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Metrological evaluation of a Coordinate Measuring Machine with 5-axis measurement technology

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Abstract

The 2-axis rotary probing system of a coordinate measuring machine (CMM) integrated to its three linear axes enables the machine to measure in 5-axis mode, with good potential to reduce the time of the measurement cycles, thus improving the machine performance and optimizing the measurement strategy. An important advantage of 5-axis measurement is that, for some geometric features, the probe can move and measure the feature while the CMM remains static or executing simple linear displacements, reducing the influence of dynamic effects on the results. To evaluate this potential advantage, a set of 170 tests were planned and executed on two CMMs equipped with 3-axis and 5-axis probing systems, measuring dimensional and form characteristics at increasing measurement speeds. A comparison of the results showed the influence of dynamic errors on measuring with a CMM in 3-axis mode at higher measurement speeds and the effectiveness of 5-axis measurement technology in terms of the CMM performance in scanning mode.

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Keywords: Coordinate Measuring Machines, 5-Axis Scanning Probes, Dimensional Metrology

1. Rotary probes and the 5-axis measurement technology:

Coordinate measuring machines are the most commonly used equipment for the measurement of dimensional and geometric tolerances in industrial production and, besides presenting good accuracy, they must be able to measure with increasing speeds to attend higher demands of productivity in industrial processes. However, achieving accuracy with velocity in dimensional metrology applied in industry poses a challenge, especially in multi-axis measuring machines such as CMMs. The accuracy of CMMs is dependent on many factors, internal and external to the machine. High precision of the mechanical components, such as guides and bearings, accurate assembly, efficient electronic control and an accurate probe system are some of the most important internal factors [1].

The touch probe is a critical component of a CMM, and it must present good accuracy in static and dynamic (scanning) measurements, in order to locate points over the surface of a part to calculate the associated features and evaluate dimensional and geometric tolerances. Many technologies have been developed and tested, ranging from rigid probes in the 1960s to current sophisticated scanning probes [2][3]. The measuring probe of Carl Zeiss (1973), the touch trigger probe of Renishaw (1978) and many other technologies are some important examples of the extensive development of probes for CMMs. In this area, some of the most recent and promising advances are the rotary probes that enable a CMM to measure in a 5-axis approach. These probes consist of two concepts (Figure 1).

One concept is not in fact a probe, but a rotary head moving a touch trigger probe continuously at two angles. In contrast to the discrete indexing head that moves the probe to a fixed angle and remains in this position during the probing of points, the rotary head can move the probe continuously and is

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synchronized with the CMM. One of its main operational advantages is the possibility to change the stylus orientation during a measurement process without the need for probe recalibration, reducing the measurement time. As it is possible to measure when moving the probe more and the machine less, dynamic errors can be minimized. This probe head operates with a conventional industry standard touch trigger probe.

The other concept is, in fact, a scanning probing system integrated into a two-axis articulating head. Besides ensuring flexibility and productivity through changing the stylus orientation without recalibration, the use of this system can be explored to accelerate the scanning of some symmetric features and reduce dynamic errors of the CMM. When scanning circular features, for example, the rotational axes can perform a circular movement while the transversal axes of the CMM remain static (scanning of a circle) or move at a constant velocity (scanning of a cylinder or a cone). Accelerated movements of the mechanical structure of the CMM can be avoided, and the scanning speed can be increased without compromising the accuracy [4]. The sensor principle of this scanning probe is based on a hollow stylus with an internal laser beam projected from the probe head to a reflector at the tip, and then reflected back to an optical sensor. When the probe tip touches the part, the stylus deflects and the reflector tilts, changing the position of the reflected laser beam. This returned beam is received by the position sensor and it is used to calculate the tip position.

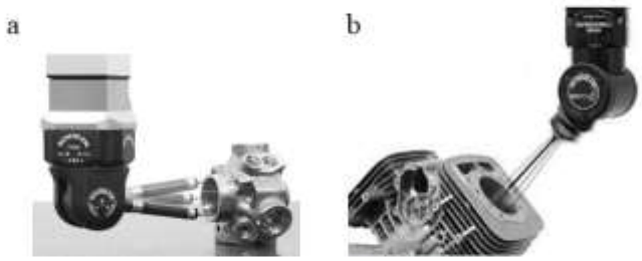

Fig. 1. (a) 2-Axis rotary head with trigger probe; (b) 2-axis scanning probe.

2. Potential metrological advantages for CMMs

The concept of rotary probes has, as one of the main potential metrological advantages, the capacity to maintain accuracy at higher speeds. In every CMM, movements that induce accelerations and decelerations distort the machine structure, resulting in measurement errors that increase with measurement speed and acceleration. This effect is much more critical in scanning operation mode. Pereira and Hocken [5] stated that a major limitation of the CMM is the execution of measurements with low uncertainty at a reasonably fast rate. CMMs with scanning capabilities offer a high density of points at high speeds, but under this condition, they are considerably less accurate. When performing faster measurements, the dynamics of the whole machine will have an adverse effect on the accuracy. The machines have been designed with much slower measurement tasks in mind and accuracy was always the top priority.

According to Weekers et al. [6], the sensitivity of a CMM toward dynamic errors is strongly dependent on its structural loop. Deformations of the structural loop, e.g., due to driving forces and moving loads that cause (dynamic) errors with respect to the probe position, will inevitably affect the measurement accuracy. In general, dynamic measurements where the bridge of the CMM (XY plane) is moved are more greatly affected, because the heavy mechanical structure causes greater inertia loads and geometric distortions. The stability of air bearings is another influencing factor during dynamic measurements. Figure 2 shows the result of an experiment to evaluate the horizontal stability of lateral air bearings during acceleration and deacceleration of the machine [7]. The horizontal displacement of the column was measured during acceleration and reversal movements of the X axis. The poor damping of air bearings is another factor that can affect dynamic measurements.

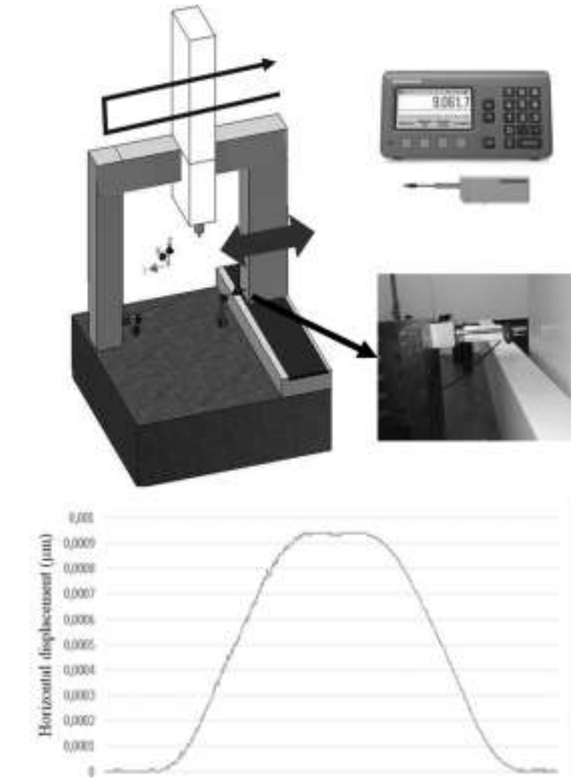

Fig. 2. CMM displacement caused by inertia load on air bearing.

Since the 5-axis measurement minimizes the need for machine accelerations, inertia loads can be smaller and, consequently, the dynamic errors can be reduced. Higher measurement speeds can be achieved while maintaining an acceptable level of accuracy. Although 3-axis scanning can run at speeds of up to 80 mm/s, accuracy is compromised at over 20 mm/s. Figure 3 illustrates an expected advantage of 5-axis measurements over 3-axis measurements in the scanning of a circular feature.

Another metrological improvement is that the use of 5-axis technology applied with a standard kinematic touch probe makes it possible to correct errors due to a variation in the measuring force along the direction of the probe. This is carried out by mapping probing errors during the calibration of the tips and correcting these errors during the probing of the part feature. This strategy enables the use of 5-axis measurement technology to improve the accuracy of a standard kinematic touch trigger probe.

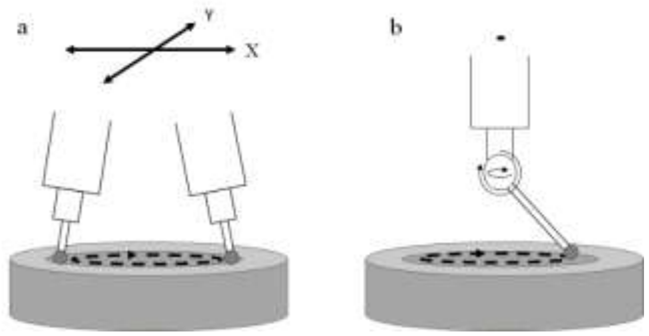

Fig. 3. Dynamic effects on CMMs operating in scanning mode: (a) 3-axis and (b) 5-axis.

Besides the higher productivity and time efficiency, the ability to acquire a high density of points without compromising in terms of time and accuracy can lead to better measurement strategies for the control of dimensional and geometric tolerances. With more points, a better mathematical reconstruction of the geometries can be achieved, improving the reliability of the measurement results and providing a better geometric analysis of the part measured. Figure 4 illustrates, as an example, the effect of the density of points on the mathematical construction of a simulated datum. If a higher density of points is captured, the simulated datum constructed is similar to a datum simulated by a hard gage.

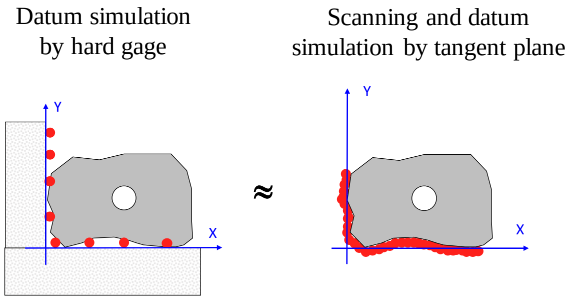

Fig. 4. Advantage of a high density of points in datum simulation.

There are other indirect metrological advantages of 5-axis measurements, such as a longer stylus for a deeper inspection of holes, less influence from the air bearings, longer stability and less maintenance of the CMM due to less use of the motors, bearing and guides.

3. Metrological evaluation of 5-axis technology

Since the concept of rotary probes has the potential metrological advantage of maintaining the accuracy at higher speeds, in this paper experiments were designed to evaluate the accuracy of two CMMs, both equipped with scanning probes (3-axis and 5-axis), at increasing measurement speeds.

The experiments consisted of measuring ring gages at increasing speeds and evaluating the influence of the speed over the results for the diameter and roundness of the ring gage. Two similar CMMs were employed in these experiments: one equipped with a fixed scanning probe configuring a 3-axis measurement and the other equipped with a scanning probing system integrated into a 2-axis articulating head, configuring a 5-axis measurement.

To evaluate the influence of the CMM dynamics, the ring gage was measured in the XY, XZ and YZ planes and each measurement condition was repeated 5 times. The experimental arrangement can be seen in Figure 5, along with the kinematic model of the tested CMMs. The two CMMs have the same kinematic model and similar mechanical structures.

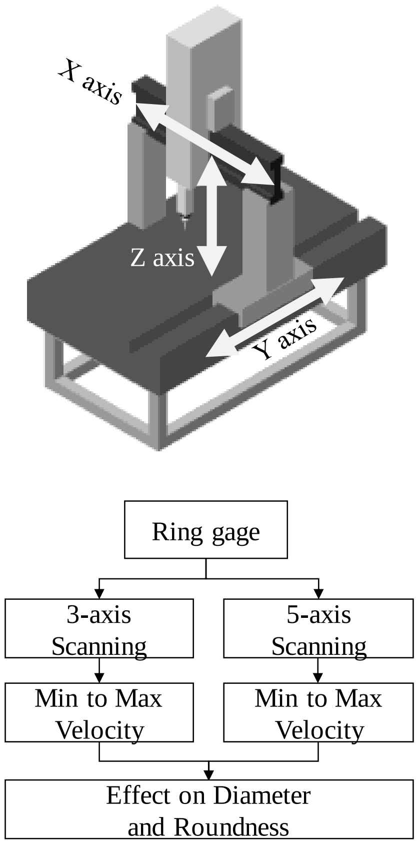

Fig. 5. Experimental arrangement.

Given that the main objective was to evaluate the loss of accuracy at higher measurement speeds, a reference measurement condition was established at slow speed and the results collected at higher speeds were compared to those obtained under this condition. The measurement acceleration was adjusted to 100 mm/s^2 in all the experiments. The probing strategy (path and sampling) was kept the same for both CMMs in all experiments. To allow the CMM to reach the programmed speed and avoid bad data when accelerating or decelerating at the start and end of the scan, an over scan of 360º in the 3-axis scanning and 8 complete laps in the 5-axis scanning were applied. The diameter was calculated by the method of maximum inscribed circle and for the roundness a gaussian filter of 150 UPR was applied to the points and the result was calculated by minimum zone method [8]. The CMMs have the same CNC controller and software and operate in measurement rooms with controlled temperature (20 ± 1º C).

3.1. Tests with the fixed scanning probe: CMM in 3-axis mode

A bridge-type CMM LK G80 C with a fixed scanning probe (Renishaw SP25) was tested with a ring gage of 50 mm diameter (Figure 6). The roundness of this gage was measured on a form measuring machine (Mitutoyo RA1600) to evaluate its form integrity (absence of damage), revealing a roundness of 0.36 ± 0.03 µm (minimum zone fitting and 150 UPR filter). The diameter of the ring gage was not calibrated, since the objective of the test was to evaluate the stability of the results varying the measurement speed.

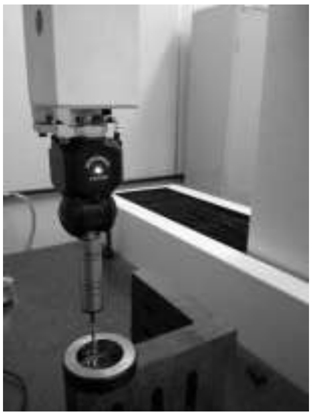

Fig. 6. CMM with fixed scanning probe.

A measurement at the speed of 5 mm/s was taken to obtain a reference result for the diameter and roundness and the speed was then increased in steps of 5 mm/s up to 50 mm/s. It was not possible to reach higher speeds because the CMM was not able to follow the circular path at 55 mm/s. The result for the diameter variation can be seen in Figure 7 for the three planes of the CMM. The effect of speed on the results is clear, and this is related to the movement of the CMM bridge (Y axis). Despite a good repeatability (±1.0 µm), the diameter results decreased with speed, confirming the expected behavior shown in Figure 3, due to deflection of the Z spindle at higher speeds. In the XZ plane, where the bridge of the CMM remained static, the variation in the diameter was much smaller because of the weaker influence of the CMM dynamics on the accuracy.

Since the repeatability was good, the systematic errors could be compensated mathematically for this specific condition. Another possible strategy to correct the errors is to calibrate the probe at the same measurement speed. However, under the normal operation of a CMM, this strategy would be difficult to implement as the measurement conditions change from part to part, which is associated with the dimensional control during serial production.

Analysis of variance was applied to the results, confirming the statistical relevance and the hypothesis of the influence of speed on the diameter result (Table 1) could be accepted, as the p value was < 0.05.

Table 1. ANOVA results for velocity and diameter variation – 3-axis mode.

Velocity	XY	XZ	YZ
F Factor	56.29	4.00	31.79
p value	3.02E-12	0.005	6.25E-10

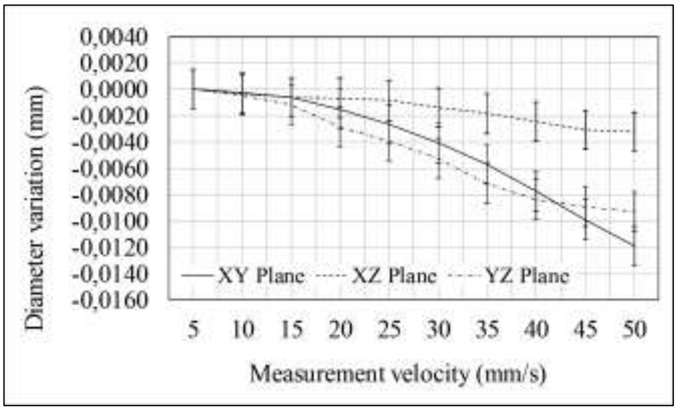

Fig. 7. Influence of velocity on measured diameter – 3-axis mode.

The roundness results obtained in the same tests can be seen in Figure 8. Once again, in the measurement planes that required the movement of the CMM bridge (XY and YZ planes) there was a much stronger influence of the velocity on the results. In the XZ plane, where the bridge remained static, the roundness was much more stable for higher speeds, confirming the superior performance for the scanning probe with less dynamics effects of the CMM. The repeatability in the XZ plane was 1.0 µm and in the XY and YZ planes the values were 1.2 µm and 1.1 µm, respectively.

As expected, the influence of the dynamic response of the machine was predominant along the axes that require the movement of the heavier parts of the CMM (bridge). With the CMM bridge static, the lower degree of distortion caused by acceleration and deacceleration of machine had a weaker influence on the results, indicating that the XZ plane is the best option for higher speeds using a fixed scanning probe.

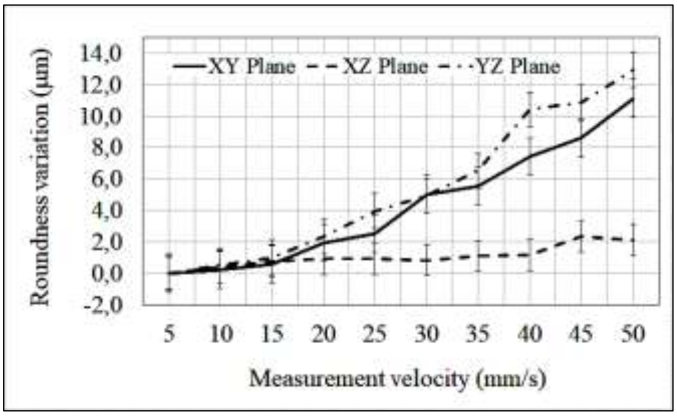

Fig. 8. Influence of scanning velocity on roundness measurement - 3-axis mode.

The analysis of variance applied to these results confirmed their statistical relevance and the hypothesis of the influence of speed on roundness could be accepted (Table 2), even in the XZ plane, as the p value was < 0.05.

Table 2. ANOVA results for velocity and roundness variation – 3-axis mode.

Velocity	XY	XZ	YZ
F Factor	75.69	3.277	88.11
p value	2.79E-22	0.004	1.60E-23

The results obtained in the previous tests showed a considerable influence of the speed on the accuracy of the dimensional and form measurements. The CMM tested has a very robust and heavy mechanical structure with large steel columns, a granite guideway along the X axis and a ceramic spindle along the Z axis, and this configuration contributed to the results. However, even with the use of smaller machines with lighter materials (aluminum, composite carbon fiber, etc.) similar behavior is expected.

3.2. Tests with the rotary scanning probe: CMM in 5-axis mode

For the tests in the 5-axis mode, a bridge-type CMM LK V HA 10.10.8 with rotary scanning probe (Renishaw REVO) was employed. The CMM has a ceramic bridge and spindle (Z axis), and aluminum columns. This CMM was also tested by measuring the diameter and roundness on a 50 mm calibrated ring gage (Figure 9). The ring gage was measured under a reference condition, at slow speed, to assure its surface integrity (absence of damage) and to establish reference values for the diameter and roundness. The measurement parameters (probe tip, sampling, filtering, mathematical reconstruction, etc.) were similar to those applied in the previous tests.

The tests were conducted in the three cartesian planes, repeating each measurement 5 times. As the ring gage has circular symmetry, the rotational axes of the probe were used to perform circular movements of the stylus tip, and the cartesian axes of the CMM remained quasi static. Under this condition, the velocity was increased from 10 mm/s (reference condition) to 100 mm/s, in steps of 10 mm/s. The diameter and the roundness were calculated from the points probed under this condition.

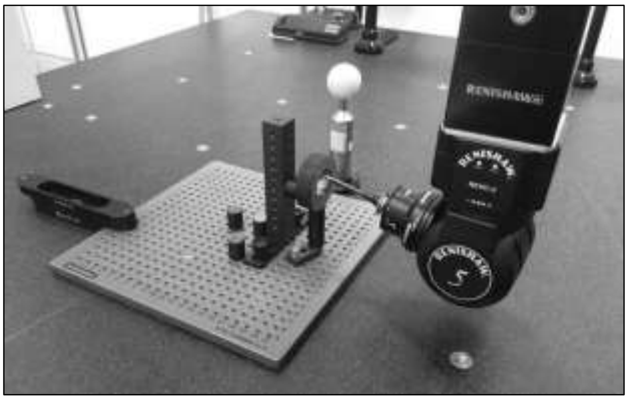

Fig. 9. CMM with rotary scanning probe.

The results for the diameter measurements in 5-axis mode can be seen in Figure 10 for the three planes of the CMM. A maximum variation of 2.1 μm was encountered for measurement speeds of 10 to 100 mm/s, confirming a much higher stability of the results without the influence of the CMM movements. Similar measurements taken in the 3-axis mode resulted in a maximum variation of 12 μm at measurement speeds of 10 to 50 mm/s. This variation of 2.1 μm is close to the maximum permissible error (MPE – ISO10360-2 [9]) for this CMM model. The repeatability in all tests was under 1.0 μm and the influence of the measurement plane on the stability of the results was negligible compared to the reference condition of 10 mm/s.

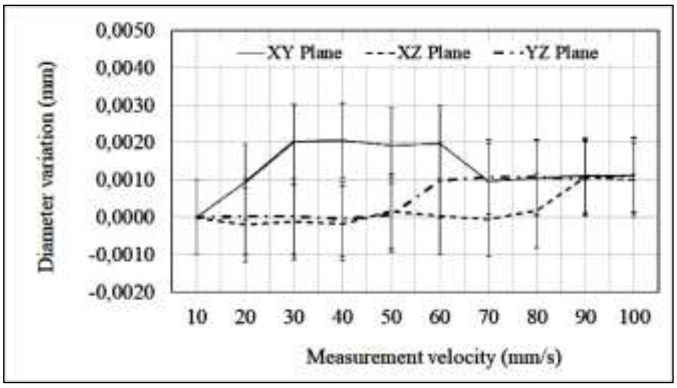

Fig. 10. Influence of velocity on measured diameter.

The analysis of variance applied to these results did not show statistical relevance and the hypothesis of the influence of speed on roundness results was rejected (Table 3), as the p value was > 0.05.

Table 3. ANOVA results for velocity and diameter variation – 5-axis.

Velocity	XY	XZ	YZ
F Factor	1.442	0.645	0.924
p value	0.24	0.74	0.52

The results for the roundness variation in 5-axis mode can be seen in Figure 11 for the planes testes. The maximum variation in the roundness at 100 mm/s was 3.1 μm in the YZ plane compared with 12.9 μm obtained at 50 mm/s in the 3-axis measurements.

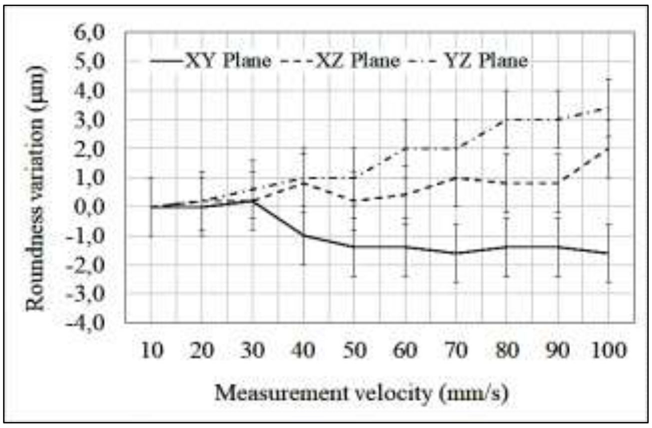

Fig. 11. Influence of scanning velocity on roundness measurement – 5-axis mode.

The analysis of variance did not show statistical relevance in the XY and XZ planes (p value > 0.05) and the hypothesis of the influence of speed on roundness results was rejected, except for the results of the tests in the YZ plane (Table 4).

Table 4. ANOVA results for velocity and diameter variation – 5-axis mode.

Velocity	XY	XZ	YZ
F Factor	1.595	1.034	4.572
p value	0.18	0.44	0.002

Further tests were carried out at higher speeds, up to 500 m/s, according the same measurement strategy applied in the previous tests, but it was possible to test the CMM only in the XZ and YZ planes. During the last tests in the XY plane the machine presented technical problems that did not allow the continuation of the experiments in this study. However, the tests in the XZ and YZ planes were sufficient to evaluate the measurements at very high speeds.

The results for the diameter and roundness are shown in Figures 12 and 13, and the results obtained previously at 100 mm/s were considered as the reference. Both the diameter and roundness presented stability at very high speeds, compared to the condition of 100 mm/s. Statistical analysis using ANOVA did not reveal a significant influence of speed on the results (minimum p value of 0.21). The repeatability of the roundness results varied from ±1.0 μm to ±2.5 μm. Under these extreme conditions, however, the probe must be well balanced and the CMM must present good static stiffness.

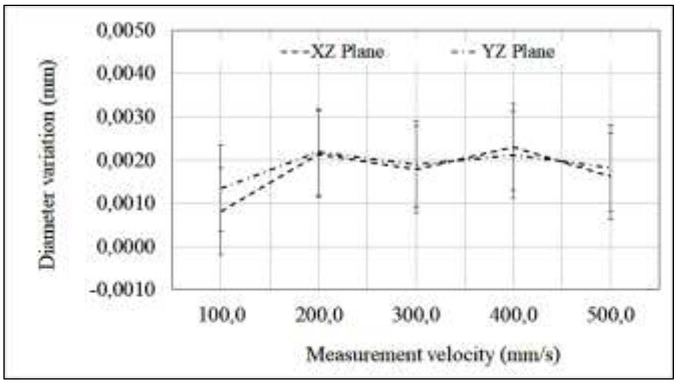

Fig. 12. Diameter measured at very high speed scanning – 5-axis mode.

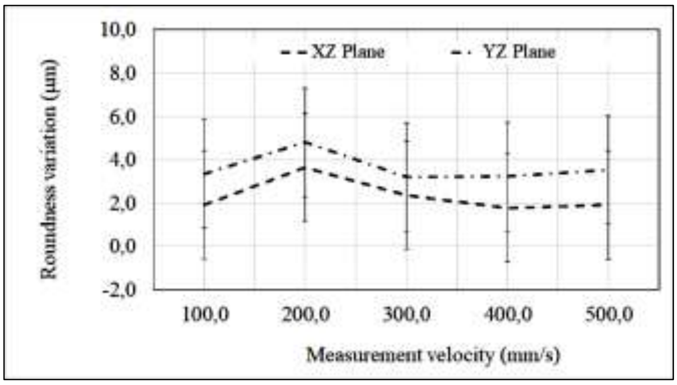

Fig. 13. Roundness measured at very high speed scanning – 5-axis mode.

4. Conclusions

The 5-axis measurements with the use of scanning rotary probes highlighted new possibilities for coordinate measurement machines, offering advantages in terms of productivity and accuracy. In this study, CMMs with different probe systems were tested to evaluate the effects of speed on the measurement uncertainty when measuring the diameter and roundness of a circular feature. A ring gage was measured in a CMM with a fixed scanning probe and in a CMM with a scanning rotary probe. The scanning velocity was increased from a reference condition to the maximum possible in each case.

In the 3-axis measurements, due to the influence of the CMM dynamics, the results showed stability from 5 to 15 mm/s. For higher speeds the diameter decreased up to 12 μm due to Z axis deflection and the roundness increased up to 12.9 μm due to the bridge deflection and twist during the circular path of the probe tip. The measurement in the XZ plane (with the CMM bridge static) showed good stability up to 40 mm/s, this being a better option to reach a lower uncertainty for scanning with a fixed probe. In all planes of the CMM it was possible to reach a maximum velocity of 50 mm/s before the CMM controller presented errors. The errors encountered were mainly systematic, since the results showed good repeatability and strategies for error correction could be applied.

In the 5-axis measurements, with the CMM static and the rotary probing moving, the results showed notably better stability at much higher scanning speeds. The measuring machine was able to measure at speeds of up to 500 mm/s in scanning mode, with a variation of 3.0 μm in diameter and 4.0 μm in roundness compared to the condition set as the reference (low speed). This variation was comparable to the uncertainty estimated in the experiments. The technology of 5-axis measurement opens new possibilities for coordinate metrology, but the measuring machines and experimental conditions must be well adjusted to attain the best performance that probing systems can achieve. The results of this study are valid for these experimental conditions and cannot be generalized to include other situations. Depending on the measuring machine and measurement strategy, the 5-axis probing systems may have a higher or lower performance.

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