses the *WINDOWS* operating system. It is a special software for identifying parameters of surfaces, contours and shape-characteristics of a part [9]. The device scanning system is set at $h/2$ height, meaning 4.2 mm in the direction of the Z coordinate of the calibration ring and the stylus diameter is 1.5 mm.

The experimental portion of the work was executed using the *ZEISS PRISMO Ultra* coordinate measuring device with a maximum permitted error in length measurement $0,5+L/350$ μm , a fixed *VAST Gold* sensor and a rotary table. The part was measured using a contact technology of scanning. Results of the experimental measurement are shown in Table 2.

Table 2
Conditions of the surrounding environment

Room temperature in the laboratory	+20 °C
Relative air humidity	60% ÷ 70%
Reference measuring temperature	20 °C
Sea-level elevation	100 ÷ 125 V: max. 3000 m 230 ÷ 240 V: max. 2000 m

Three scanning stylus of varied diameters were used during the execution of the experiment, according to Table 3. Calibration of scanning systems must be performed in order to achieve precise measurements. The calibration is always performed prior to the measurement of new parts and is intended to correct systemic errors using a calibration ball. The *OS_RT* scanning system, using a stylus with an 8 mm diameter, is designed for measuring and calibration using a rotary table. Calibration conditions are listed in Table 3.

Identification of sensors in the measuring plan:

- *DP_ZS_1.5* – stylus with a $\varnothing 1.5$ mm diameter,
- *DP_ZS_3* – stylus with a $\varnothing 3$ mm diameter,
- *DP_ZS_5* – stylus with a $\varnothing 5$ mm diameter.

Basic coordinate systems for the given part must be defined in the software in preparation for the CMM measurement. This process was performed by enabling the positioning of the coordinate system into the center of the calibration ring.

Table 3
Stylus calibration conditions

Sensor Diameter	Ø8 [mm]	Ø5 [mm]	Ø3 [mm]	Ø1.5 [mm]
Mode	Tenzor			
Sensor Geometry	Sphere			
Opening Angle	180°			
Dynamic Scanning	100%	100%	100%	100%
Calibration Ball Position	180° turning: 0°			
Scanning Power	200 mN	200 mN	200 mN	100 mN

The measurements of diameter and roundness of the part - calibration ring are performed three times according to the structure stipulated in Figure 4. The measuring plan consisted of the following elements:

- Plane 1, Circle 1 – form a basic coordinate system
- Circle 2, Circle 4, Circle 6, Circle 8 and Circle 10 – elements intended for measurement with the Ø1.5 mm stylus.
- Circle 2_3mm, Circle 4_3mm, Circle 6_3mm, Circle 8_3 mm, Circle 10_3mm - elements intended for measurement with the Ø3 mm stylus.
- Circle 2_5mm, Circle 4_5mm, Circle 6_5mm, Circle 8_5 mm, Circle 10_5mm – elements intended for measurement with the Ø5 mm stylus.

The ‘circle’ element must be scanned in order to evaluate roundness. An example of a settings strategy for the measurement of the ‘circle’ element is shown in Figure 5. The following parameters must be set in order to measure this element:

- Scanning rate: 2 mm.s⁻¹, 4 mm.s⁻¹, 6 mm.s⁻¹, 8 mm.s⁻¹, 10 mm.s⁻¹.
- Number of scanning points: 3000.
- Angle range: 380°.
- Filter type: Gauss, Spline.

Figure 5 shows an example of the result evaluation settings of the ‘circle’ element measurements and Figure 6 shows filter settings for evaluation. The measurement plan (Fig. 7) is created and applied to the scanning of a ring with the *VAST Gold* stylus sensor and scanning with the activation of a rotary table. Two measurement plans were created and applied with the exact same conditions for evaluation:

- measurement plan for measuring with the *VAST Gold* fixed stylus without the activation of the rotary table,
- measurement plan for measuring with the *VAST Gold* fixed stylus with the activation of the rotary table (Fig. 7).

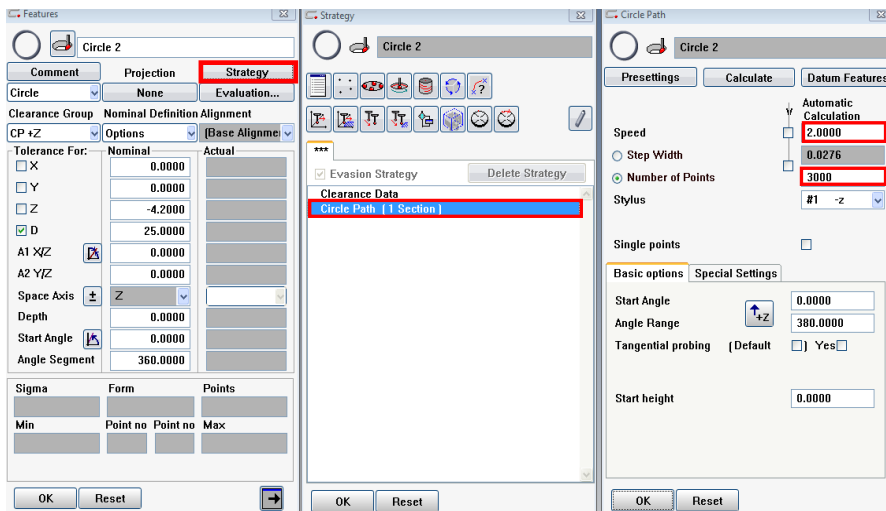


Figure 5

Settings strategy and number of scanning points in the CALYPSO interface

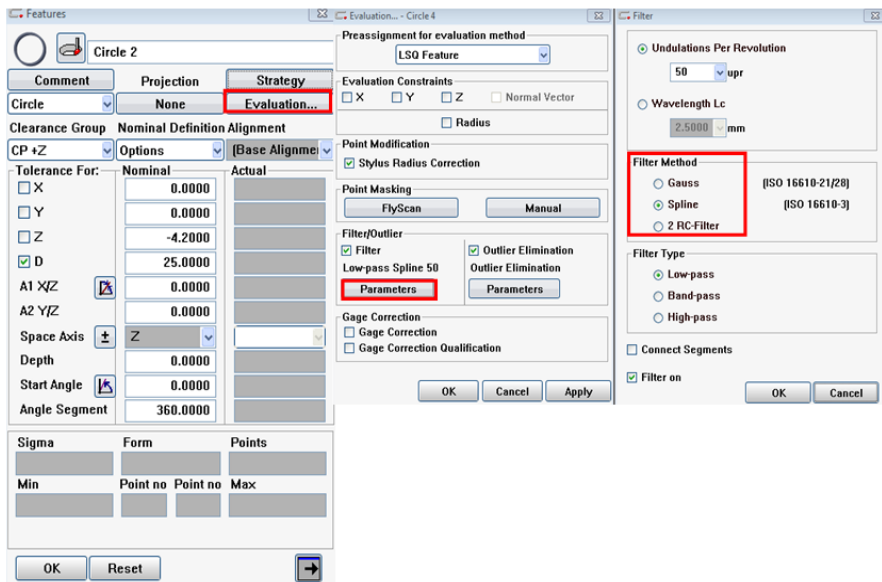


Figure 6

Filter settings for evaluation in the CALYPSO interface

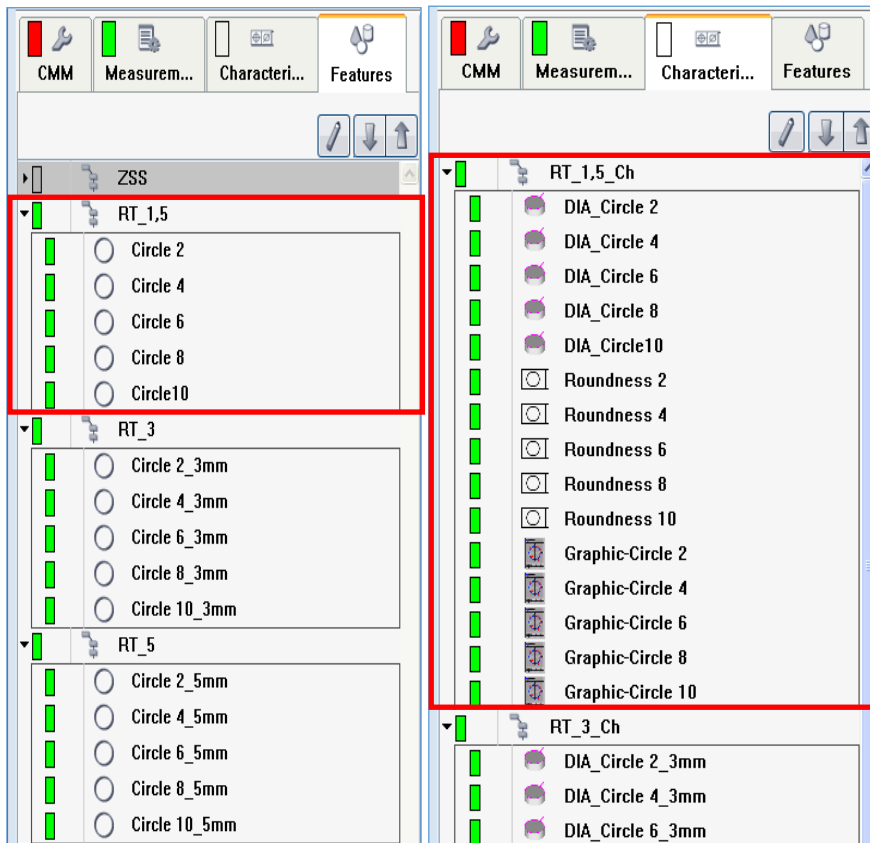


Figure 7

Overview of the measurement plan created in the CALYPSO interface: A – Element selection.

B – Measurement characteristics

2.3.2 Execution of the Measurements

The measurement process began with the calibration of the RONDCOM 60A measuring device, calibration of the PRISMO Ultra CMM scanning systems and the calibration of the rotary table that is a part of the PRISMO Ultra CMM and is placed upon the working surface of the device. The calibration of the roundness was performed using gauge blocks (Fig. 8). Calibration process of the $\varnothing 1.5$; $\varnothing 3$; $\varnothing 5$ and $\varnothing 8$ mm styli was executed using a ceramic calibration ball of 30 mm diameter. The depiction of the rotary table calibration process using a calibration cylinder is shown in Figure 9. Using the calibration cylinder, the scanning system is able to automatically determine the placing of the rotary table and its parameters.

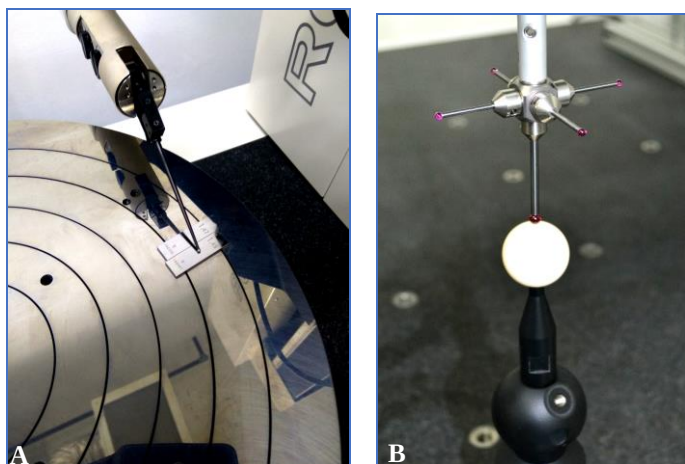


Figure 8

Calibration of the scanning systems: A – ROND COM 60A. B - CMM PRISMO Ultra

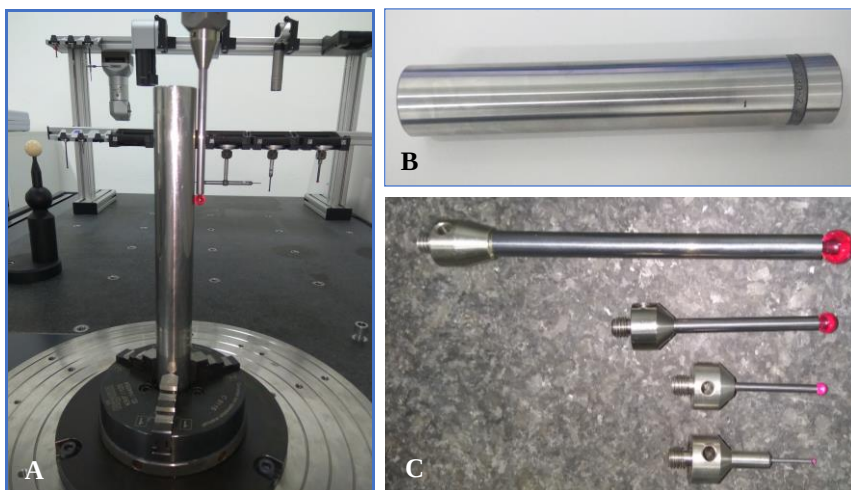


Figure 9

Calibration of the rotary table: A – calibration process. B – calibration cylinder. C – Stylus

The calibration $\varnothing 25$ mm ring was fastened to the rotary table of the ROND COM 60A circle-measuring device and secured against shifting and turning. The roundness values obtained from the ROND COM 60A measuring device are established as reference roundness values for the executed experiment. The placement of the calibration ring and the process of measuring roundness and diameter using the PRISMO Ultra CMM is depicted in Figure 10. When measuring with the use of the rotary table, the calibration ring was fastened into

the clamps of the rotary table, while in measuring using the fixed VAST Gold stylus, the ring was placed and fastened directly on the measuring table of the device. The final phase of the experiment was the setting off of the plan created in the CALYPSO interface. The scanning of the ring took place automatically through exchanging scanning stylus.

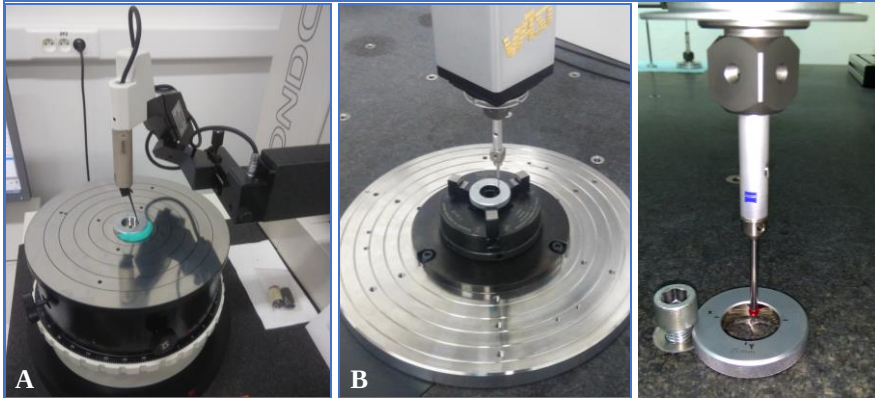


Figure 10

Execution of the measurement:

A - Measurement of the reference value using RONDCOM 60A

B - Measurement using the CMM PRISMO Ultra

2.4 Analysis and Evaluation of Results of the Experimental Work

Analysis against data scanned on the calibration ring was performed in order to analyze and evaluate the results of the experimental part of this work.

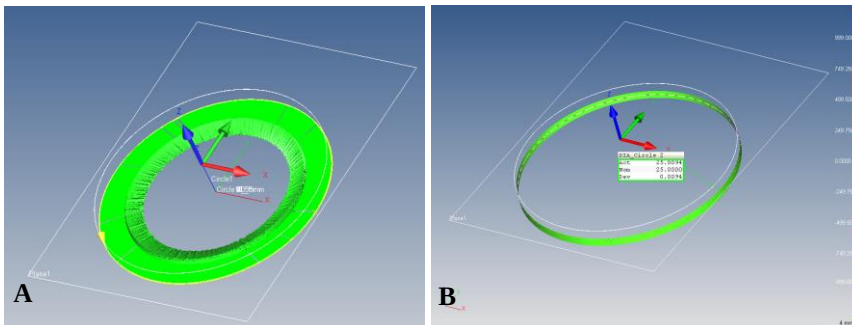


Figure 11

Measured points in the CALYPSO interface: A - Scanned element; B – Deviation of the ring diameter

A correlation between roundness tolerance and the diameter value declared by the calibration certificate was established for the values obtained from the RONDCOM 60A. After the scanning of the calibration ring, the software evaluated data in both a numeric and graphic form. The CAD window of the software provides a view of the scanned elements (Fig. 11).

2.4.1 Evaluation of Roundness Tolerance

The values measured by the RONDCOM 60A are listed in Table 4. These values were considered basic reference values for the evaluation of the roundness tolerance of the CMM PRISMO Ultra. The results of the experiment of measuring roundness obtained from the CMM PRISMO Ultra are shown in Tables 5 and 6.

Table 4
Measurement of roundness using the RONDCOM 60A – reference values

Measurement speed [mm.s ⁻¹]	Roundness [μm]	
	Stylus Ø1.5 mm	
	Filter GAUSS	Filter SPLINE
2	0.2650	0.2640
4	0.2710	0.2750
6	0.2730	0.2860
8	0.2800	0.3010
10	0.2880	0.2870

Table 5
Measurement of roundness using fixed VAST Gold stylus scanning

Measurement speed [mm.s ⁻¹]	Roundness [μm]					
	Stylus Ø1.5 mm		Stylus Ø3 mm		Stylus Ø5 mm	
	Filter GAUSS	Filter SPLINE	Filter GAUSS	Filter SPLINE	Filter GAUSS	Filter SPLINE
2	1.2760	1.2789	1.1798	1.1781	1.3686	1.3787
4	1.2592	1.2785	1.1545	1.1699	1.3455	1.3548
6	1.2312	1.2635	1.1741	1.1975	1.3643	1.3723
8	1.2322	1.2580	1.2115	1.2218	1.3872	1.3751
10	1.2368	1.2520	1.2571	1.2609	1.4114	1.4114

Table 6
Measurement of roundness with stylus scanning and a rotary table

Roundness [μm]							
Measurement speed [mm.s^{-1}]	Stylus $\varnothing 1.5$ mm		Stylus $\varnothing 3$ mm		Stylus $\varnothing 5$ mm		
	Filter GAUSS	Filter SPLINE	Filter GAUSS	Filter SPLINE	Filter GAUSS	Filter SPLINE	
	2	1.1898	1.2037	1.1686	1.1433	1.1891	1.2056
	4	1.1569	1.1768	1.0197	1.0102	1.1681	1.1705
	6	1.1588	1.1818	1.1731	1.1191	1.1874	1.1873
	8	1.1969	1.2112	1.1494	1.1092	1.2199	1.2480
	10	1.2304	1.2467	1.1713	1.1971	1.2420	1.2540

The following influences were taken into consideration when evaluating roundness tolerance:

- The effect of the measuring method on roundness tolerance while changing the scanning rate.
- The effects of the scanning stylus diameter on roundness tolerance while changing the scanning rate.
- The effect of the filter on roundness tolerance while changing the scanning rate.

The relations are shown graphically in Figure 12 a, b, c, d.

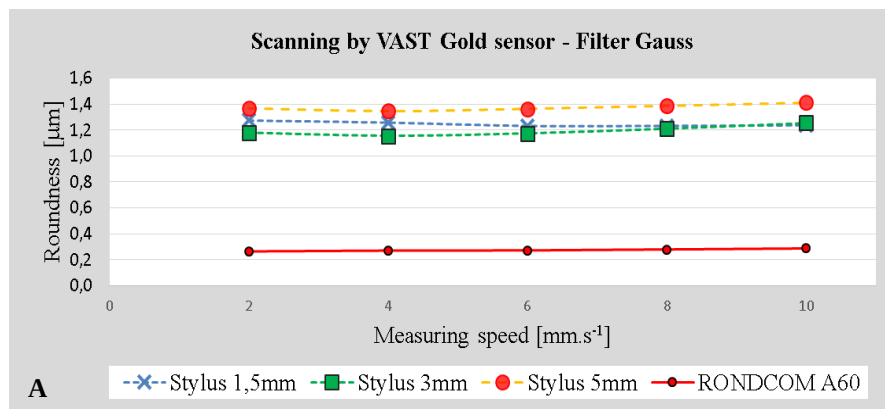


Figure 12

Evaluation of Roundness Tolerance: A – Scanning by VAST Gold sensor – filter Gauss. B – Scanning by VAST Gold sensor – filter Spline. C – Rotary table – filter Gauss. D – Rotary table – filter Spline

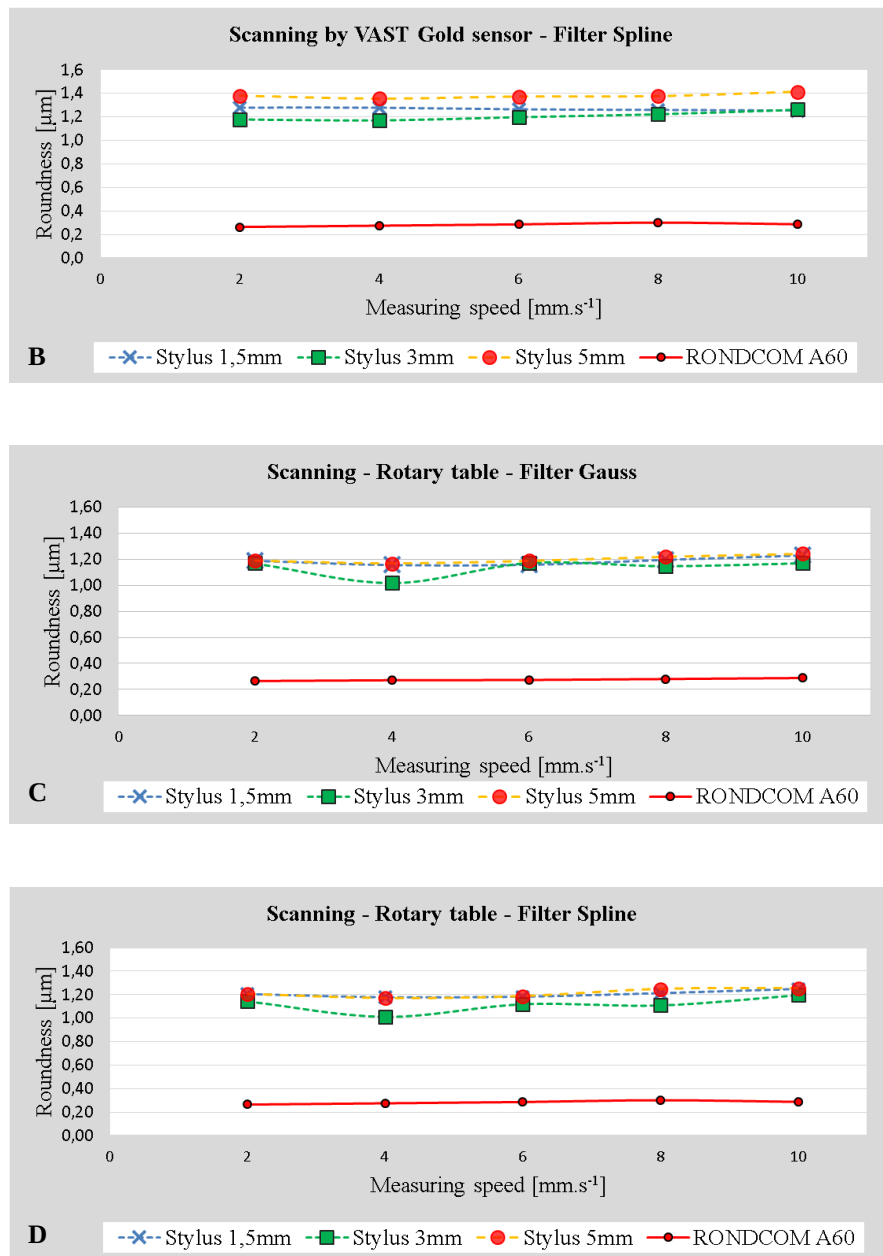


Figure 12

Evaluation of Roundness Tolerance: A – Scanning by VAST Gold sensor – filter Gauss. B – Scanning by VAST Gold sensor – filter Spline. C – Rotary table – filter Gauss. D – Rotary table – filter Spline

2.4.2 Diameter Measurement

The results of the experiment of diameter measurement measured using the CMM PRISMO Ultra are shown in Tables 7 and 8. The 25.0049 mm reference diameter of the ring was used based on the calibration certificate.

Table 7

Diameter measurement using the fixed VAST Gold stylus scanning

Diameter of ring [mm]						
Measurement speed [mm.s ⁻¹]	Stylus Ø1.5 mm		Stylus Ø3 mm		Stylus Ø5 mm	
	Filter GAUSS	Filter SPLINE	Filter GAUSS	Filter SPLINE	Filter GAUSS	Filter SPLINE
	2	25.00497	25.00496	25.00503	25.00503	25.00482
	4	25.00493	25.00493	25.00502	25.00502	25.00482
	6	25.00493	25.00493	25.00502	25.00502	25.00481
	8	25.00492	25.00491	25.00488	25.00488	25.00480
	10	25.00488	25.00488	25.00497	25.00497	25.00479

Table 8

Diameter measurement using rotary table scanning

Diameter of ring [mm]			
Measurement speed [mm.s ⁻¹]	Stylus Ø1.5 mm		Stylus Ø5 mm
	Filter GAUSS	Filter GAUSS	Filter GAUSS
	2	25.00713	25.00628
	4	25.00715	25.00637
	6	25.00716	25.00639
	8	25.00716	25.00641
	10	25.00717	25.00642

The following influences were taken into consideration when evaluating the diameter measurement:

- The effect of the measuring method on diameter measurement while changing the scanning rate.
- The effect of the filter on diameter measurement while changing the scanning rate.
- The effects of the scanning *VAST Gold* stylus diameter on diameter measurement while changing the scanning rate.

The relations are shown graphically in Figure 13 a, b, c.

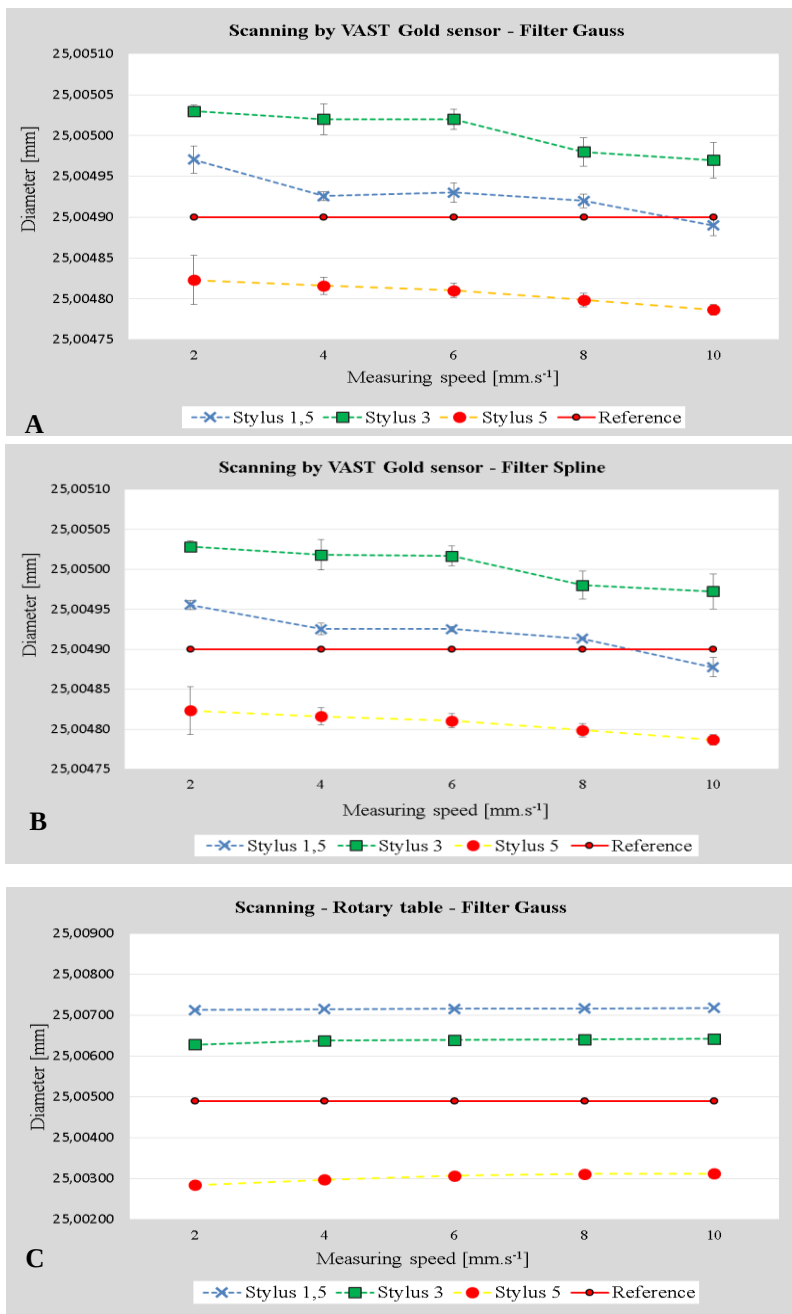


Figure 13

Evaluation of the Diameter: A – Scanning by VAST Gold sensor – filter Gauss. B – Scanning by VAST Gold sensor – filter Spline. C – Rotary table – filter Gauss

Evaluation and Conclusion

The evaluation of the extensive experiment is divided into three parts. The first part evaluates the effect of the method of measurement, the effect of the scanning stylus and the effect of the filter on the assessment of the roundness tolerance. In the second part of the evaluation, the effect of method, scanning stylus diameter and filter were established for the assessment of diameter. The last part focuses on a comparison of the graphic representation of roundness.

Roundness evaluation:

Effect of the method of measurement: measurement using a rotary table better corresponded to the reference value compared to the VAST Gold sensor method. However, the difference of roundness between both methods of measurement is within the range of $(0 \div 0.2) \mu\text{m}$.

Effect of the stylus diameter: The results from the $\varnothing 3 \text{ mm}$ diameter best correspond with the declared etalon value. The difference in the result when measuring by $\varnothing 1.5 \text{ mm}$, $\varnothing 3 \text{ mm}$ and $\varnothing 5 \text{ mm}$ stylus is $(0.1 \div 0.4) \mu\text{m}$.

Effect of the filter: The Gauss and Spline filter does not have a significant effect on roundness measurement. The maximum difference was recorded when measuring with the VAST Gold stylus at the rate of 6 mm.s^{-1} with $\varnothing 1.5 \text{ mm}$ diameter. The difference of measured values in this case was $0.0323 \mu\text{m}$. The best corresponding values for different filter evaluation were achieved in measuring roundness with a $\varnothing 3 \text{ mm}$ stylus and the VAST Gold sensor.

Effect of scanning rate: The rate of 4 mm.s^{-1} was established as the most suitable scanning rate in measuring with the rotary table and using a $\varnothing 3 \text{ mm}$ stylus. The difference in roundness between the reference value and measured value for the Spline filter was $0.7402 \mu\text{m}$ and for the Gauss filter $0.7497 \mu\text{m}$.

Graphic Comparison of Roundness

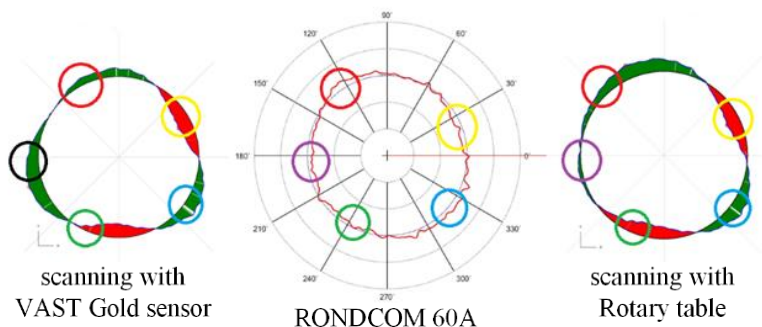


Figure 14

Graphic comparison of roundness. Scanning rate: 2 mm.s^{-1} _filter: GAUSS

Graphic results of the measurement show Figure 14 that the method of stylus scanning using a rotary table better corresponds with graphic results obtained using the RONDCOM 60A device. Circles identify similar areas in the same color. An area identified by a black circle indicates the least corresponding value.

Evaluation of the Diameter:

Effect of the method: The method of stylus scanning with the VAST Gold sensor best corresponds with the etalon value and is therefore more suitable than measurement using a rotary table.

Effect of the scanning stylus diameter: Values closest to the reference values were measured using the VAST Gold sensor at the scanning rate of 6 to 10 mm.s⁻¹ with the Ø1.5 mm stylus diameter. Diversion from the reference value at this scanning rate was a maximum of 0.03 µm.

Effect of the filter: The comparison of the Gauss and Spline filters shows negligible differences in the measurement results. When scanning using the VAST Gold sensor, the recorded divergences were in the range of $(0 \div 0.02)$ µm. With the increase of scanning rate using the VAST Gold sensor, the measured values had a decreasing tendency. When measuring using the rotary table, the measured values had the opposite tendency, meaning that the measured diameter values increased with the increasing scanning rate.

As is apparent from this experiment, to precisely evaluate roundness, the best option is to use measurement with a rotary table, Ø3 mm stylus diameter, 4 mm.s⁻¹ scanning rate and the Spline filter. To measure diameter, the most suitable combination is VAST Gold sensor with an Ø1.5 mm stylus diameter, 6 to 8 mm.s⁻¹ scanning rate and the Spline filter. However, the use of the Gauss filter does not indicate significant differences for evaluating a diameter.

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