INTERIM CHECK FOR MACHINE TOOLS

0. INTRODUCTION

One of the most appreciated services that STANIMUC offers to industry is the check up, periodic or non-periodic, of the state of health of the machine tools in operation, whichever is their number, many or few, through the measurement of the accuracy of the circular interpolation by means of the “ball bar”. STANIMUC owns the different types of Renishaw ball bar, as the wired QC10 and the wireless QC20-W, as well as the Zerodur plate for calibrating the length.

Figure 1 – QC10 wired ball bar

Figure 2 – QC20-W wireless ball bar

1 DOWNTIME

The speed of installation of the instrument and the easy practical execution of the programmed movements allow to check in one working day an average of three three-axes machines. The downtime of a machine can be therefore deemed as less than three hours.

The time required depends on several variable factors. It can be made much shorter if only one measurement per coordinate plane (XY, YZ, ZX) is carried out. Moreover, if it is not the first check on that machine, the machine can be made available already equipped with a fixture (arm, cube, square) allowing to easily fix the socket on the workpiece side approximately in a central location in the machining volume.

On the other side, the time may become longer if corrections and/or compensations are applied during the measurements, for instance on the axes gains, on reduction of the reversal spikes or on the backlash. In this case not only a photograph of the actual situation is taken, but in few hours, with consecutive corrections, the machine performance is eventually even improved.

Similarly, more time may be required if the check is carried out on more than three axes: on a boring machine with two movable tables the check can be carried out in front of each table, or on a machine with two spindle heads on a cross rail the check can be carried on each head.

2. INSTALLATION AND OPERATING CONDITIONS

2.1 Brand new machine

Usually, during the installation of a machine, the accuracy of the circular interpolation is measured after the completion of two basic operations, whose results directly affect its performance.

The first one is the geometric test, checking that errors as straightness and squareness of axes be minimized, beside the angular errors, which can be detrimental because of the Abbe's error.

The second one is the measurement and simultaneous compensation of the so-called "pitch error", intended as a length measurement, although "pitch" means also an angular error. This operation allows to minimize the systematic part of the positioning errors. Repeatability, being the random part of the error, cannot be handled through numerical compensation, and may require mechanical adjustments.

2.2 Machine in operation

An instant photograph quite thorough of the machine performance can be taken by carrying out, at least, the check in the three median planes parallel to the coordinate planes of the working volume. In each plane the maximum diameter allowed for by the shorter axis is recommended: for instance, if the two interpolating axes are as long as 700 mm and 1000 mm, a 600 mm measurement diameter can be chosen.

The powerful diagnostic software of the ball bar provides then a lot of information on the sources of error, as described in the following clauses.

3. MAINTENANCE AND HISTORICAL ARCHIVE

Some corrections or compensations can be applied during the check, as mentioned above, with the instrument on board the machine, but others may require longer operations, although not necessarily more complex. A straightness error may require some adjustments of the bed levelling, in the same way as a squareness error between a column and one or two horizontal axes. In this case the action can be planned depending on the needs, even at a later stage.

The machine may also show a good condition, or a tolerable decay of the geometric and dynamic features, not requiring maintenance or adjustments yet. It is nevertheless useful to establish a historical archive allowing to regularly monitor the machine conditions and to plan maintenance actions before the machine starts to produce scraps, mostly when machining expensive materials.

4. ERROR ANALYSIS

The diagnostic software provides, for each plot, the percent contribution of the several error sources to the resulting error. In the following clauses the basic sources are described.

4.1 Scaling Error

Scaling Error is the difference between the measured travels of the two contouring axes in the area used for the test. Possible causes may be an inaccurate compensation of the linear deviations, different temperatures, or angular deviations of the axes, such as pitch or yaw, affecting the travel length through the Abbe's error. Two examples are given hereunder.

1 - On a milling and boring machine with movable column (Figure 3), if the linear deviations have been properly compensated considering the temperature of the optical scales, it is not unusual that the plot in the XY plane shows an oval shape, with the vertical Y-axis longer than the horizontal X-axis. This is caused by the temperature of the Y-axis (heated by the spindle head) being generally higher than the temperature of the X-axis, whose optical scale lies in a colder microclimate, down in the bed, isolated from the outer environment by the telescopic guards.

2 - When a table moving on a cross slide over a fixed bed (Figure 4) is moved outside the underlying bed, it is subject to a deflection (pitch angular deviation) which, through the Abbe's error, extends its travel (X-axis) compared to the cross slide (Y-axis), which runs always resting on the bed.

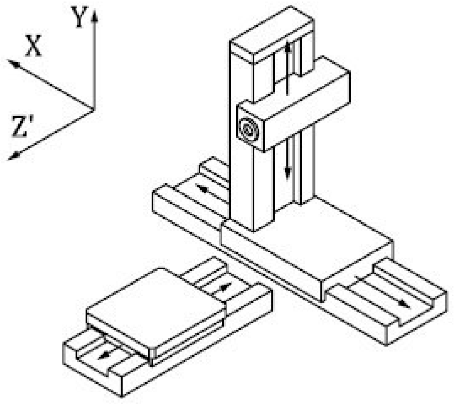


Figure 3 – Scaling error
Y-axis longer than X-axis

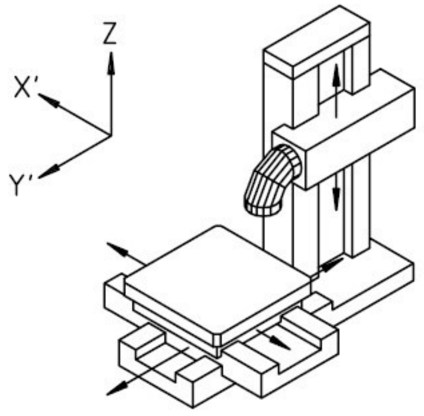


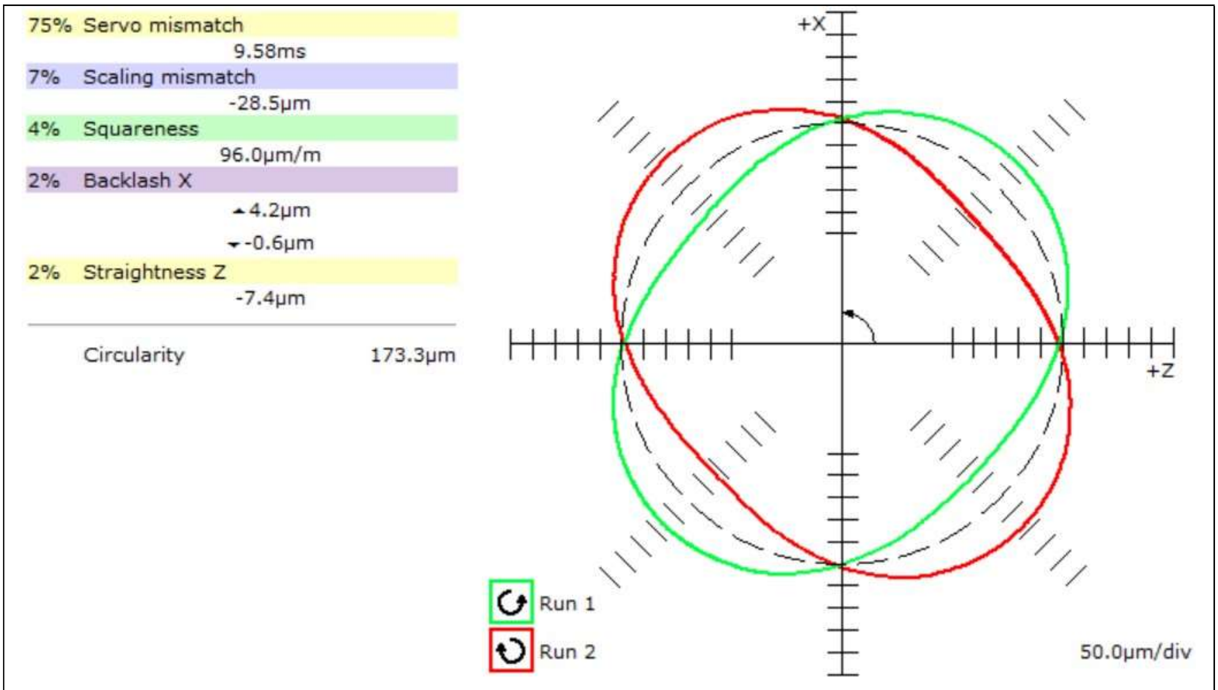
Figure 4 – Scaling error
X-axis longer than Y-axis

4.2 Servo mismatch

Contouring in the two opposite directions may result in two elliptical plots with longer axis in the 1st and 3rd quarter in one direction and in the 2nd and 4th quarter in the opposite direction. The amount of distortion usually increases with increasing feedrate. This effect confirms the usefulness of repeating the same test at different feedrates, while increasing very little the time required.

Servo mismatch occurs when the servo loop gains of the axes are mismatched. Servo mismatch is quantified in milliseconds, which is the time by which one of the machine axes servos leads the other. Usually this deviation can be quickly compensated during the test, with the instrument on board the machine, balancing the loop gains of the axes servos and repeating the test.

Figure 5 shows a remarkable mismatch between the Z-axis and the X-axis, causing a deviation even larger than the squareness deviation, although this one is quite high.


75% Servo mismatch
9.58ms
7% Scaling mismatch
-28.5μm
4% Squareness
96.0μm/m
2% Backlash X
▲4.2μm
▼-0.6μm
2% Straightness Z
-7.4μm

Circularity 173.3μm

Figure 5 – High mismatch between the Z-axis and the X-axis, even higher than the squareness deviation.

4.3 Lateral play

The plot may show a symmetrical shape similar to a peach. The clockwise and counter-clockwise runs appear one inside the other. This deviation, caused by a lateral play between the moving component and the machine guideways, is not affected by the machine feedrate, but is affected by the direction.

It may occur, for instance, when a torque is generated, during the movement of an axis, between the pull of the ball screw and the friction forces, resulting in a rotation of the moving component (pitch or yaw) in opposite orientations in the two directions of motion. It may happen both on vertical and horizontal axes.

In figure 6, if the movable column is subject to a yaw rotation when reversing the motion of the horizontal Y-axis, the spindle head, hanging out from the ram, moves in the X direction in two opposite modes, right in one direction of the Y-axis and left in the opposite one.

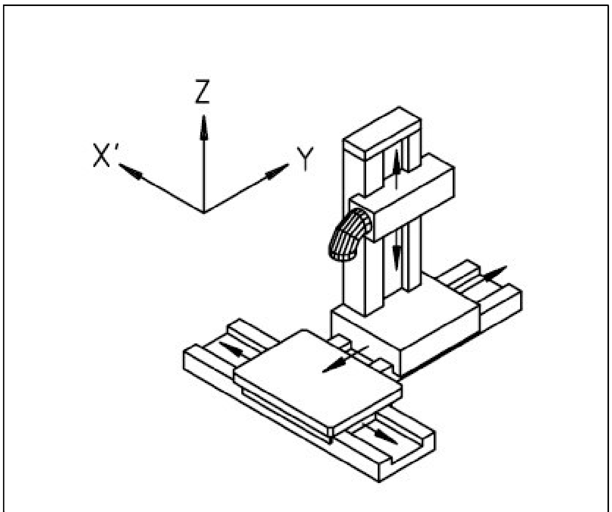


Figure 6

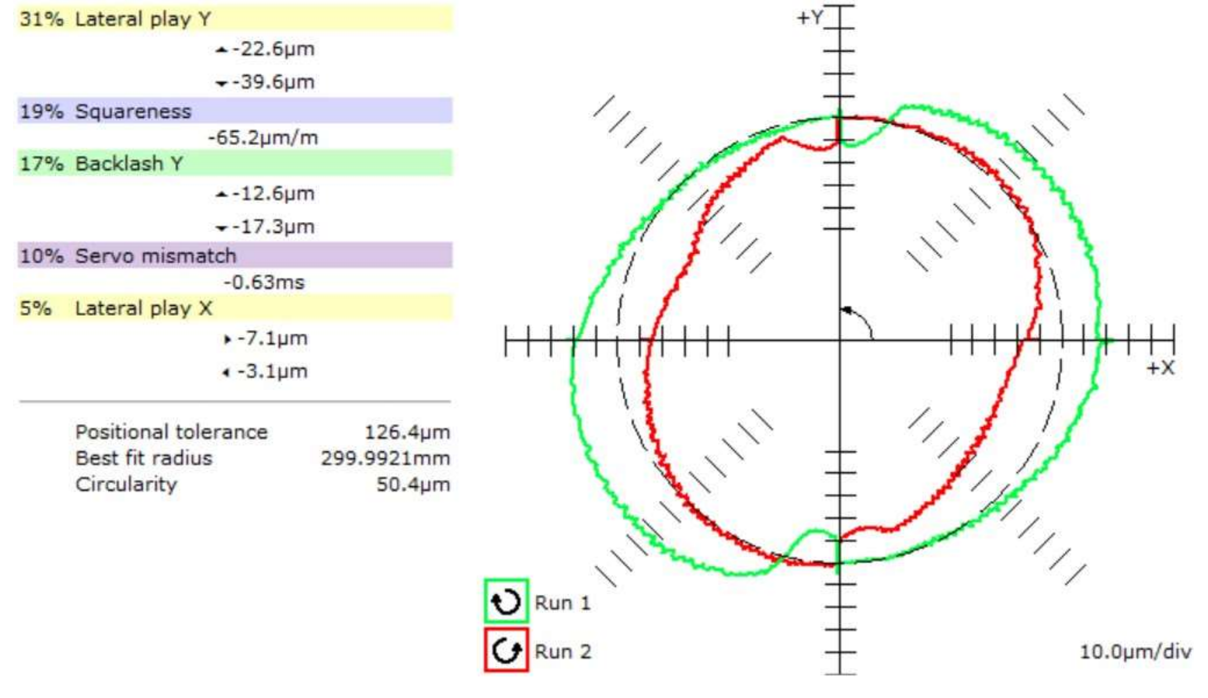


Figure 7– Lateral play

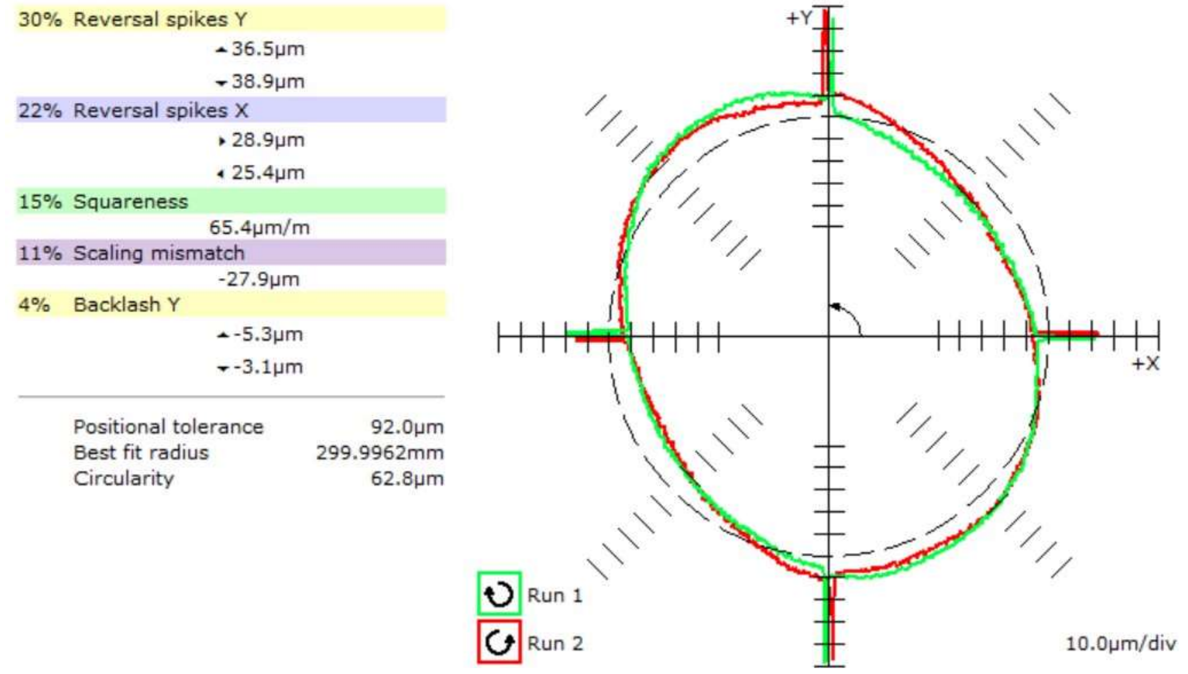
Figure 7 shows, together with other deviations, a clear lateral play. The red counterclockwise plot lies always inside the green clockwise. When the Y-axis moves forward, the path runs always on the left side of the plot (lower X values), and when the Y-axis moves backward, the path runs always on the right side (higher X values).

4.4 Reversal spikes

The plot may show a short spike at the reversal point of an axis. When an axis moves in one direction, then slows down until it stops and reverses the motion, the motion during the reversal is not smooth. The size of the spike often varies with the machine feedrate, confirming again the benefit of repeating the same test at different feedrates. The possible causes may be several.

- The axis motor applies an inadequate amount of torque at the reversal point of the axis, while the friction forces are changing direction.
- The servo response time of the machine is inadequate. The machine is unable to compensate for the backlash in time; causing a loss of control of the motion while the backlash is being compensated.
- Servo response at the reversal point is poor, causing a short delay during the change of direction of the driving forces.

Figure 8 shows evident dynamic reversal spikes, which in figure 9 have been over-compensated. Moreover, in figure 9 the X-axis reversal is different in the two opposite points.



30% Reversal spikes Y
▲36.5μm
▼38.9μm
22% Reversal spikes X
▶28.9μm
◀25.4μm
15% Squareness
65.4μm/m
11% Scaling mismatch
-27.9μm
4% Backlash Y
▲-5.3μm
▼-3.1μm

Positional tolerance 92.0μm
Best fit radius 299.9962mm
Circularity 62.8μm

Figure 8 – Dynamic reversal spikes and squareness deviations

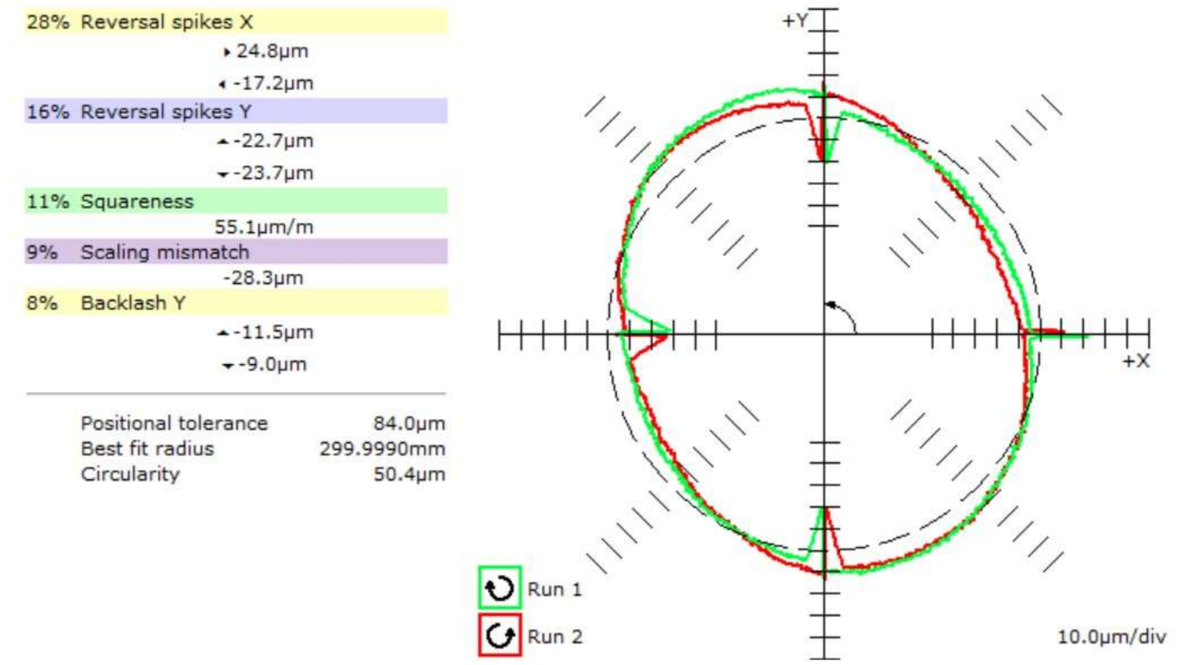


Figure 9 – Over-compensation of the dynamic reversal spikes.

4.5 Reversal error (backlash)

It may be caused by plays in the drive section of the axis, by the axial play of a ball screw, by a play in the guideways, or by other mechanical sources. It may be either positive or negative, i.e. show a lost motion at the reversal point, or on the other hand an overlapping of the axis travels, similar to an over-compensation of the lost motion.

Figure 10 clarifies the difference between the dynamic reversal spikes (spikes on the X-axis) and the reversal error (jumps on the Y-axis).

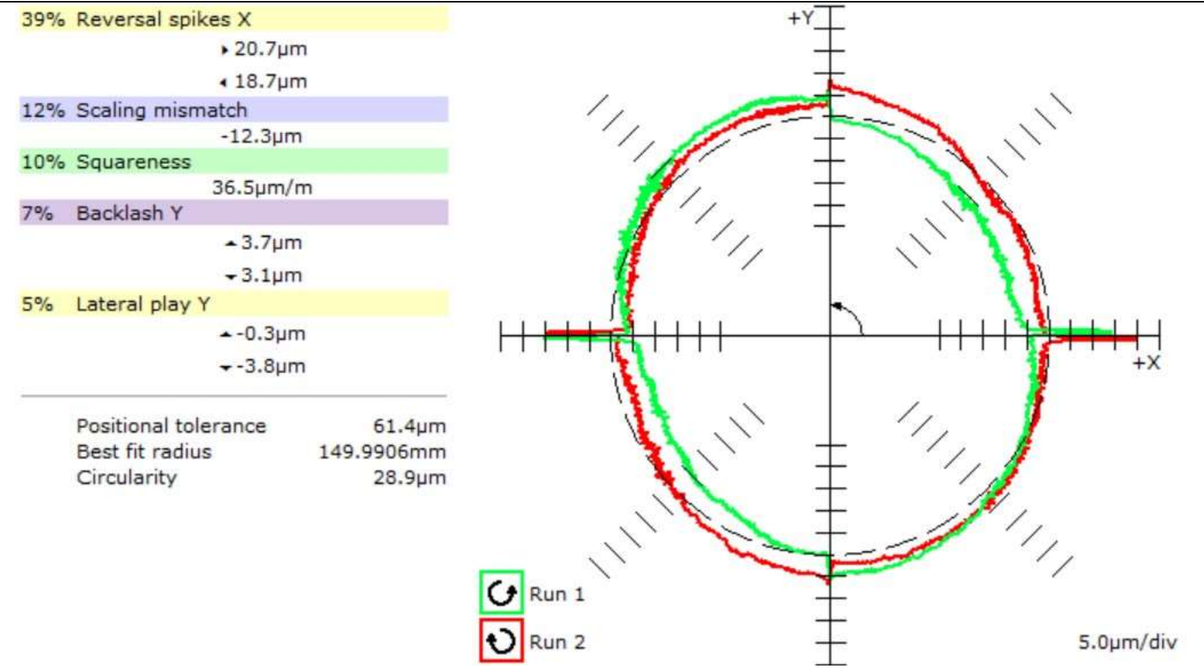
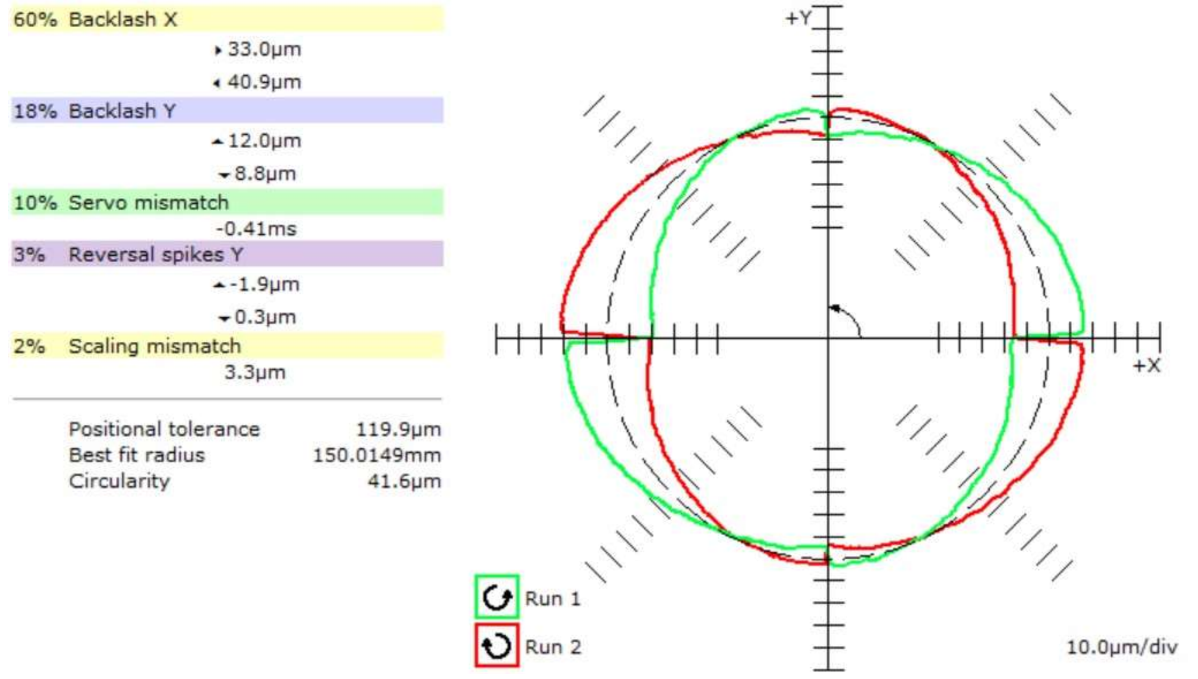


Figure 10 – Dynamic reversal spikes on the X-axis and reversal error (backlash) on the Y-axis.

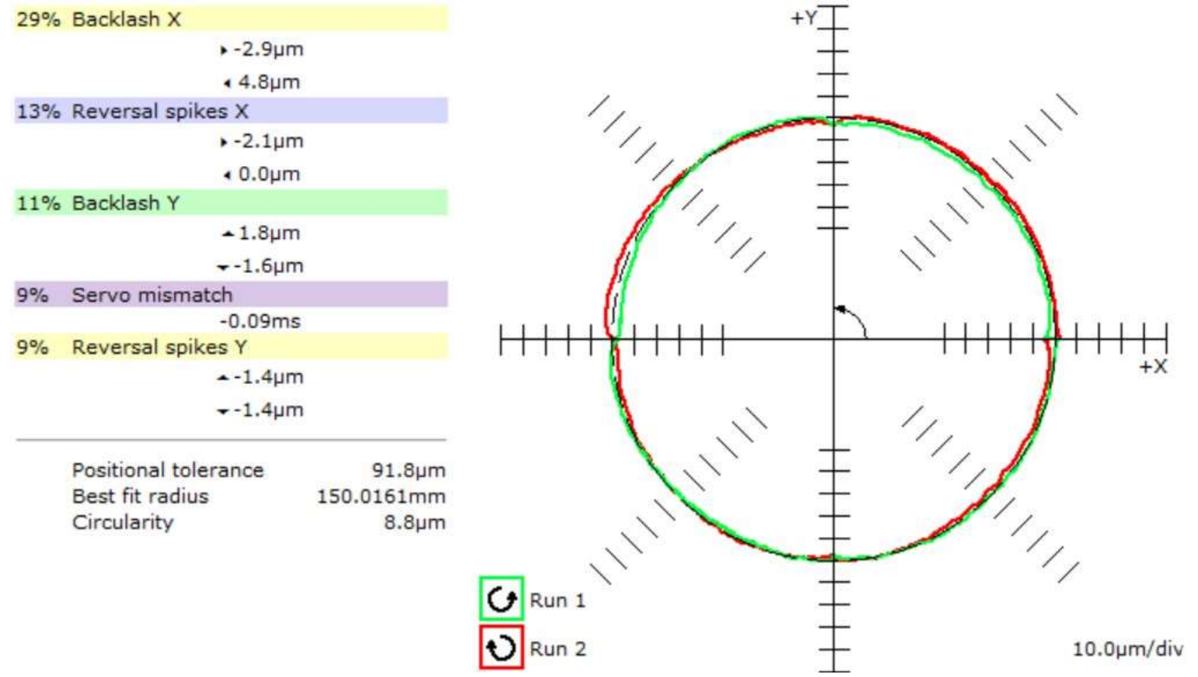
Figures 11 and 12 show the two steps of the same test, before and after the backlash compensation. If the reversal error is quite constant along the axis travel the compensation is immediate and removes (or minimizes) the error. If the reversal error is different from point to point the compensation applied is accurate and effective only on the contouring area, but will be different and not effective in other points of the axis travel. It is not unusual that even on the same contouring area one axis is affected by different reversal errors in the two opposite reversal points, as quoted by the diagnostic software in figure 11.



60% Backlash X
▸ 33.0µm
◂ 40.9µm
18% Backlash Y
▴ 12.0µm
▾ 8.8µm
10% Servo mismatch
-0.41ms
3% Reversal spikes Y
▴ -1.9µm
▾ 0.3µm
2% Scaling mismatch
3.3µm

Positional tolerance	119.9µm
Best fit radius	150.0149mm
Circularity	41.6µm

Figure 11 – Reversal error (backlash) before compensation



29% Backlash X
▸ -2.9µm
◂ 4.8µm
13% Reversal spikes X
▸ -2.1µm
◂ 0.0µm
11% Backlash Y
▴ 1.8µm
▾ -1.6µm
9% Servo mismatch
-0.09ms
9% Reversal spikes Y
▴ -1.4µm
▾ -1.4µm

Positional tolerance	91.8µm
Best fit radius	150.0161mm
Circularity	8.8µm

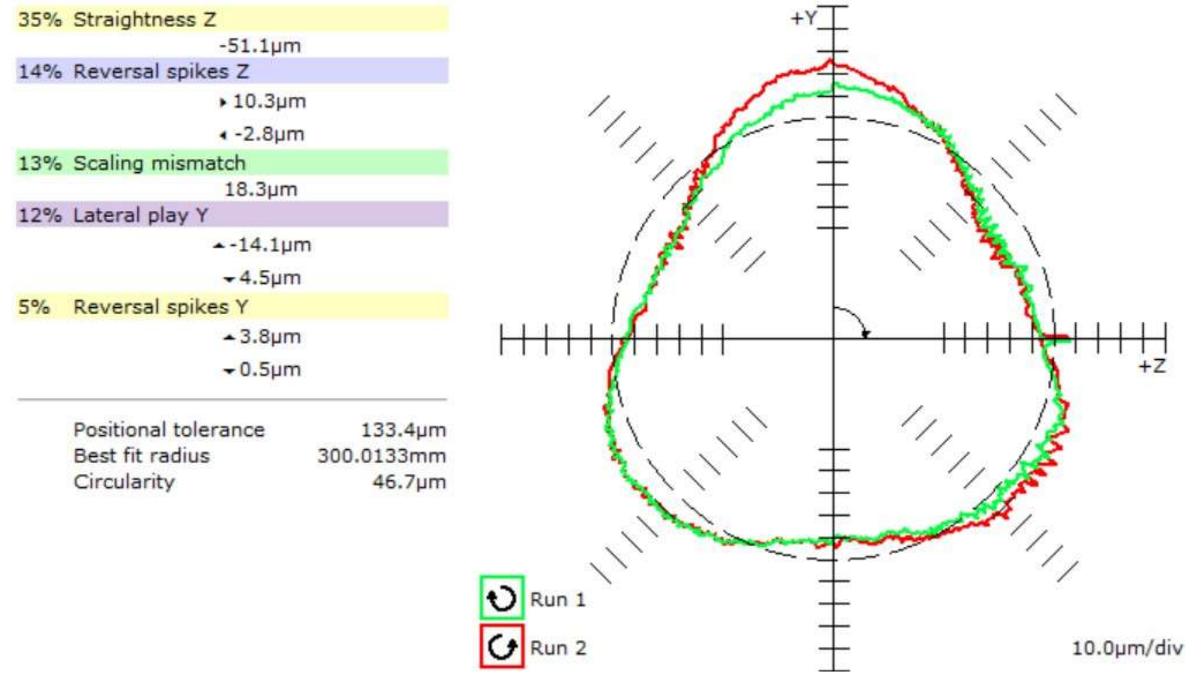
Figure 12 – Reversal error (backlash) after compensation

4.6 Straightness

A straightness error of an axis moves both opposite poles of the other axis in the same direction, i.e. one inwards and the opposite outwards. The plot shows a trilobe shape. The error has a geometric nature and is therefore related to the contouring area where the test is performed. It may be different in other sections of the same axis.

Since the purpose of the interim check is to identify in a short time several errors (geometric, dynamic, software-related), the maximum possible diameter should be selected in each plane, as shown in figures 13 and 14, where the interpolation has been measured over a 600 mm diameter.

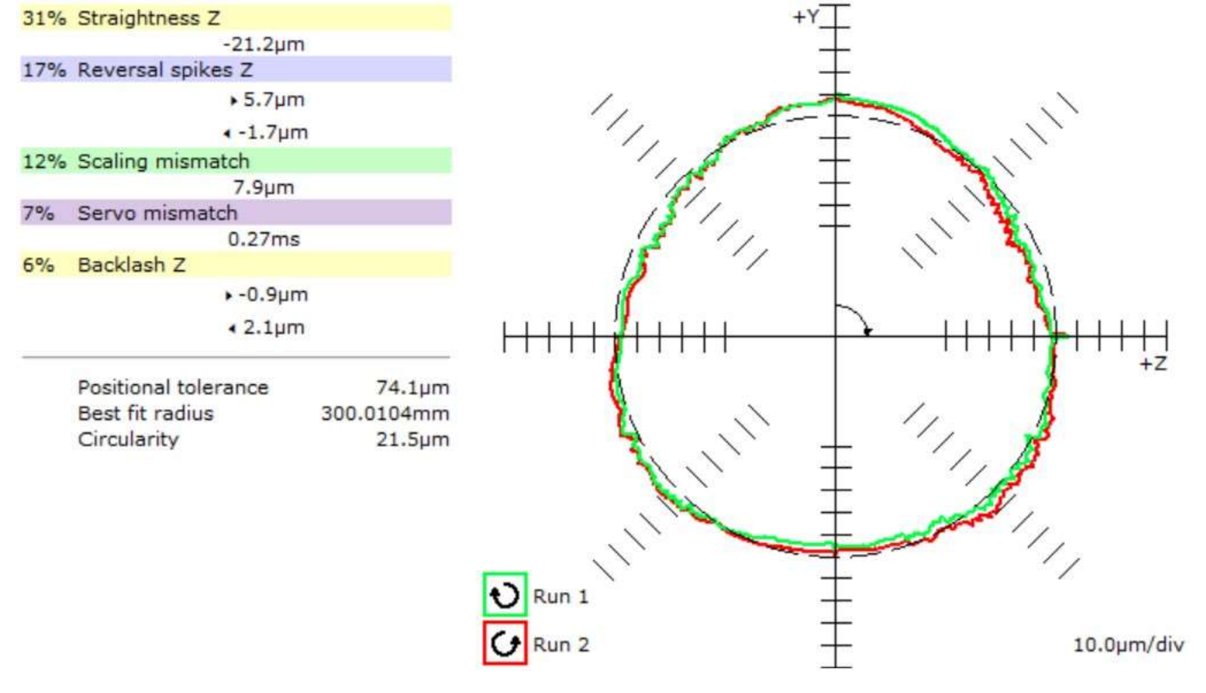
It is therefore necessary to use arms of sufficient stiffness for fixing the magnetic ball sockets. Figure 13 shows the case of a wrong evaluation of the Z-axis straightness, due to the deflection of the horizontal arms, and figure 14 shows the results of the same measurement repeated after replacing the arms by stiffer fixtures.



35% Straightness Z
-51.1µm
14% Reversal spikes Z
▸ 10.3µm
◂ -2.8µm
13% Scaling mismatch
18.3µm
12% Lateral play Y
▴ -14.1µm
▾ 4.5µm
5% Reversal spikes Y
▴ 3.8µm
▾ 0.5µm

Positional tolerance	133.4µm
Best fit radius	300.0133mm
Circularity	46.7µm

Figure 13 – Wrong evaluation of the Z-axis straightness. Poor stiffness of the arms.



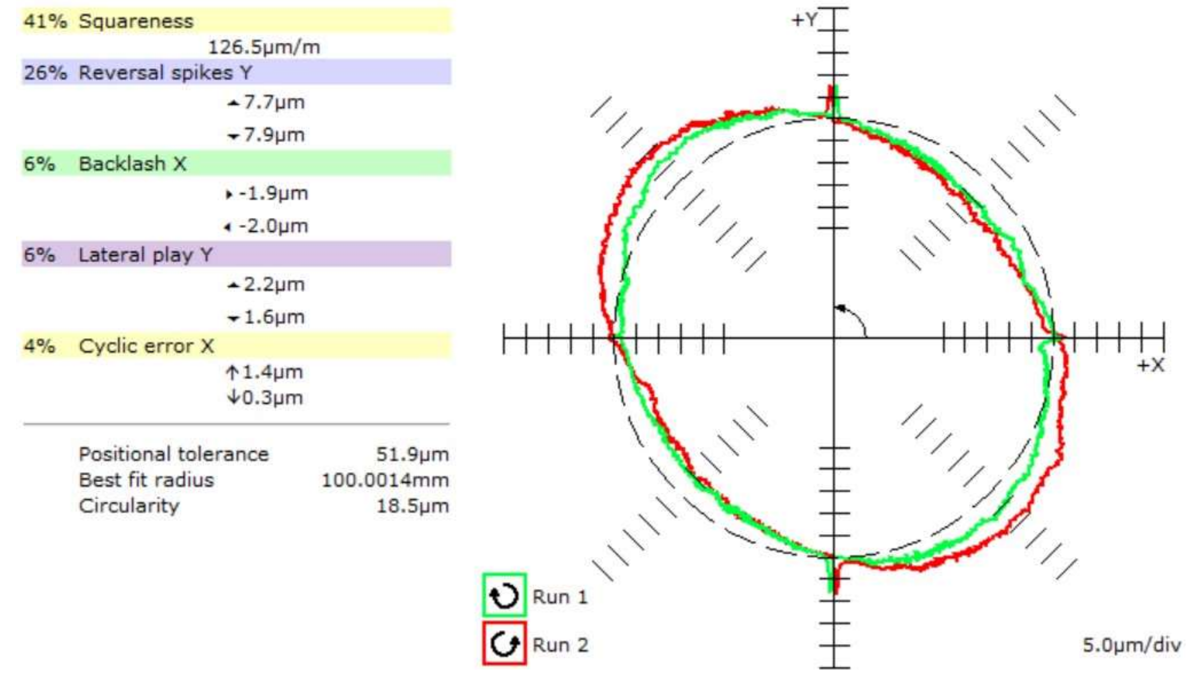
31% Straightness Z
-21.2µm
17% Reversal spikes Z
▸ 5.7µm
◂ -1.7µm
12% Scaling mismatch
7.9µm
7% Servo mismatch
0.27ms
6% Backlash Z
▸ -0.9µm
◂ 2.1µm

Positional tolerance	74.1µm
Best fit radius	300.0104mm
Circularity	21.5µm

Figure 14 - Correct evaluation of the Z-axis straightness. Adequate stiffness of the arms.

4.7 Squareness

The plot shows an elliptical shape, with the longer axis always in the same quarters (1st and 3rd or 2nd and 4th), whichever is the contouring direction, clockwise or counterclockwise. Its orientation provides also the algebraic sign of the error, useful for taking corrective actions. Figure 15 shows an example of a squareness error quoted as 0,127 mm/m, with the angle α > 90°



41% Squareness
126.5µm/m
26% Reversal spikes Y
▴ 7.7µm
▾ 7.9µm
6% Backlash X
▸ -1.9µm
◂ -2.0µm
6% Lateral play Y
▴ 2.2µm
▾ 1.6µm
4% Cyclic error X
↑ 1.4µm
↓ 0.3µm

Positional tolerance	51.9µm
Best fit radius	100.0014mm
Circularity	18.5µm

Figure 15 – Squareness deviation between the Y-axis and the X-axis.

5. SUMMARY OF RESULTS

Not all errors belong to the categories mentioned above. The results, immediately plotted at the end of the measurement, highlight features of various nature, as shown in the following figures. This confirms how an instant photograph of the performance, rapidly taken by means of the ball bar, can even reveal unexpected or hidden errors, falling outside the geometric or positioning accuracy, which can be identified only through dynamic tests.

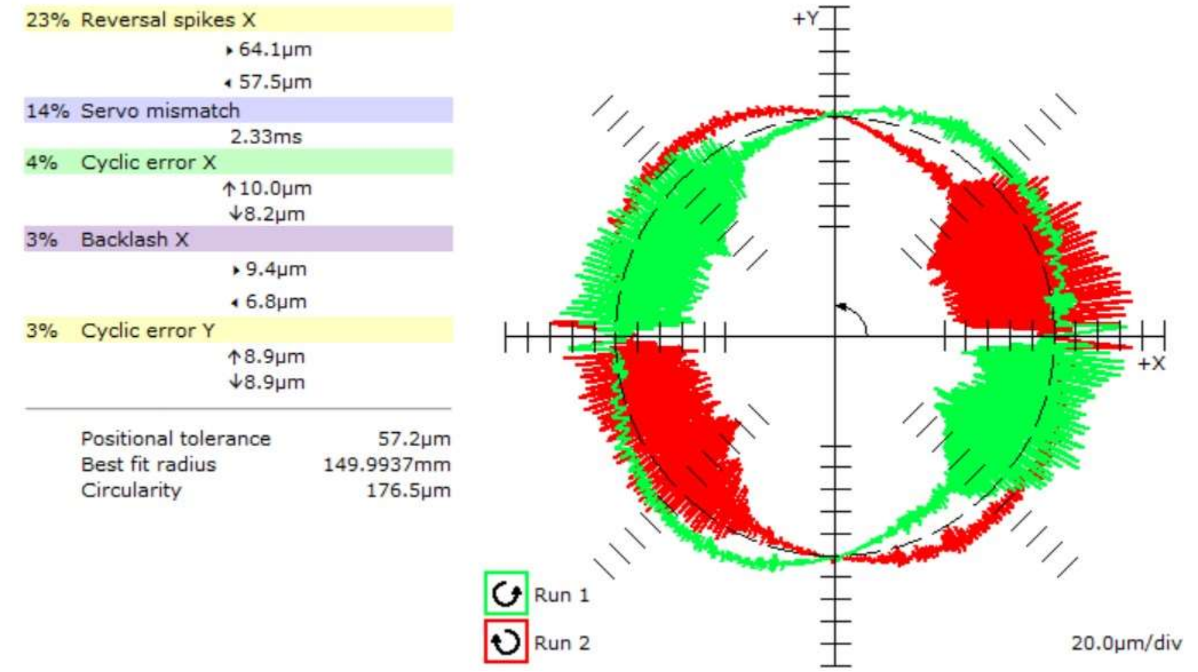


Figure 16 – Y-axis leading the X-axis. Strong vibrations occur when the X-axis is slowing down, in both directions.

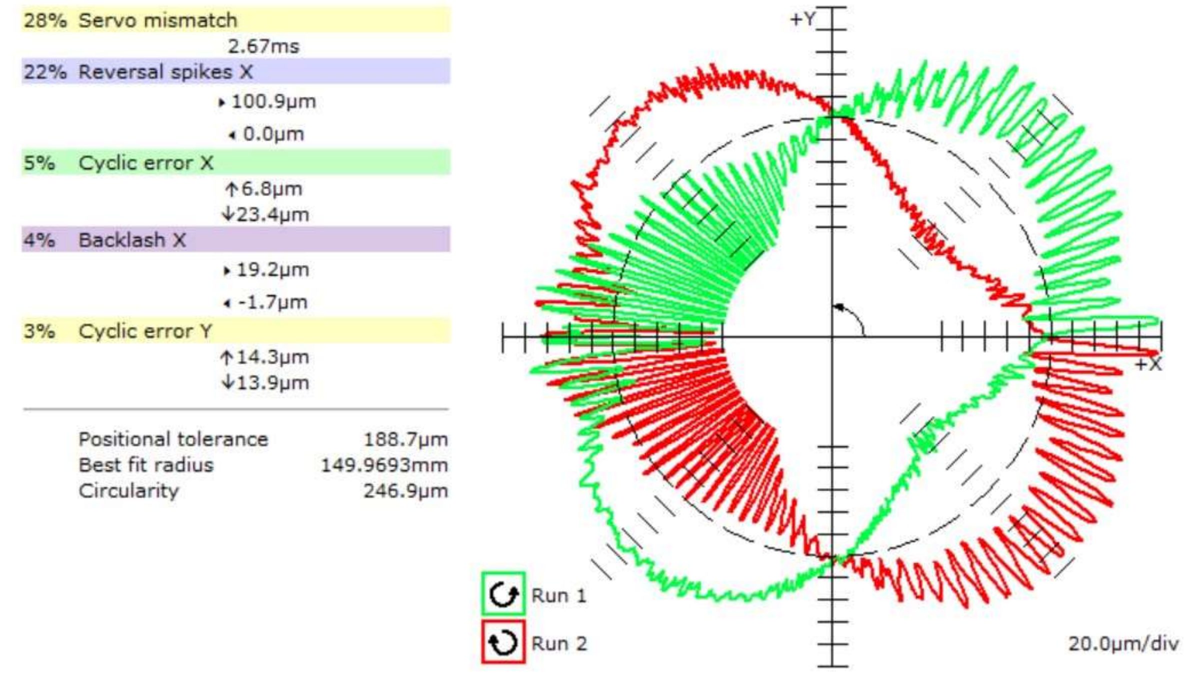
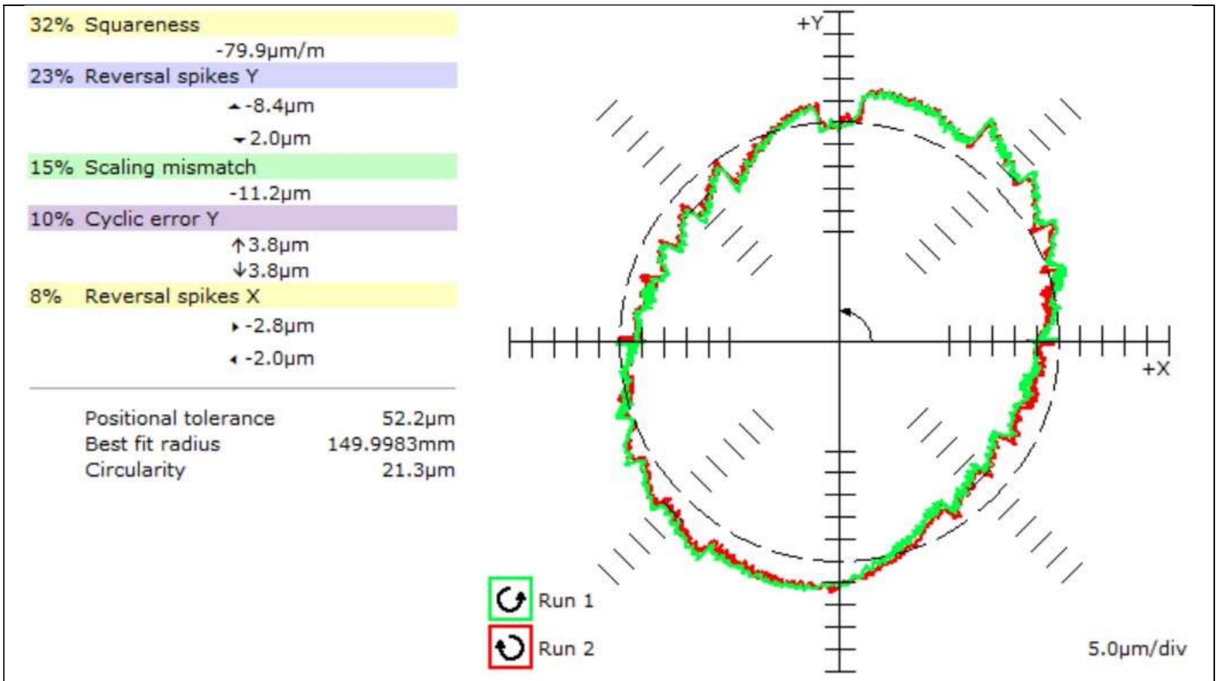


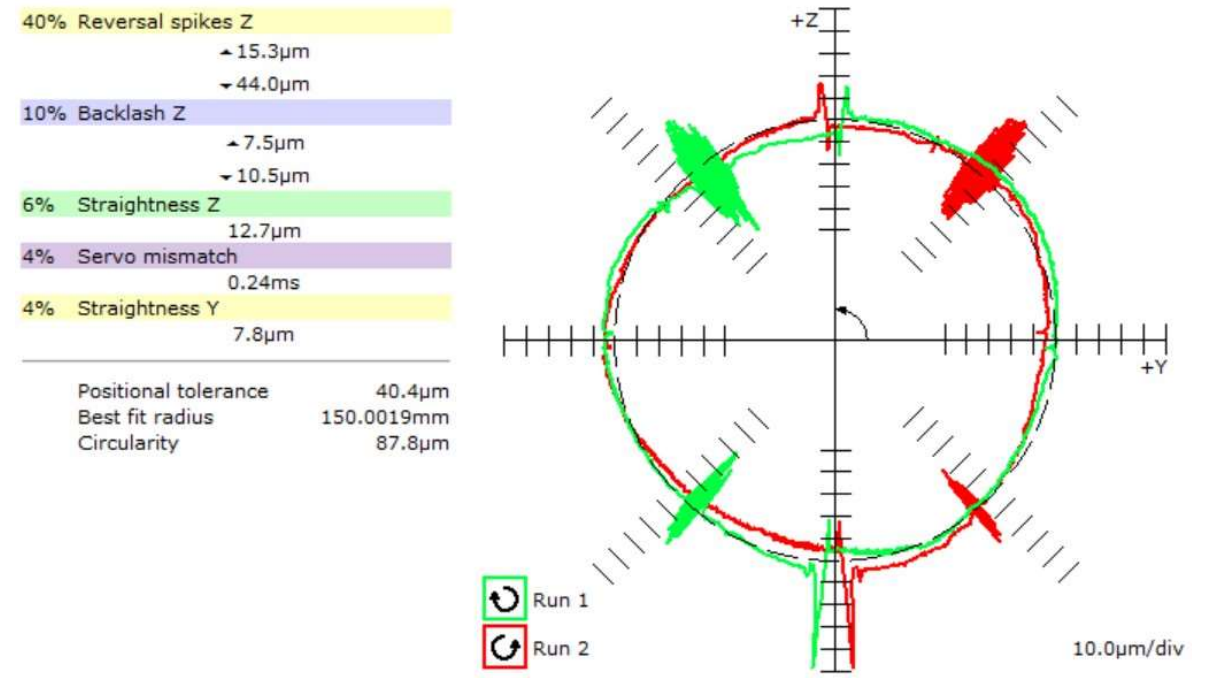
Figure 17 – Y-axis leading the X-axis. Strong vibrations occur when the X-axis moves backwards.



32% Squareness
-79.9µm/m
23% Reversal spikes Y
▲-8.4µm
▼2.0µm
15% Scaling mismatch
-11.2µm
10% Cyclic error Y
↑3.8µm
↓3.8µm
8% Reversal spikes X
▶-2.8µm
◀-2.0µm

Positional tolerance	52.2µm
Best fit radius	149.9983mm
Circularity	21.3µm

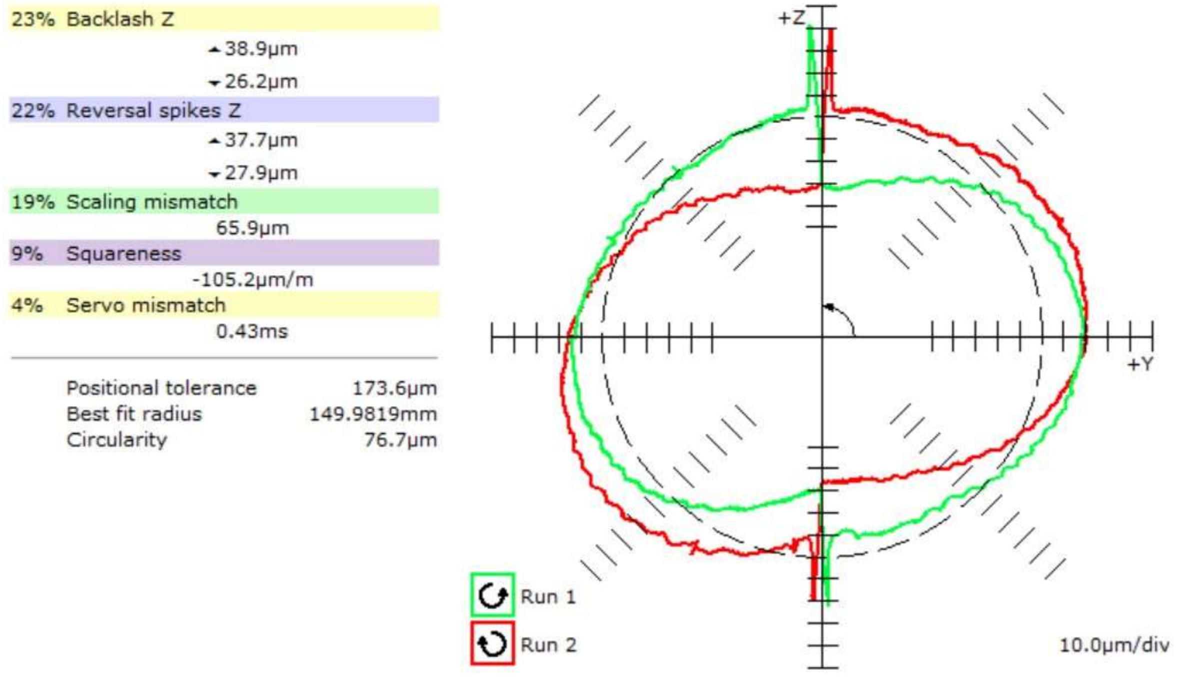
Figure 18 – Steps on the plot show the points where the "pitch errors" have been compensated. The controller did not interpolate the compensation between each other.



40% Reversal spikes Z
▲15.3µm
▼44.0µm
10% Backlash Z
▲7.5µm
▼10.5µm
6% Straightness Z
12.7µm
4% Servo mismatch
0.24ms
4% Straightness Y
7.8µm

Positional tolerance	40.4µm
Best fit radius	150.0019mm
Circularity	87.8µm

Figure 19 – Vibrations occur close to 45°, where the feed speed of both axes is similar, as though a resonance might cause them.



23% Backlash Z
▲38.9µm
▼26.2µm

22% Reversal spikes Z
▲37.7µm
▼27.9µm

19% Scaling mismatch
65.9µm

9% Squareness
-105.2µm/m

4% Servo mismatch
0.43ms

Positional tolerance	173.6µm
Best fit radius	149.9819mm
Circularity	76.7µm

Figure 20 – The plot shows how the measurement of circular interpolation, simple and fast, identifies in few minutes numerous deviations.

6. MEASUREMENT ON THE THREE COORDINATE PLANES

On milling machines, boring machines and machining centres, mostly when the spindle has only one orientation (parallel to the Z-axis), the XY plane has often been considered as the only important plane for contouring operations, and consequently for interpolation tests.

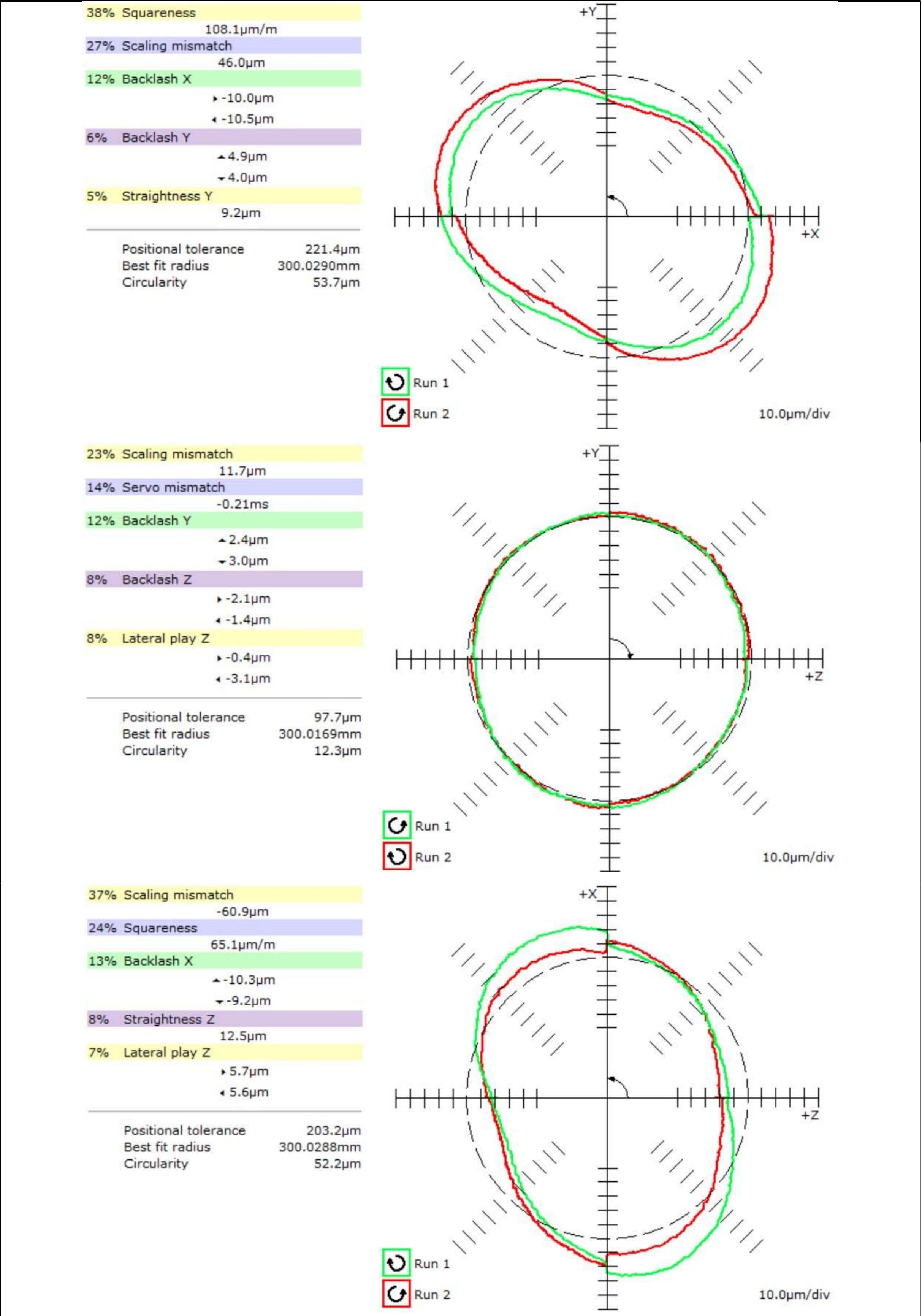
The practical experience has proved the opposite, as shown in the following figures. The first reason is that machines with universal spindle heads can generally perform contouring operations in several planes, but even without this feature the test in the three coordinate planes can reveal unexpected performance.

Figure 21 shows the three plots of measurements carried out one after the other on a 4-axes machining centre with horizontal spindle.

Figure 22 shows the outcome of the three measurements on another machine. One single measurement in the XY plane could not provide such a thorough information.

Similarly, only the ZX plane has often been considered on lathes and turning centres, for obvious reasons, but nowadays many machines are equipped with the Y-axis (although they are often quite short), making therefore useful the measurement in three planes on turning centres as well.

Moreover, though the measurement is carried out on a circular path, its purpose is not limited to forecast or analyze the machine performance in a contouring operation, but it provides, as shown, much more information, not always achievable by other instruments.



38% Squareness
108.1µm/m
27% Scaling mismatch
46.0µm
12% Backlash X
▸ -10.0µm
◂ -10.5µm
6% Backlash Y
▴ 4.9µm
▾ 4.0µm
5% Straightness Y
9.2µm

Positional tolerance	221.4µm
Best fit radius	300.0290mm
Circularity	53.7µm

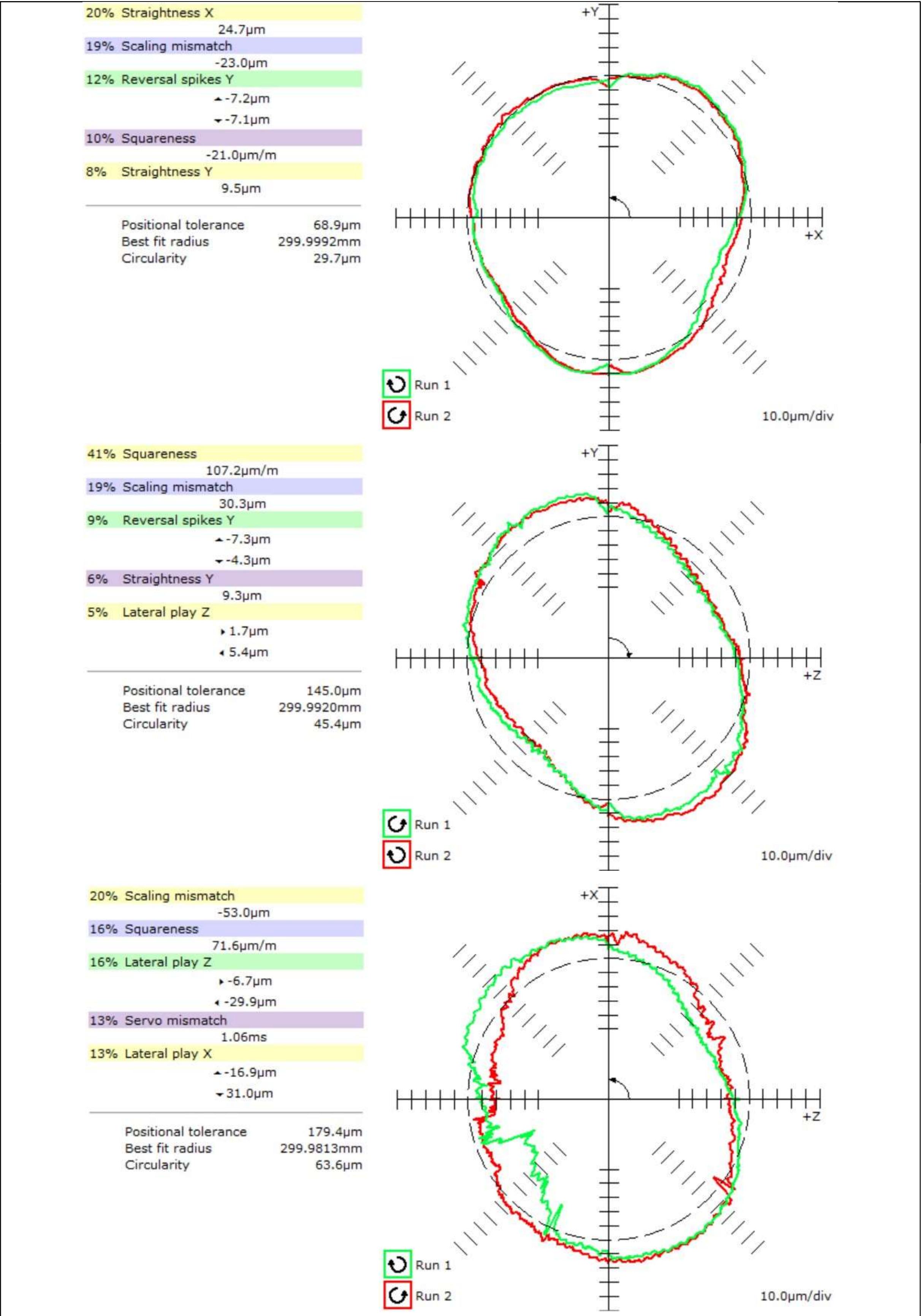
23% Scaling mismatch
11.7µm
14% Servo mismatch
-0.21ms
12% Backlash Y
▴ 2.4µm
▾ 3.0µm
8% Backlash Z
▸ -2.1µm
◂ -1.4µm
8% Lateral play Z
▸ -0.4µm
◂ -3.1µm

Positional tolerance	97.7µm
Best fit radius	300.0169mm
Circularity	12.3µm

37% Scaling mismatch
-60.9µm
24% Squareness
65.1µm/m
13% Backlash X
▴ -10.3µm
▾ -9.2µm
8% Straightness Z
12.5µm
7% Lateral play Z
▸ 5.7µm
◂ 5.6µm

Positional tolerance	203.2µm
Best fit radius	300.0288mm
Circularity	52.2µm

Figure 21 – Interpolation in the three planes of the same machine



```
20% Straightness X
          24.7µm
19% Scaling mismatch
          -23.0µm
12% Reversal spikes Y
          ▴-7.2µm
          ▾-7.1µm
10% Squareness
          -21.0µm/m
8%  Straightness Y
          9.5µm

    Positional tolerance      68.9µm
    Best fit radius      299.9992mm
    Circularity               29.7µm
```

```
41% Squareness
          107.2µm/m
19% Scaling mismatch
          30.3µm
9%  Reversal spikes Y
          ▴-7.3µm
          ▾-4.3µm
6%  Straightness Y
          9.3µm
5%  Lateral play Z
          ▸ 1.7µm
          ◂ 5.4µm

    Positional tolerance     145.0µm
    Best fit radius      299.9920mm
    Circularity               45.4µm
```

```
20% Scaling mismatch
          -53.0µm
16% Squareness
          71.6µm/m
16% Lateral play Z
          ▸ -6.7µm
          ◂ -29.9µm
13% Servo mismatch
          1.06ms
13% Lateral play X
          ▴-16.9µm
          ▾31.0µm

    Positional tolerance     179.4µm
    Best fit radius      299.9813mm
    Circularity               63.6µm
```

Figure 22 – Interpolation in the three planes of the same machine

Figure 23 – Milling and boring machine – Measurement in the YZ plane

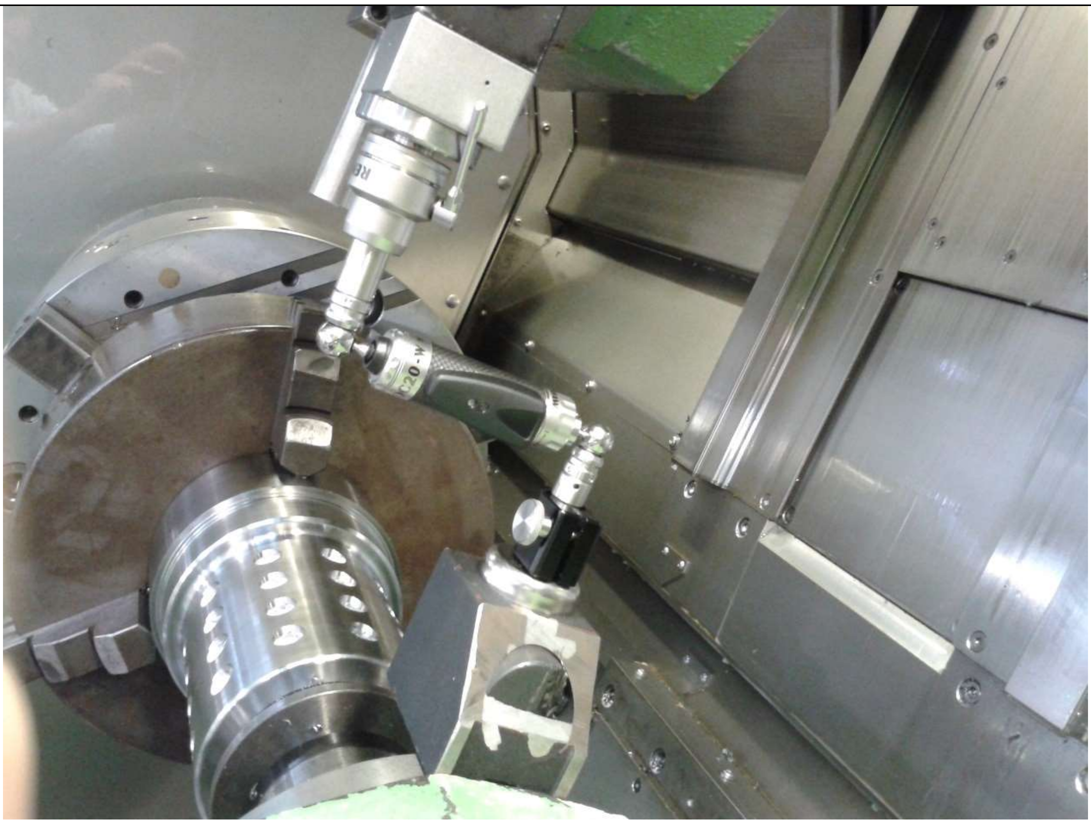


Figure 24 – Turning centre with Y-axis – Measurement in the YZ plane