Calibration of machine squareness

by M.A.V. Chapman

Introduction

This paper describes a variety of methods for evaluating the squareness between the linear axes of motion of a machine tool, in accordance with the 2012 version of ISO230-1 (Test code for machine tools - Geometric accuracy of machines operating under no-load or quasi-static conditions). Computer simulation is used to compare and contrast the squareness results that each method produces, depending on the squareness, straightness and angular (pitch or yaw) errors present in the machine's axes and the location of the test within the machine's working zone. The paper concludes with a performance comparison table and advice on how to evaluate and apply machine squareness errors as part of a volumetric accuracy compensation process.

Squareness between two axes of linear motion - definitions

ISO230-1 section 3.6.7 defines the squareness error between two axes of linear motion as *"the difference between the inclination of the reference straight line of the trajectory of the functional point of a linear moving component with respect to its corresponding principal axis of linear motion and (in relation to) the inclination of the reference straight line of the trajectory of the functional point of another linear moving component with respect to its corresponding principal axis of linear motion."*

ISO230-1 states that the reference straight lines may be obtained by straight line fitting the measured trajectory of a functional point on each axis using either;

a) the mean minimum zone reference straight line, or

b) the least squares fit reference straight line, or

c) the end-point fit reference straight line

Figure 1 illustrates the various fitting methods. The red traces show the variation in straightness deviation (i.e. the trajectory) recorded as the axis moves. The dotted blue lines indicate the reference lines obtained by fitting using either minimum zone, least squares or end point methods. The inclination (slope) of the reference line is indicated on the end point fitted trace. Note that the inclination of the reference line is likely to vary according to the fitting method used. The most widely used fitting methods are end point and least squares because of the ease of calculation. It is advisable to use the same fitting method for both reference lines when calculating the squareness error. All reference line fitting calculations in this paper are based on the least squares method.

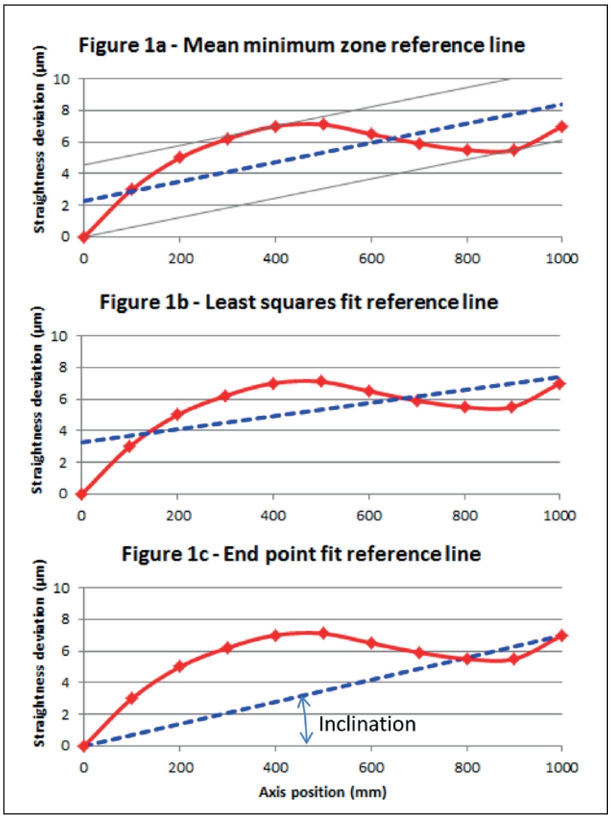

Figure 1

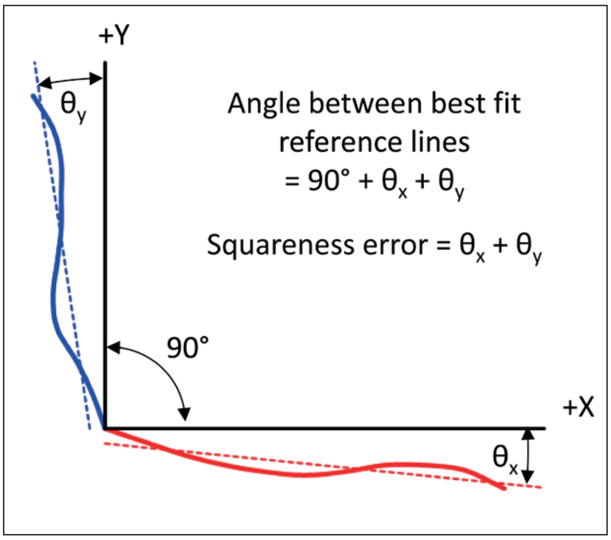

Figure 2

Figure 2 illustrates how the squareness error between two linear axes of motion is calculated. The solid black lines represent the X and Y axes of the machine. The solid red and blue lines represent the variation in straightness deviation in the motion of the X and Y axes (i.e. their trajectories) recorded along the length of the axis. Note that the scale of these deviations has been greatly exaggerated for clarity. The dotted red and blue lines show the least squares fitted reference lines to each of these trajectories. The inclination, (slope), of the reference lines are shown as θ_x and θ_y. In this example, the squareness error is calculated by adding θ_x and θ_y. Note that there are various alternative sign conventions that can be used. Renishaw's ballbar and laser squareness analysis software indicates a positive squareness result if the angle between the positive directions of the two axes of motion is >90°. This sign convention is used throughout this paper.

Notes:

1. *ISO230-1 recommends a different sign convention based on defining one machine axis as a "datum axis" and the other as the "referred axis" and using the right hand rule to define the direction of the squareness error as a rotation of the referred axis relative to the datum axis. In Figure 2 above, if X is taken as the datum axis, then the squareness error of Y relative to X is +ve. But, if Y is taken as the datum axis, the squareness error of X relative to Y is -ve. To avoid confusion ISO230-1 recommends also adding a note stating if the angle between the axes is larger or smaller than 90°! Clearly when comparing squareness test results it is important to understand the sign convention that has been used.*
2. *Although ISO defines the inclination of the reference lines relative to their respective machine axis (X, Y or Z), when the squareness error is measured, the inclinations are typically measured relative to the orthogonal lines defined by a reference artefact or laser beams. The end result is the same, however, there may be an error in the squareness of the artefact, indexer or optical prism which needs to be included in the calculation. If the error is not known, the reference may need to be reversed, the measurement repeated and the average squareness result used.*
3. *A squareness result is said to be "global" if it is based on a test using the full working length of the machine's axes. Tests involving portions of the axes give a "local" squareness result.*

Squareness between two axes of linear motion - test methods

ISO230-1:2012 now includes five methods for assessing machine squareness, as follows;

1) Mechanical square and indicator (section 10.3.2.2)
2) Mechanical straightedge, indicator and indexing table (section 10.3.2.3)
3) Optical square and laser straightness interferometer (section 10.3.2.4)
4) Circular test (section 10.3.2.6 and ISO230-4)
5) Diagonal displacement test (section 10.3.2.6 and ISO230-6)

Each method will now be described on more detail.

Method 1 – Bi-axial straightness test using a mechanical square and indicator

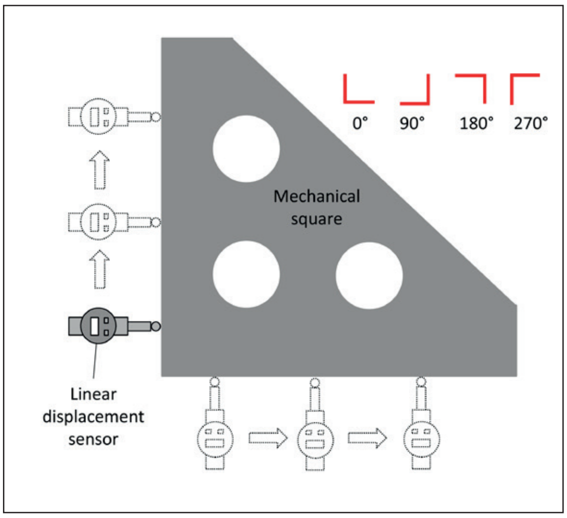

Figure 3

This method involves positioning a mechanical square such that it is nominally aligned to the machine axes of interest and then measuring the straightness deviation of each axis in turn, using a linear displacement sensor (e.g. digital indicator or clock gauge). This setup is illustrated in Figure 3. This configuration is referred to as "L" shaped in this paper. Once the straightness data has been collected for both axes, the inclination (slope) of each set of data is calculated (by least squares, end point, or minimum zone fitting) and the two inclinations are compared to give the squareness error. Care needs to be taken to ensure the correct sign conventions are used throughout, depending on the orientation of the square, the indicator, and direction sense of the axes.

If a mechanical straightedge is also available, then an alternative "T" shaped arrangement is possible as shown in Figure 4. This arrangement has the advantage that it can be reversed (left to right mirror image of Figure 4) to eliminate any error in the square by using the reversal technique. It also allows testing of one of the axes close to the centre of the machine's working zone.

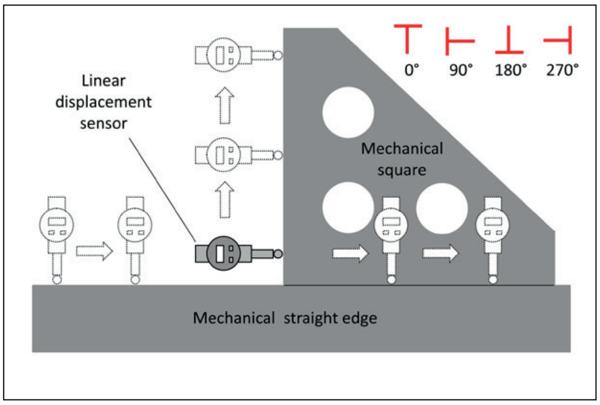

Figure 4

Note that when measuring the squareness of two horizontal axes, it is possible to use the "L" and "T "shaped set-ups in four different orientations (0°, 90°, 180° or 270°) by rotating the equipment accordingly. However, when one of the axes is vertical, only two "L" shaped orientations (0° and 90°), or one inverted "T" shape (180°) are straightforward. The different orientations are mentioned here because they are included in the simulations later.

Method 2 – Bi-axial straightness test using straightedge, indicator and indexing table

This method utilises a mechanical straightedge mounted on an angular indexer. After measuring the straightness deviation of the first axis the indexer is used to rotate the straightedge through 90° so that the straightness of the second axis can be measured. This method is illustrated in Figure 5 and is referred to as the "+" shaped configuration in this paper.

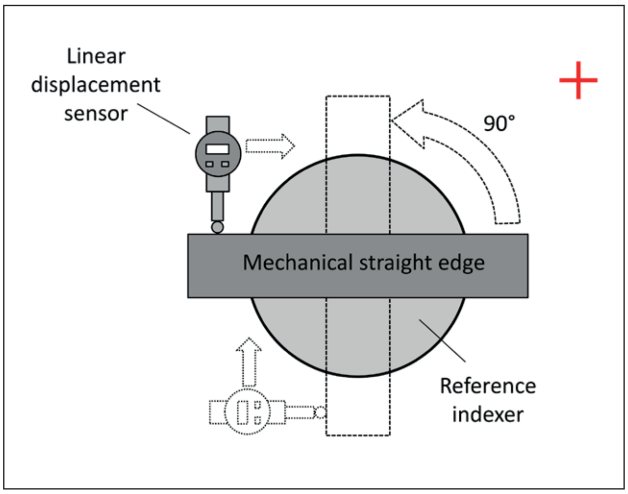

Figure 5

The squareness is calculated in the same way as Method 1.

The advantage of this method is it allows testing of both machine axes whilst they are positioned close to the centre of the working zone. However it does require a precision indexer with an accuracy which is better than the accuracy of the squareness result required.

Method 3 – Bi-axial straightness test using optical square and laser straightness interferometer

This method uses a laser interferometer system, (such as Renishaw's XL-80 system), with straightness optics and an optical square. The equipment can be set up (depending on the machine configuration) in either "L" or "T" shaped configurations. Figure 6 shows an "L" shaped configuration which is often used for testing the squareness between two horizontal axes. The setup works as follows; The straightness reflector projects an optical straightedge in space which the optical square turns through 90°. Straightness deviations from these optical straightedges are measured (indicated) by the straightness interferometer.

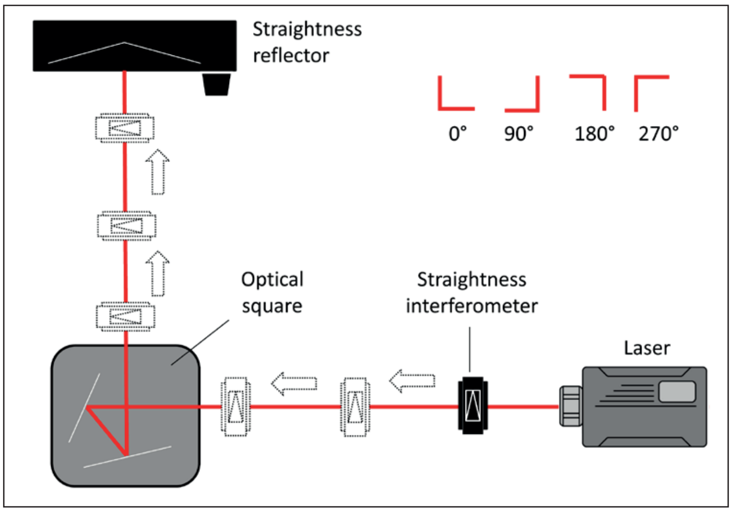

Figure 6

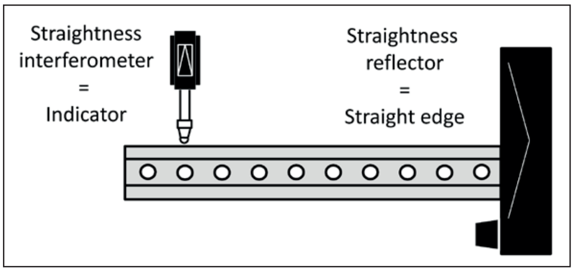

Figure 7

There is a direct analogy between the straightness reflector and optical square in Figure 6 and the mechanical square in Figure 3. Both provide the same "L" shaped reference lines. The straightness deviations from the optical straightedges in Figure 6 are measured by the straightness interferometer, in the same way as the straightness deviations from the mechanical straightedges in Figure 3 are measured by the linear displacement sensor. The direct analogy between a mechanical straightedge with an indicator and a straightness reflector with an interferometer is illustrated in Figure 7 and explained in more detail in the Renishaw white paper entitled "TE325 - *Interferometric Straightness Measurement and Application to Moving Table Machines*". Again, when measuring the squareness of two horizontal axes, it is possible to arrange the components in any of four "L" shaped orientations (0°, 90°, 180° or 270°) by rotating the equipment accordingly, depending on machine access limitations. All four "L" shaped orientations have been included in the simulations later.

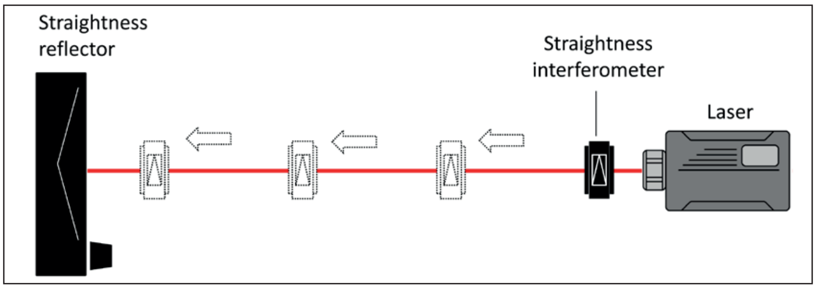

Figure 8a

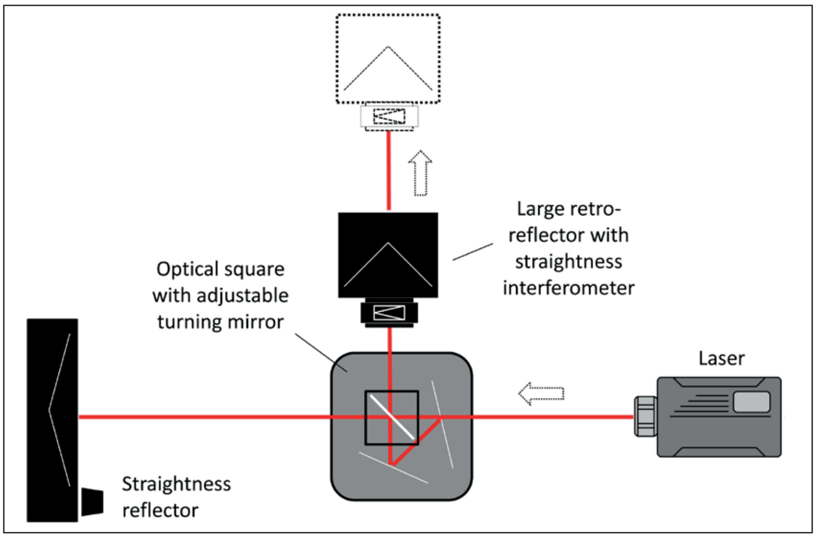

Figure 8b

It is also possible, by using an additional turning mirror and large retro-reflector to rearrange the components and carry out the test in a "T" shaped configuration, as shown in Figures 8a & b. This configuration is often used when one of the axes being tested is vertical. The horizontal axis is tested using the laser, straightness interferometer and reflector, as shown in Figure 8a. The vertical axis is tested with the turning mirror, optical square and large retro-reflector added, as shown in Figure 8b. Note that it is essential that the alignment of the straightness reflector is not altered between the measurements of each axis since it generates the reference line for both tests. Again there is a direct analogy between the laser interferometer measurements shown in Figures 8a and b, and those obtained with a mechanical square, as shown in Figure 4.

The squareness results are calculated in exactly the same way as in methods 1 & 2 although, due to manufacturing tolerances, it is usually necessary to include a small correction for a tiny error in the angle of the optical square, often referred to as the “prism error”. This correction is applied automatically by the analysis software, after the user has entered a “prism error” value.

The benefit of laser based measurements is that they can easily be used to provide global squareness measurements on large machines where suitable mechanical straightedges and squares may be unavailable, overly cumbersome or expensive, and can cause mechanical distortion of the machine structure due to their weight.

Method 4 - Circular test

For machines capable of carrying out precise circular interpolation under CNC control, machine squareness can be determined using a dynamic circular test with a telescoping ballbar, such as Renishaw’s QC20-W, as shown in Figure 9. This test method is described in ISO230-4. The machine is programmed to move at a low feedrate over a 360° circular path (shown by the red dotted line) in CW then CCW directions. One end of the telescoping ballbar is attached to a pivot on the machine table at the centre of the circle. The other end is attached to a pivot attached to the machine spindle. As the machine moves around the circle, a sensor in the ballbar measures any variation in the radius to produce an error trace (as shown exaggerated in solid red). If there is a squareness error, the mean CW and CCW ballbar error trace will have an elliptical shape as shown. The squareness error can be estimated by comparing the lengths of the 45° diagonals (i.e. the major and minor axes of the ellipse). Renishaw’s ballbar plot diagnosis software carries out extensive calculations to isolate the squareness error from any other machine errors (e.g. backlash, servo, scale mismatch, cyclic, straightness errors) that may be present; thereby ensuring the squareness result is not contaminated by these errors. Renishaw’s software also allows estimation of squareness from partial arc tests (down to 220°).

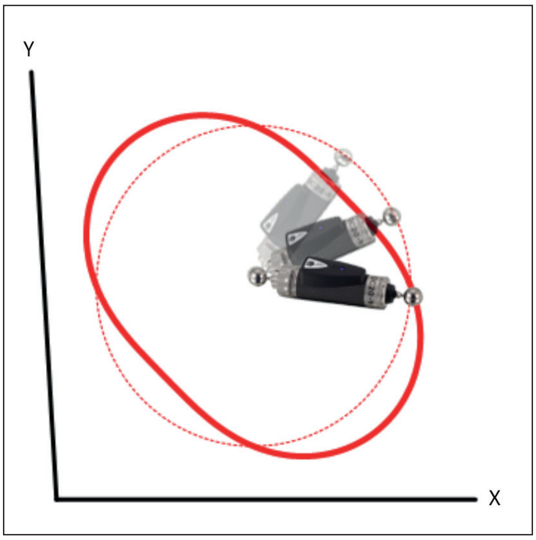

Figure 9

The advantage of the ballbar test is that it is quick and simple. The speed of the test means the squareness results are largely unaffected by the environmental variations (e.g. thermal drift) which can affect other methods. Extension bars can be used to alter the test radius, from 50mm – 1000mm, allowing testing of a wide range of machine sizes. Tests can be carried out at several locations and the results averaged to evaluate the squareness of machines with significant differences in axis lengths, (this technique is covered in more detail towards the end of this paper).

In the case of machines that cannot carry out circular interpolation (e.g. a CMM), a test can be carried out with Renishaw’s Machine checking gauge (MCG) instead - see Figure 10. Alternatively on smaller machines the test may be carried out using a Renishaw probe and ring gauge.

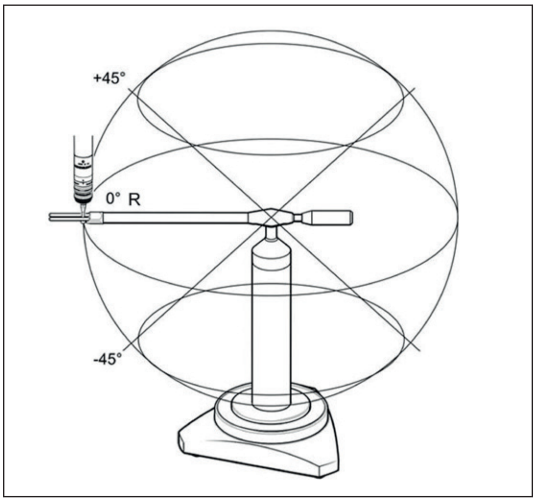

Figure 10

Method 5 - Diagonal displacement test

The final method for assessing machine squareness involves using a laser interferometer system, (such as Renishaw's XL-80 system) with linear optics to measure the length of two diagonals, as shown in Figure 11. This test method is described in ISO230-6. Typically the laser is aligned to allow the measurement of the length of the first diagonal. The laser is then realigned to allow measurement of the second diagonal. It is essential that the portion of each axis which is traversed during the test is identical for both diagonals and that the effects of any backlash are removed, ideally by measuring the length of each diagonal in both directions and taking the average.

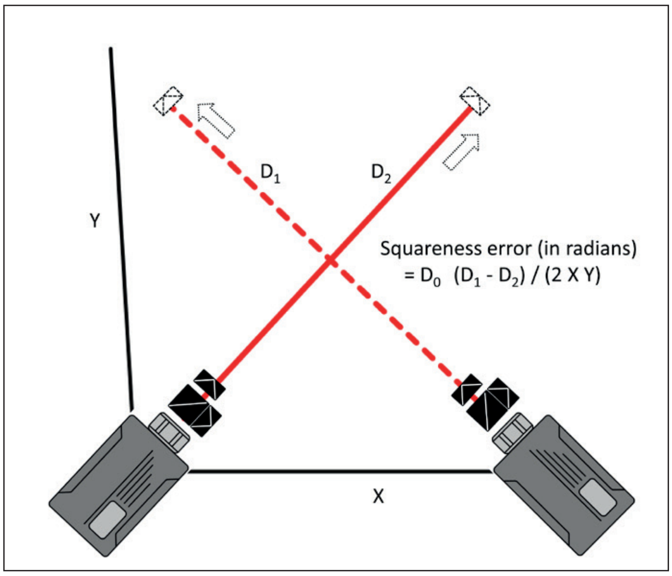

Figure 11

It is also important that the two diagonal lengths are measured promptly one after the other, to minimise the possibility of thermal drift. On small machines care must also be taken to accurately align the laser to the diagonals to minimise cosine errors.

Considering a test in the XY plane, as shown in Figure 11. If X is the programed travel length along the X axis, and Y is the programmed travel length along the Y axis, then the squareness (in radians) is given by;

$$\text{Squareness} = D_0\ (D_1 - D_2)/(2XY)$$

Where D_0 is the nominal diagonal length and D_1 and D_2 are the actual diagonal lengths.

If X=Y then this equation simplifies to;

$$\text{Squareness} = (D_1 - D_2)/\ D_0$$

The advantage of this test is that it is quick and simple and ideally suited to larger machines and those with unequal aspect ratios. The setup is less straightforward when one of the axes is vertical so a turning mirror and swivel joint maybe required. Because the result is based on just two laser distance readings, if the machine has poor repeatability it may be necessary to repeat the test to obtain a good average. Alternatively, data may be taken at multiple positions along each diagonal. The measured displacements are then compared with the programmed displacements. A least squares straight line is fitted to the linear error data for each diagonal and the slopes are compared to determine the squareness error. This paper uses the difference in the overall diagonal lengths to determine the squareness error, as recommended in ISO230-1 and ISO230-6.

Simulation of machine errors

In order to assess the performance of the different squareness test methods, five machines with differing combinations of squareness, straightness and yaw errors were simulated, as illustrated in Figure 12. All five machines have X and Y axes that are 800mm long and the simulation considers distortions in the XY plane only (however the results are generally applicable to other combinations of axes). The blue lines in Figure 12 show the resulting distortion of the XY plane of each machine, magnified 2000x and overlaid on a feint grid of undistorted 100mm squares.

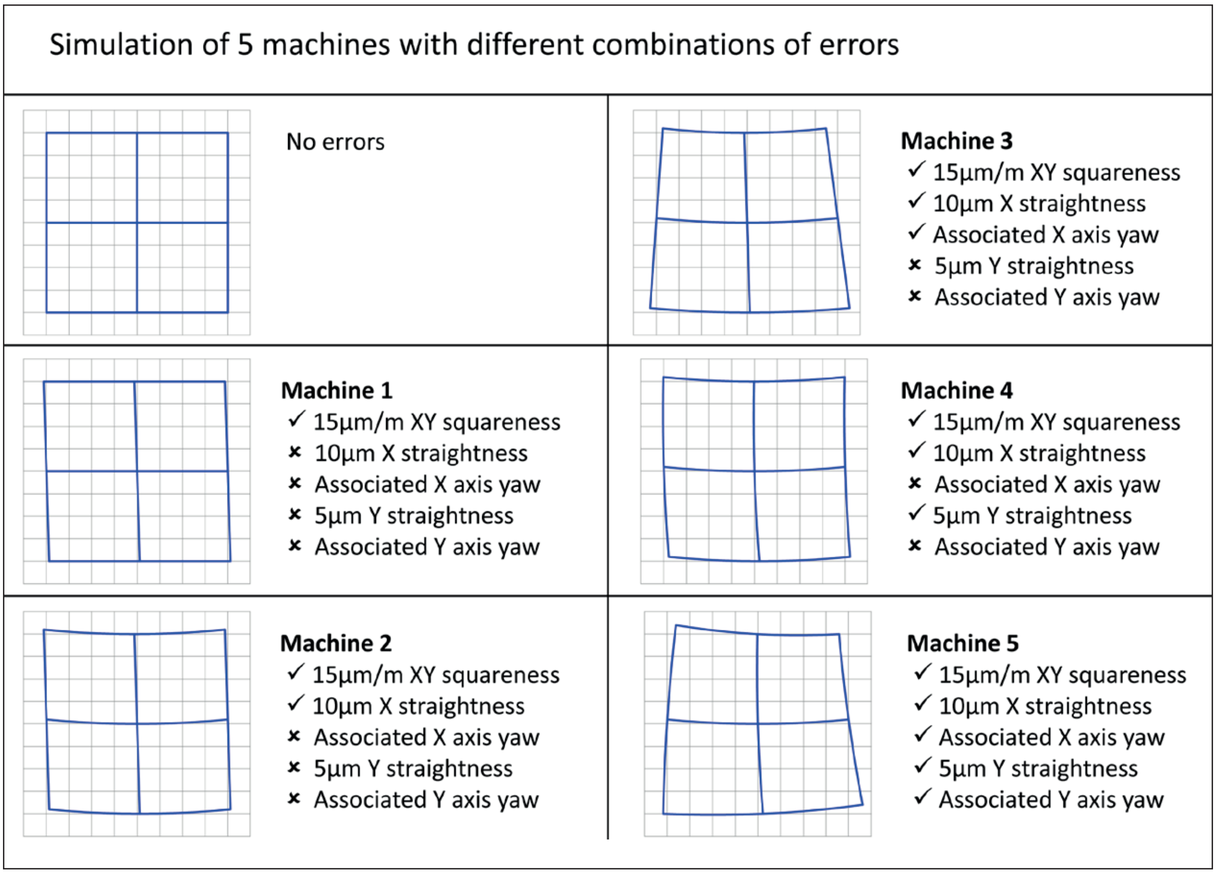

Figure 12

All five machines have an underlying global squareness error of +15µm/m. Superimposed on top of this are various combinations of straightness and yaw distortion errors from the X and Y axes. Note that when a yaw distortion error is included, the amount is that which would typically be associated with the straightness error in that axis (assuming rigid body kinematics - refer to Appendix 1 for more details). Note that a straightness error does not always cause angular distortion of the machine's XY plane, it depends on the machine's kinematic construction (the kinematic chain). This is why the simulations include straightness error combinations both with, and without, the associated yaw induced distortions. If the axis with a straightness error supports the work-holder then any resulting yaw in that axis is likely to distort the working volume as shown by Machines 3 and 5. If however the axis with the straightness error supports only the tool then, even if there is a yaw error, it will not induce an angular distortion of the machine's XY plane. These error combinations have been deliberately chosen to highlight differences in the ways the various test methods react when angular and straightness errors (which can cause local variations in squareness), are superimposed on top of a global squareness error. Machines 3 and 5 are of particular interest because, although they contain variable degrees of yaw induced distortion, they have a uniform local and global squareness distortion of 15 µm/m.

Simulation modes

Because of the direct analogy between a mechanical straightedge with indicator and a straightness reflector with interferometer, the simulation results from these two methods in “L” and “T” shaped configurations will be identical. Five different simulation modes can therefore be used to cover all the test methods and equipment combinations described earlier. The five simulation modes (a-e), and the test method/equipment they apply to, are listed below.

a. Circular test using telescoping ballbar
b. Laser diagonal test using laser interferometer and linear optics
c. Bi-axial straightness tests in “+” shaped configuration using;
    - Mechanical straightedge, indicator and 90° indexer
d. Bi-axial straightness tests in “T” shaped configuration using;
    - Mechanical straightedge, square and indicator, **or**
    - Laser straightness interferometer, optical square, large retro-reflector and turning mirror.
e. Bi-axial straightness tests in “L” shaped configuration using;
    - Mechanical square and indicator, **or**
    - Laser straightness interferometer and optical square

Figure 13 illustrates the five different simulation modes. As before, the blue lines show the distortion of the XY plane of the simulated machine, overlaid on a feint grid of undistorted 100mm squares. The movement of the machine during the test is shown in red. Any distortion in the movement of the machine is also magnified 2000x. (Note, in the case of the ballbar trace, the red line is auto-scaled and centred to match the scaling of traces typically seen during ballbar test analysis).

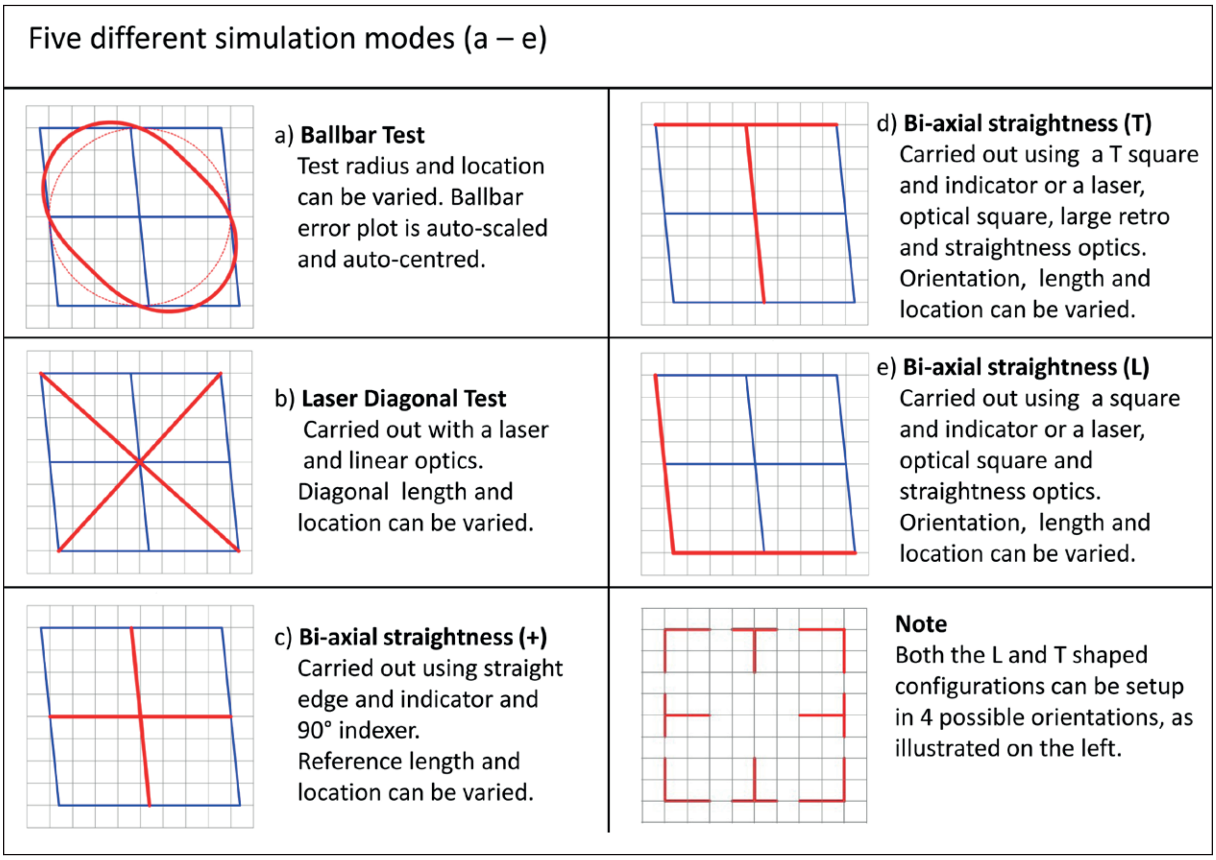

Figure 13

Note that simulation modes d and e can be carried out with the test equipment in four different orientations (0°, 90°, 180°, 270°). The simulation parameters can also be adjusted to vary the size and location of the test equipment within the 800mm x 800mm XY plane of the machine. For example, to simulate a global squareness test the ballbar radius is set to 400mm and the test located in the centre of the XY plane. For local squareness tests, the ballbar radius can be reduced and the test location altered.

Global squareness simulation results – Machine 1

Figure 14 shows the results of the global squareness test simulations for Machine 1, using each of the test simulation modes.

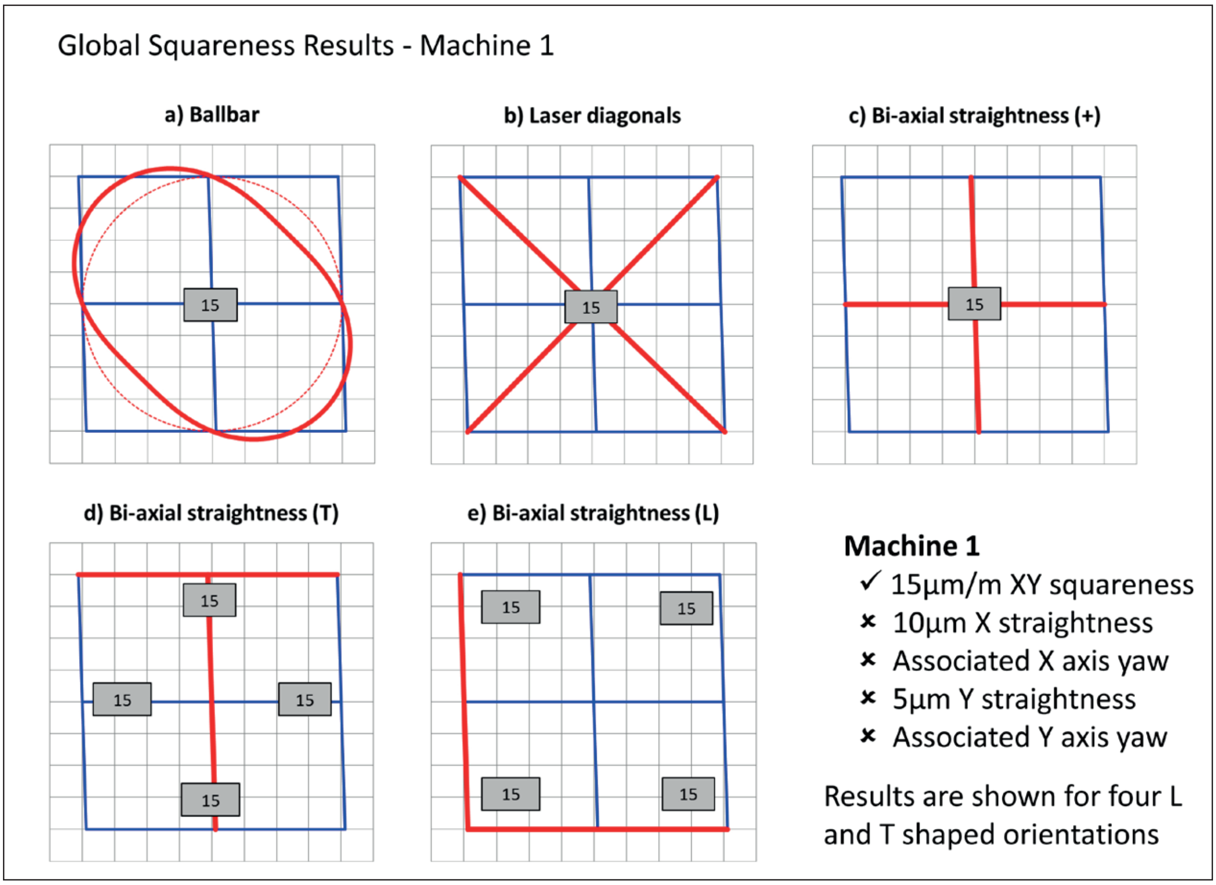

Figure 14

The numbers in the small rectangular boxes show the calculated squareness results from each simulation in µm/m. In the case of the "T" and "L" shaped configurations there are four results, one for each possible orientation of the test equipment. The results are placed close to the intersection of the axis movement paths for the equipment orientation to which they apply, however, only one red "T" or "L" shaped machine movement path is shown for clarity. For example in Figure 14 d) the top result relates to the "T" shaped equipment orientation shown in red. The right hand result relates to a "T" shaped arrangement which has been rotated clockwise by 90°.

The results for machine 1 show that the global squareness result is always 15µm/m irrespective of the test method and equipment orientation. This is exactly as expected since the simulated machine has a global squareness error of 15 µm/m and no other errors.

Global squareness simulation results – Machine 2

Figure 15 shows the results of the global squareness test simulations for Machine 2, using each of the test simulation modes.

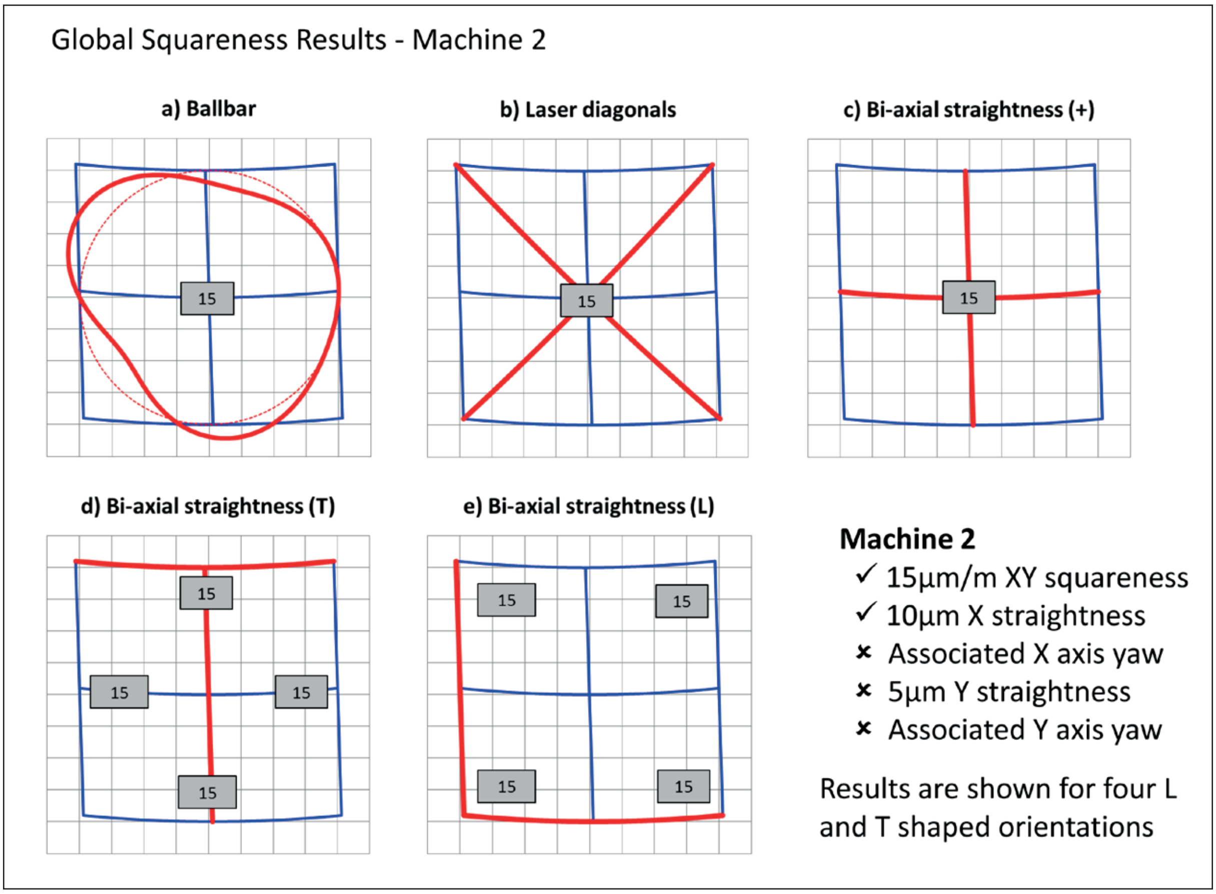

Figure 15

The results for machine 2 show that the global squareness result is again always 15µm/m irrespective of the test method and equipment orientation. This shows the addition of an X axis straightness error has not affected the performance of any of the global squareness test methods.

Global squareness simulation results – Machine 3

Figure 16 shows the results of the global squareness test simulations for Machine 3, using each of the test simulation modes.

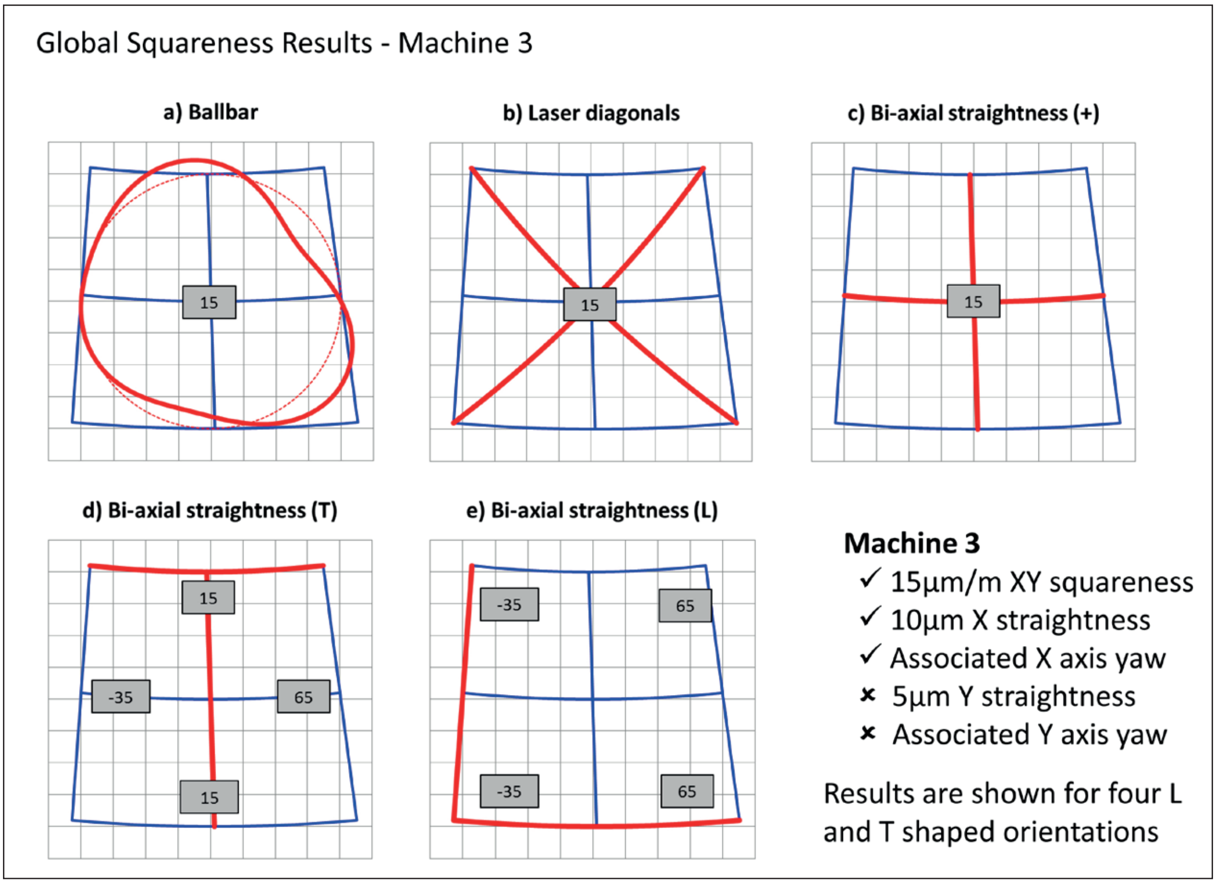

Figure 16

The results for machine 3 show that the global squareness results for the ballbar, laser diagonal and "+" shaped bi-axial straightness methods are again 15µm/m. However, the results for the "T" and "L" shaped test methods have changed. This shows these methods are sensitive to X axis yaw. These results are not "wrong", they simply highlight the change in the angle between the X and Y axes from -35µm/m to +65µm/m as the Y axis is moved from the left hand end of the X axis to the right hand end. Although the "T" and "L" shaped squareness tests involve the full travel of both axes, (and hence are classified as "global" squareness tests), they actually only indicate the squareness between the two axes when tested in a specific position. This comment also applies to the "+" shaped configuration. However, in this example the symmetry of the simulated distortion has ensured the squareness result from the "+" shaped configuration matches the value given by the ballbar and laser diagonal methods. Note that if the "L" or "T" shaped squareness results from opposing corners or sides are averaged, they match the values given by the other methods.

Note: ISO230-1 advises that ideally machine squareness should be evaluated along lines that pass through the centre of the machine's working zone. The above results indicate why. Both lines involved in an "L" shaped test typically lie along the edges of the machine's working zone, and therefore reflect the machine's squareness at the edges, rather than the centre.

Global squareness simulation results – Machine 4

Figure 17 shows the results of the global squareness test simulations for Machine 4, using each of the test simulation modes.

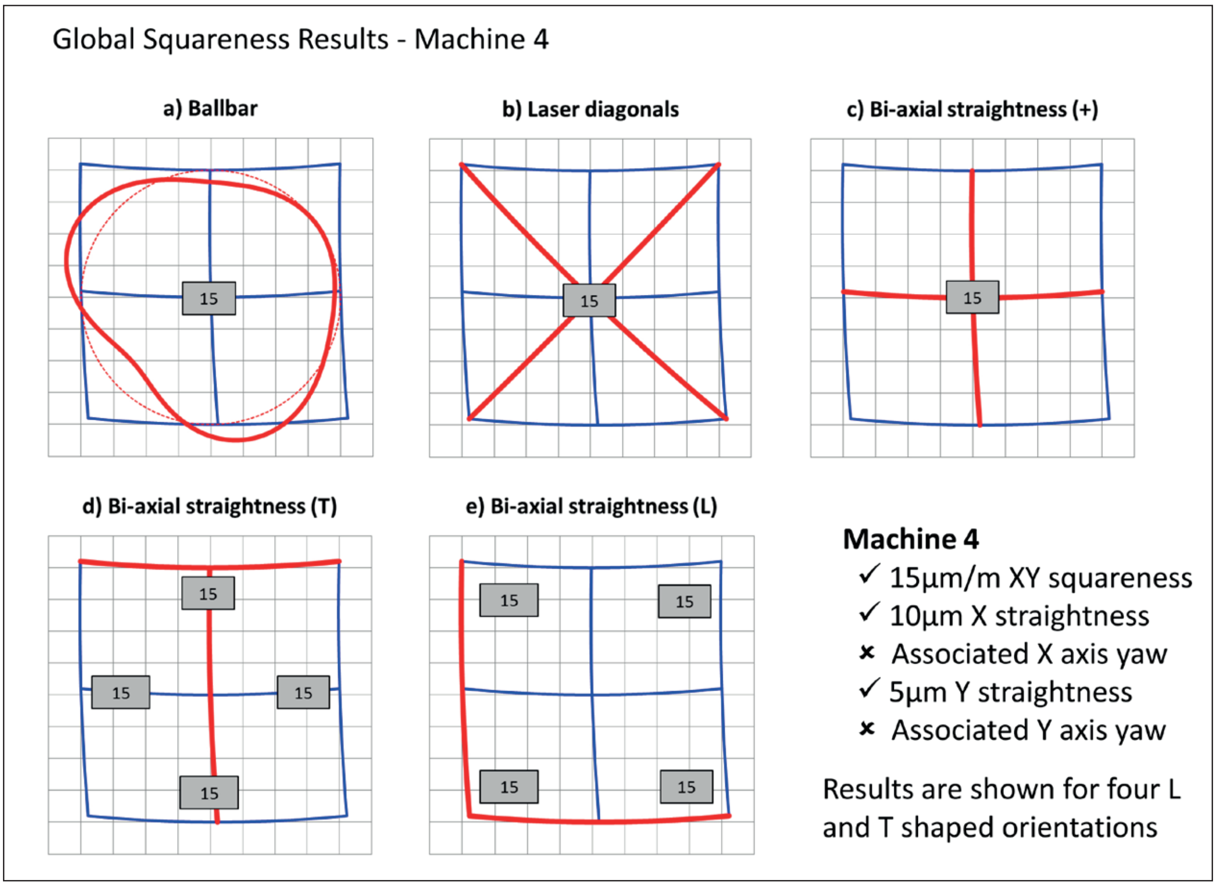

Figure 17

The results for machine 4 show that all the global squareness results are now 15µm/m again, irrespective of the test method and equipment orientation. Now that the yaw error distortion has been removed, all methods give the same result, even though there are now straightness errors on both X and Y axes.

Global squareness simulation results – Machine 5

Figure 18 shows the results of the global squareness test simulations for Machine 5, using each of the test simulation modes.

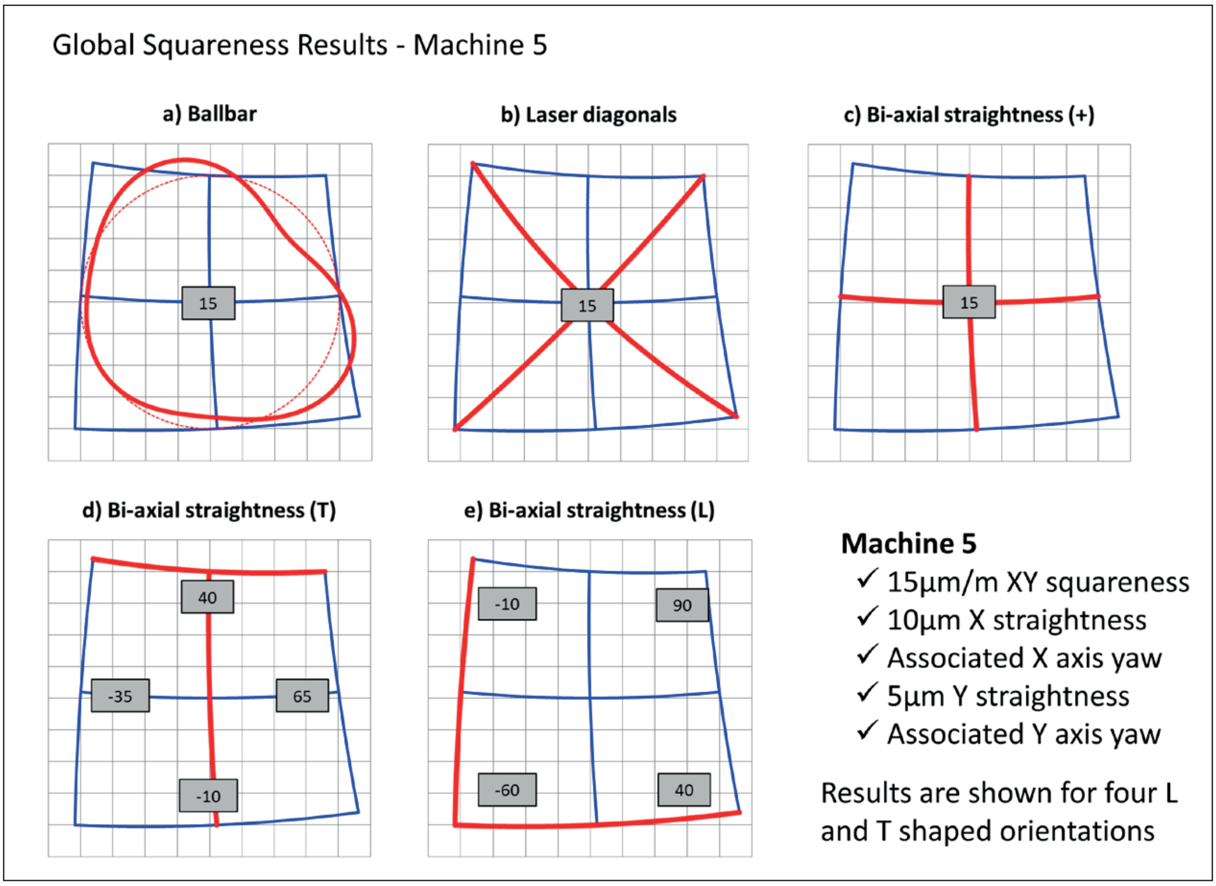

Figure 18

The results for machine 5 show that the global squareness results for the ballbar, laser diagonal and "+" shaped bi-axial straightness methods have remained at 15µm/m. However, the results for the "T" and "L" shaped test methods have changed again due to their sensitivity to X and Y axis yaw. Again, these results are not "wrong", they simply reflect the change in the angle of the X and Y axes as the Y axis is moved from one end of the X axis to the other or as the X axis is moved from one end of the Y axis to the other. Note that if the "L" or "T" shaped squareness results from opposing corners or sides are averaged, they match the values given by the other methods.

Global squareness results - Overview

If the machine's XY plane is not distorted by varying yaw errors, then the global squareness results are the same (15µm/m) for all test methods in all orientations

However, if symmetrically varying yaw errors are introduced to the machine's XY plane then;

- Ballbar, laser diagonal and "+" shaped bi-axial straightness test methods still give the same (15µm/m) global squareness result.
- "T" & "L" shaped bi-axial straightness tests give varying results depending on equipment orientation.

Local squareness simulation results - Machine 1

Local squareness tests have been simulated at five locations within the machine's XY plane using each of the test methods. Figure 19 shows the results of the local squareness test simulations for Machine 1, using each of the test simulation modes. The local squareness is evaluated over just a 200mm length of each axis in the various locations shown.

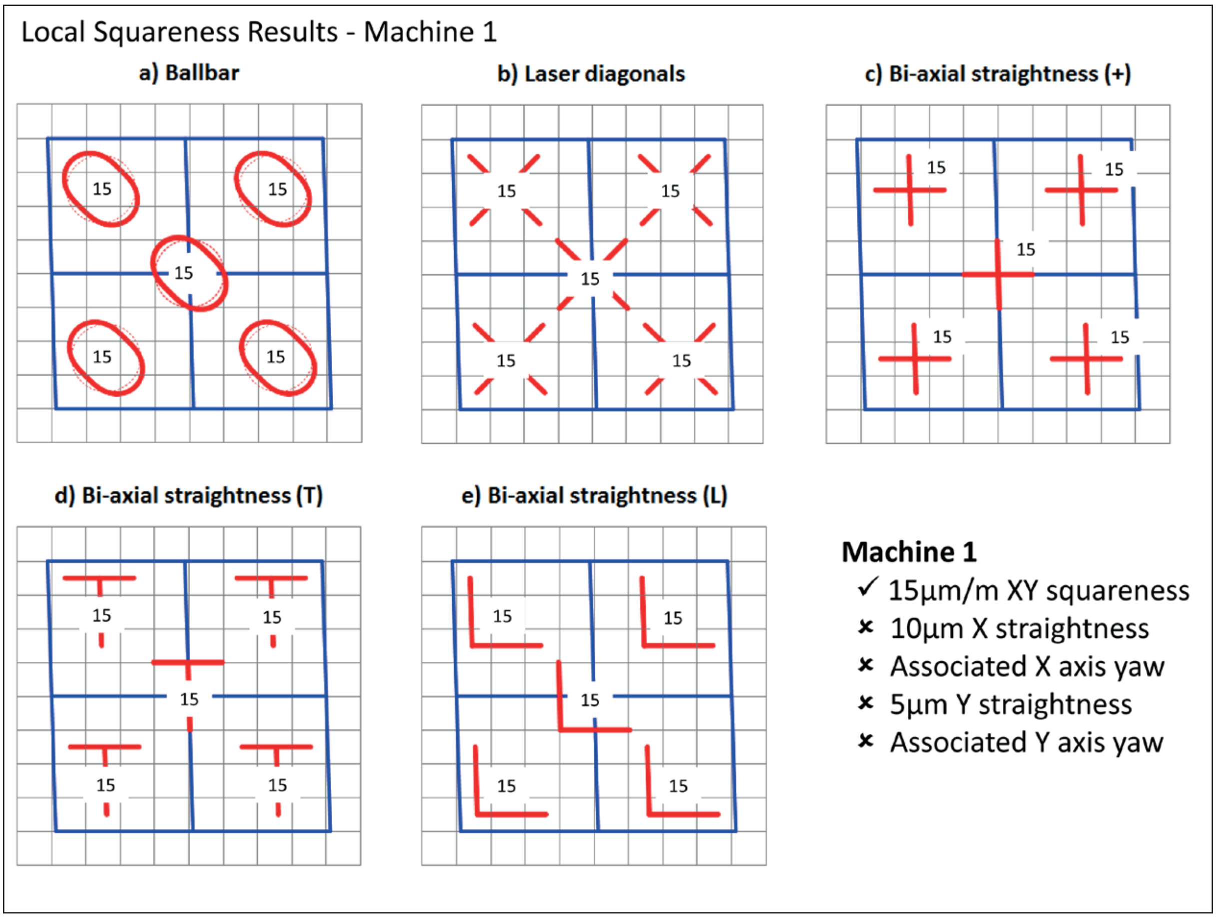

Figure 19

Machine 1 shows local squareness results of 15 µm/m, irrespective of test location and method. This is exactly as expected since the simulated machine has a global squareness error of 15 µm/m and no other errors.

Local squareness simulation results - Machine 2

Figure 20 shows the results of the local squareness test simulations for Machine 2, using each of the test simulation modes.

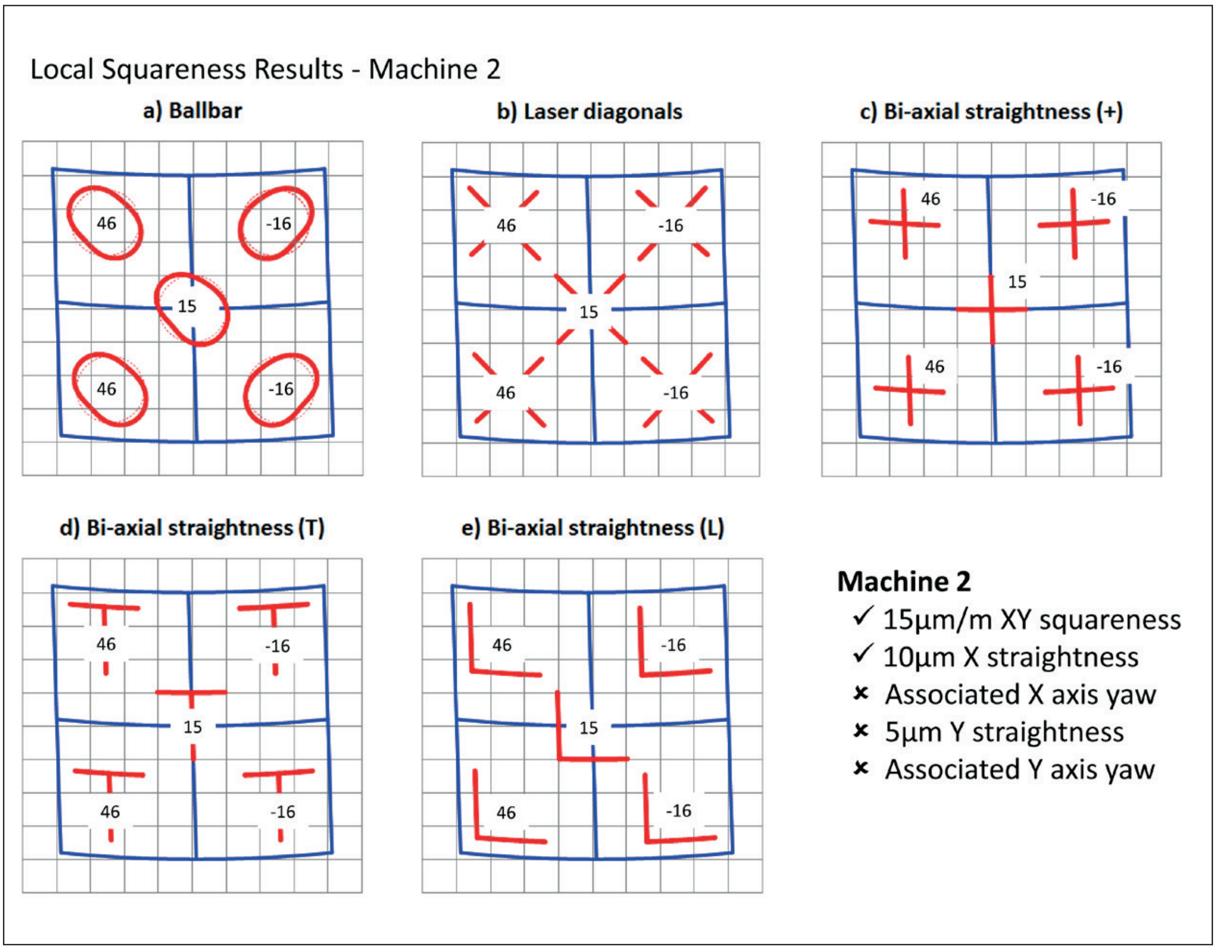

Figure 20

Machine 2 shows local squareness results that vary according to the location of the test, but all test methods give the same results. This shows that the introduction of an X straightness error has caused a variation in local squareness. Clearly on such a machine it is important to choose the location of the test carefully. All test methods give the same results because there aren't any yaw induced angular distortions errors on Machine 2.

Local squareness simulation results - Machine 3

Figure 21 shows the results of the local squareness test simulations for Machine 3, using each of the test simulation modes.

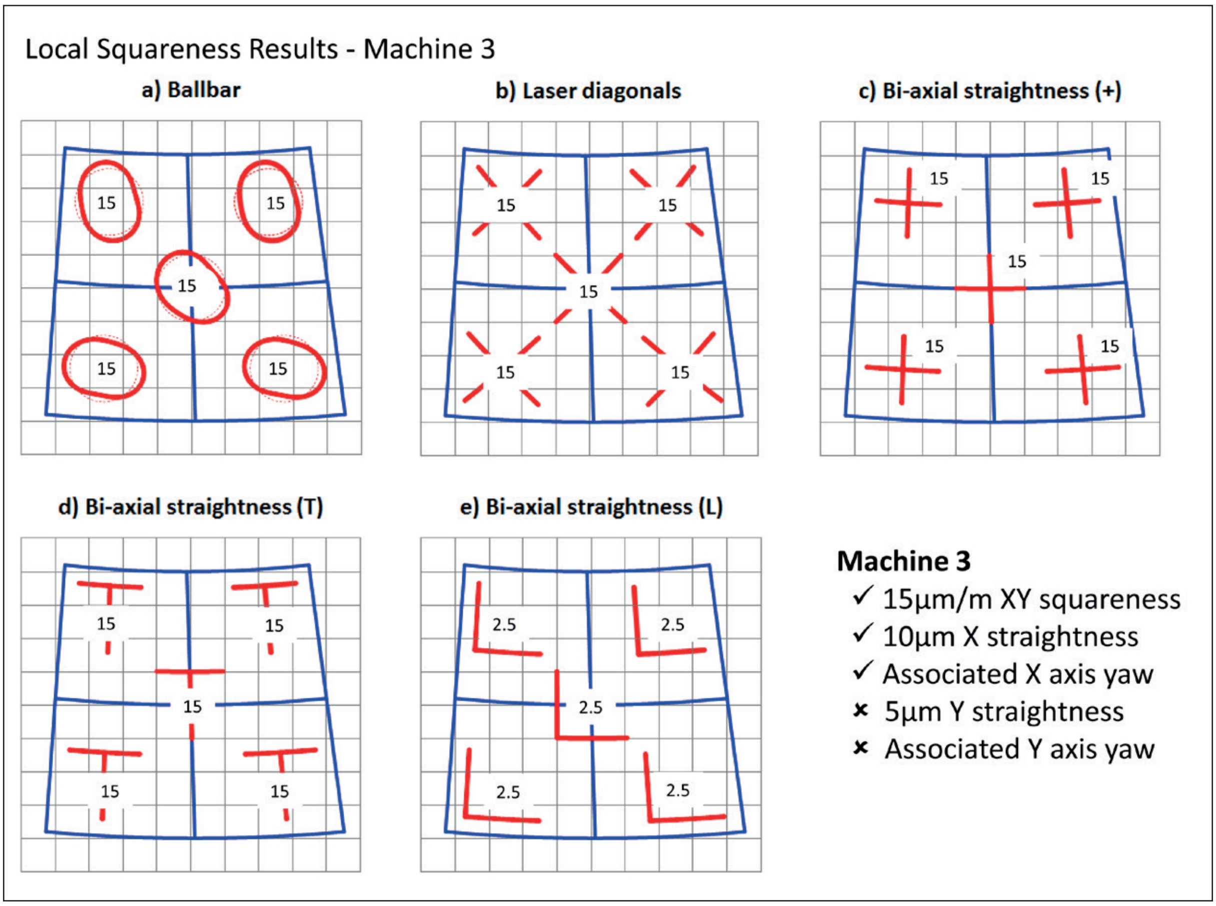

Figure 21

Machine 3 shows local squareness results that vary according to the test method, but not test location. The ballbar, laser diagonal, "+" and "T" shaped bi-axial straightness methods give the same result, but the "L" shaped bi-axial test gives a different result. The consistency of the squareness result, irrespective of test location is interesting. It shows that, if a machine has a straightness error in an axis which induces a corresponding yaw distortion (rigid body model), the local and global squareness is unaffected, even though the machine is clearly "bent".

Local squareness simulation results - Machine 4

Figure 22 shows the results of the local squareness test simulations for Machine 4, using each of the test simulation modes.

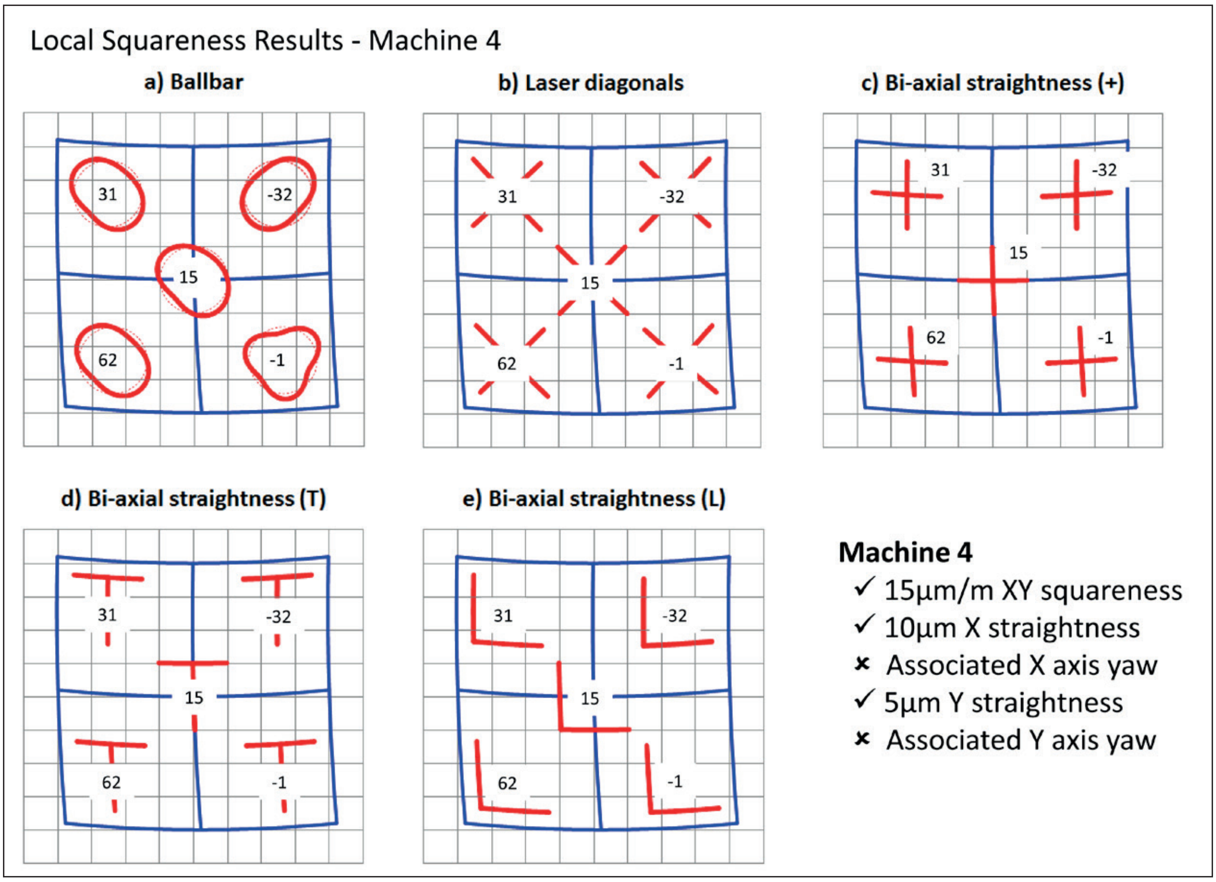

Figure 22

Machine 4 shows local squareness results that vary according to the location of the test, but all test methods give the same results. This shows that the introduction of an X and Y straightness errors has caused a variation in local squareness. Clearly on such a machine it is important to choose the location of the test carefully. All test methods give the same results because there aren't any yaw induced angular distortions errors on Machine 4.

Local squareness simulation results - Machine 5

Figure 23 shows the results of the local squareness test simulations for Machine 5, using each of the test simulation modes.

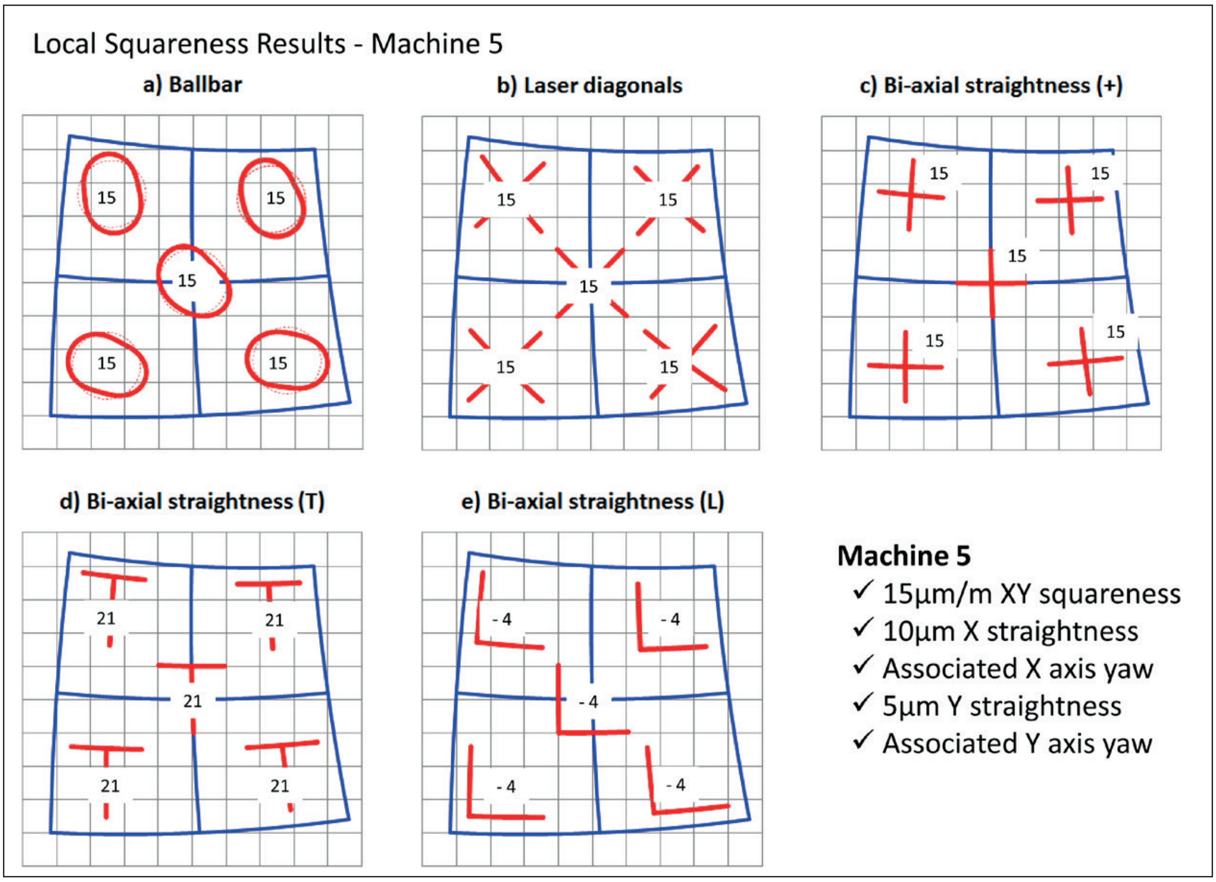

Figure 23

Machine 5 shows local squareness results that vary according to the test method, but not test location. The ballbar, laser diagonal and “+” shaped bi-axial straightness methods give the same result, but the “L” and “T” shaped bi-axial test give different results. The consistency of the squareness result irrespective of test location is again interesting. It shows that, if a machine has a straightness error in two axes which both induce corresponding yaw distortions (simple rigid body model), the local and global squareness is unaffected, even though the machine is clearly “bent”.

Local squareness results - Overview

If a machine contains a straightness error in one or more axes without any corresponding yaw induced angular distortion, then the local squareness will vary with test location but all test methods give the same squareness results.

If a machine contains straightness errors which induce corresponding angular (pitch or yaw) distortion errors, then no local squareness variations are introduced and hence the local squareness test results are independent of test location. However, the local squareness results for “T” and “L” shaped tests differ from those of ballbar, laser diagonal and “+” shaped biaxial tests. Other simulations (not shown) demonstrated that the “T” and “L” shaped local squareness results will also vary depending on equipment orientation, as they do for the global squareness test results under the same conditions.

Testing global squareness errors on machines with unequal aspect ratios

The machines simulated so far have had X and Y axes of equal length. Real machines typically have an X axis that is longer than Y, and a Z axis that is shorter. Testing the global squareness of machines with significant differences in axis lengths requires test equipment that can be configured to handle this. The bi-axial straightness and laser diagonal test methods can easily be adapted to deal with this difference. However, ballbar tests typically rely on a 360° circular test and are therefore best suited to machines with similar axis lengths. Renishaw's advanced ballbar diagnosis software partially addresses this by allowing analysis from a 220° arc, thereby allowing global squareness testing of machines with aspect ratios approaching 1½ : 1.

For machines with larger aspect ratios, it is possible to carry out multiple ballbar tests in a line along the longer axis and then average the squareness results. In order to investigate the performance of this method versus the other test methods, another machine was simulated (Machine 6) with a 750mm long X axis and a 250mm Y axis. The machine has a global squareness error of 15µm/m, an X axis straightness error of 10µm and a Y axis straightness error of 5µm. Figure 24 shows the results of the global squareness test simulations for Machine 6, using each of the test simulation modes.

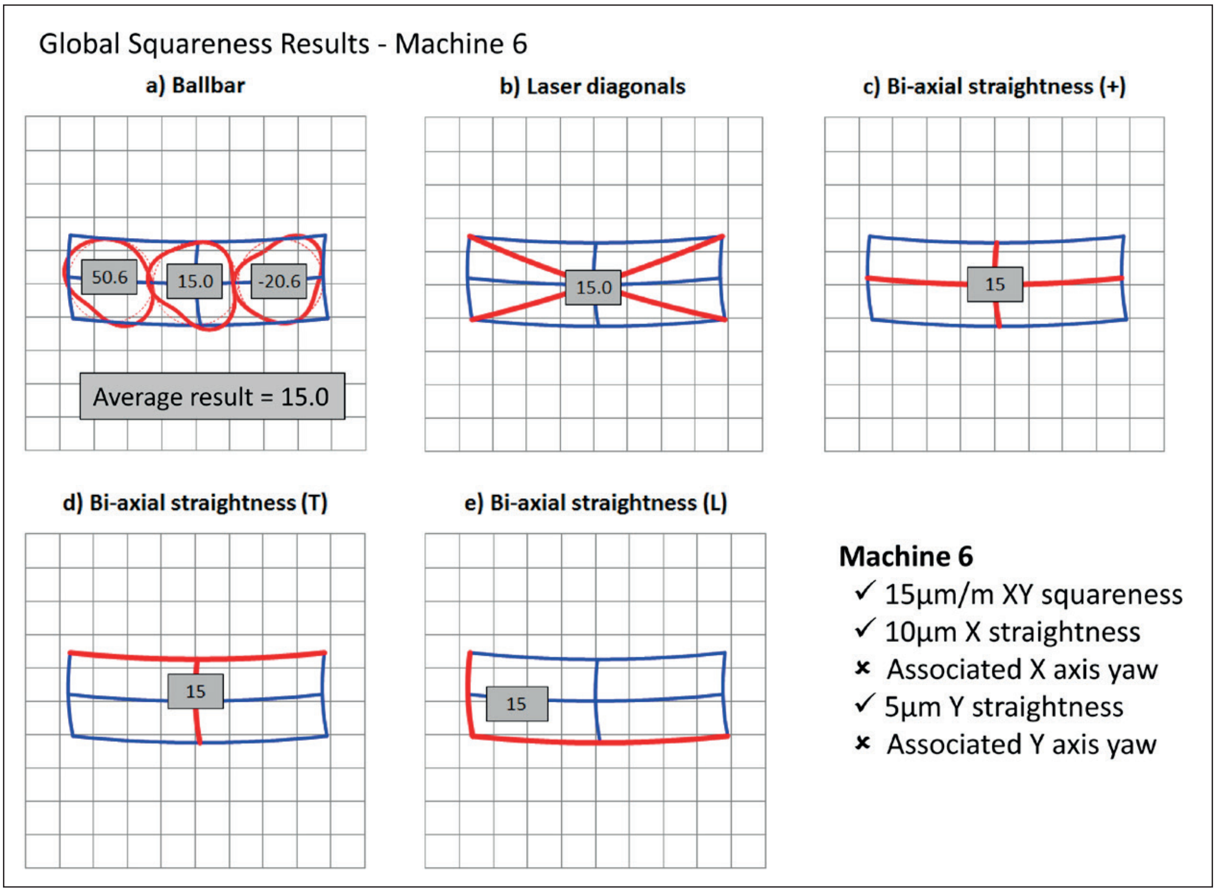

Figure 24

Note that the average of the three ballbar squareness results matches the 15µm/m global squareness results from each of the other test methods.

The straightness errors simulated on machines 1 - 6 have been simple curves. Machines with long thin axes often exhibit more complex forms of straightness error. In order to investigate the performance of the various test methods under such conditions another machine was simulated. Machine 7 is identical to Machine 6 except that its X axis shows a more complex form of straightness error, such as might be shown by an axis supported at its airy points. Figure 25 shows the results of the global squareness test simulations for Machine 7, using each of the test simulation modes.

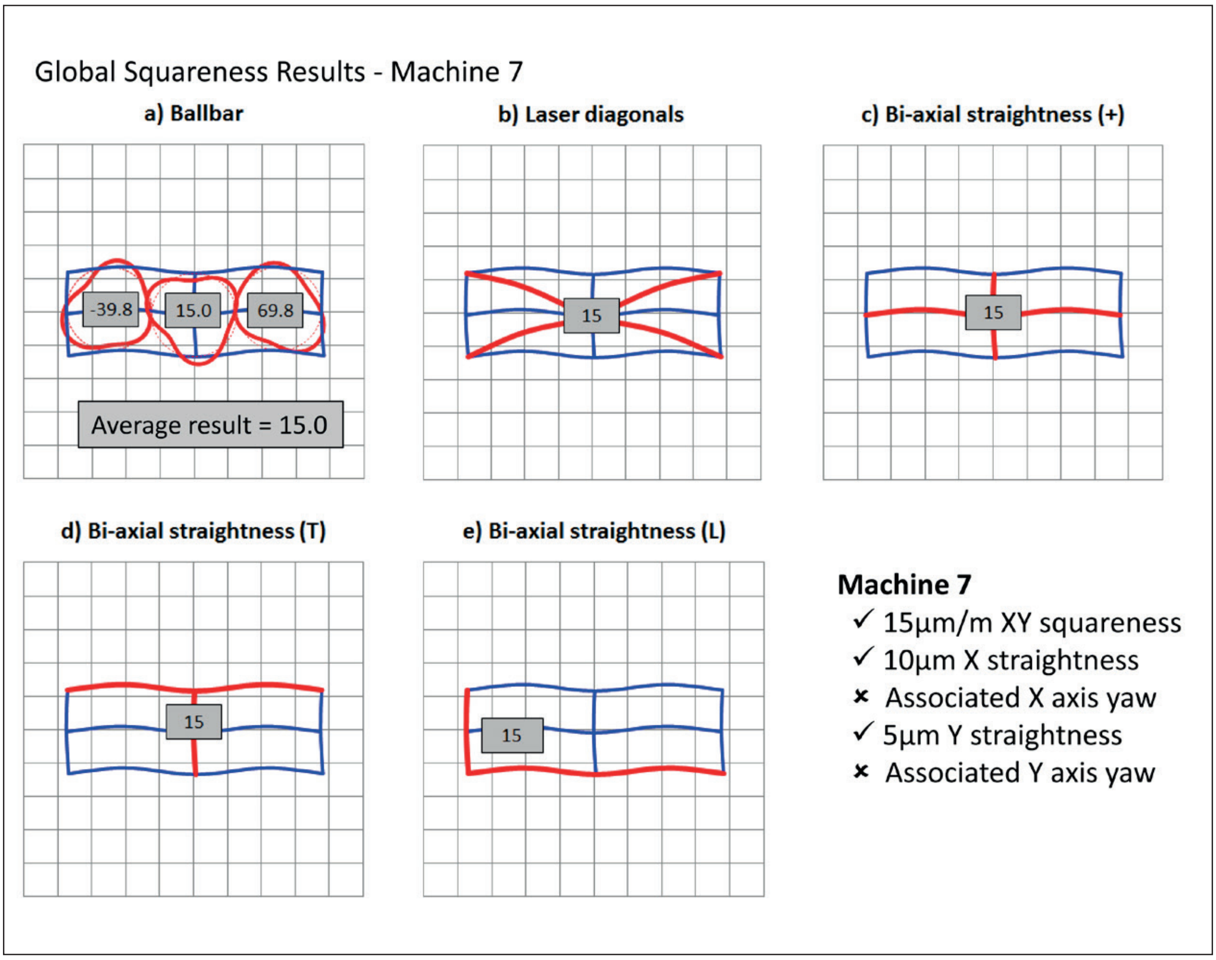

Figure 25

The average of the three ballbar squareness results again matches the global squareness result from each of the other test methods. Note that if associated X and Y axis yaw distortion errors are added in, then the global squareness results obtained from the "T" and "L" shaped bi-axial straightness methods become significantly different at 95 µm/m and 39µm/m respectively. However, the average ballbar squareness and global squareness results from "+" shaped bi-axial straightness and laser diagonal tests remain consistent at 15 arc-seconds.

The tests simulated above conveniently utilise three 125mm radius ballbar tests which exactly fit within the 750mm x 250mm area of the machine. However, on most machines it isn't possible to exactly fit several ballbar test circles into the machine's working area. Under these conditions it is possible to use overlapping circles that are evenly spaced. In order to investigate the performance of this method, 4 overlapping ballbar tests were simulated on machines 6 and 7 as shown in Figure 26.

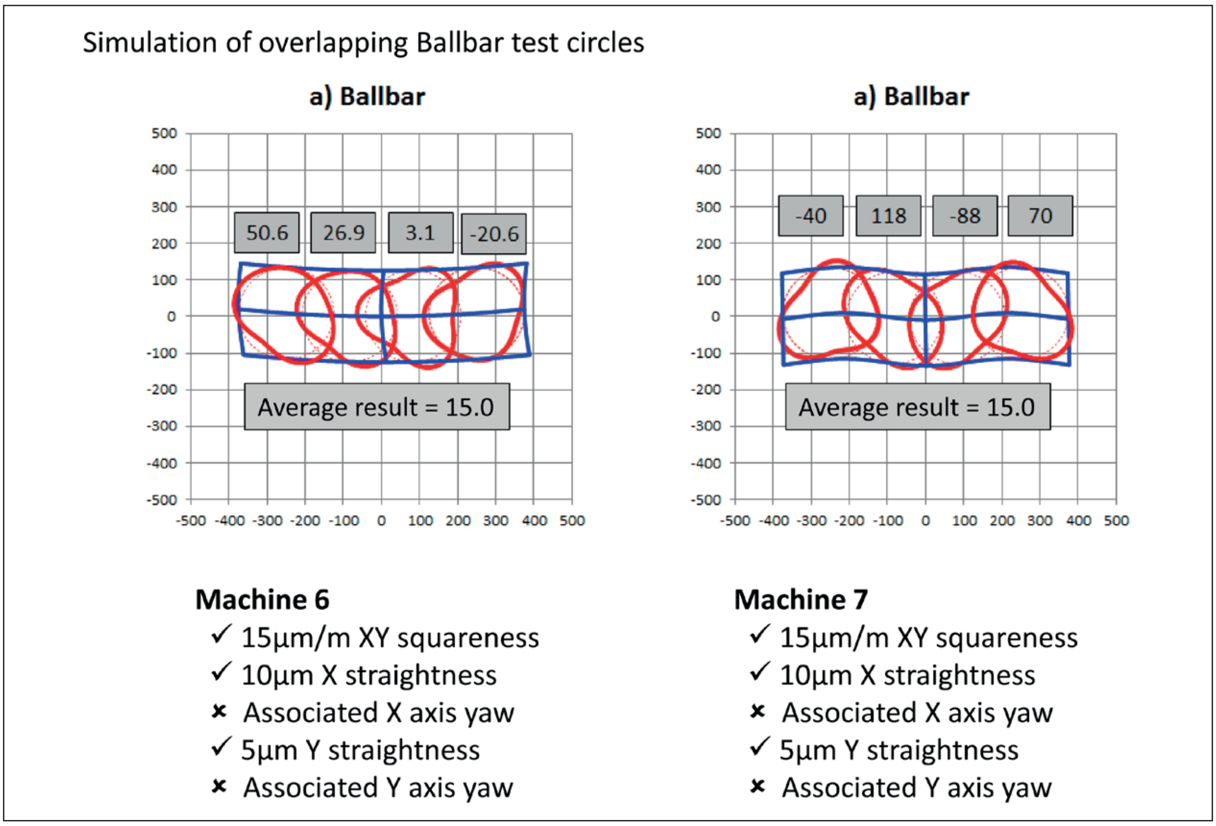

Figure 26

These simulations show that the average squareness results from the four overlapping ballbar tests match the 15µm/m average squareness result from the three adjacent ballbar tests. Whilst an exact match is not expected under all conditions, it does indicate that the method can tolerate some overlap. If more than two tests are overlapped it is recommended that the tests are arranged so that the amount of overlap is equal.

The above results indicate that using the average result from multiple ballbar tests can provide a useful method of estimating the global squareness of machines with unequal axis lengths.

Overall conclusions

The paper has reviewed the ISO230-1 definition of squareness between two linear axes of motion and the various test methods that can be used to measure it. It has modelled the test methods and compared their performance in the presence of various combinations of straightness and yaw errors in the machine's axes.

The simulations undertaken indicate the following:-

- The results obtained from the various squareness test methods listed in ISO230-1 can vary according to the test method used, the location of the test within the machine's working zone and the orientation of the test equipment.
- Ballbar, laser diagonal and "+" shaped bi-axial straightness configurations gave identical results under all conditions. However, when there are pitch or yaw induced angular distortions within the machine's working zone, the "L" and "T" shaped bi-axial straightness test configurations gave different results which also varied with equipment orientation.
- It should be noted that none of the results are "wrong", they are simply using different frames of reference. Considerable care is therefore needed when comparing squareness results between systems. It is not unlikely that results will differ if the test location or the test methods are not identical. Differences in sign convention and reference line fitting methods also need to be taken into account.

- If "L" or "T" shaped bi-axial straightness tests are repeated in opposing corners or on opposing sides of the machine's working zone and the global squareness results obtained are averaged, they will agree more closely with results obtained from ballbar, laser diagonal or "+" shaped bi-axial straightness configurations.
- The global squareness of machines with unequal axis lengths can be estimated by taking the average squareness result from multiple ballbar tests.
- Because pitch and yaw errors can cause variability in squareness test results according to the test method, location and orientation, a careful approach is required when carrying out volumetric accuracy compensations involving squareness. This topic is covered in more detail in Appendix II.

As a footnote, Figure 27 shows a rough "table of merit" for the various global squareness test methods described in ISO230-1. It is based on the results of these simulations combined with the key features and limitations of each method.

Global squareness test method merit table	Mechanical square and indicator in "L" shaped configuration	Mechanical straight edge, square and indicator in "T" shaped configuration	Mechanical straightedge and 90° indexer in "+" shaped configuration	Laser straightness interferometer and optical square in "L" shaped configuration	Laser straightness interferometer and optical square in "T" shaped configuration	Circular test with ballbar, ring gauge or MCG	Laser diagonal test
Ease of use	☆☆☆☆	☆☆☆	☆☆☆	☆☆	☆	☆☆☆☆	☆☆☆☆
Suitability for large machines	☆☆	☆☆	☆☆	☆☆☆☆	☆☆☆	☆☆☆☆	☆☆☆☆
Suitability for machines with unequal aspect ratios	☆☆	☆☆☆	☆☆	☆☆☆	☆☆☆	☆☆☆	☆☆☆☆
Immunity to yaw errors	☆	☆☆	☆☆☆	☆	☆☆	☆☆☆☆	☆☆☆☆
Immunity to changing environment	☆☆☆☆	☆☆☆☆	☆☆☆☆	☆☆	☆	☆☆☆☆	☆☆

Figure 27

Appendix I - Modelling of straightness and associated yaw errors

The equations used to model straightness errors and associated yaw errors are as follows. Consider the X axis of a machine, of length L, which has a simple bend or curve giving rise to a straightness error of S. This is illustrated in Figure 28 which shows the distortion, in blue (grossly exaggerated for clarity).

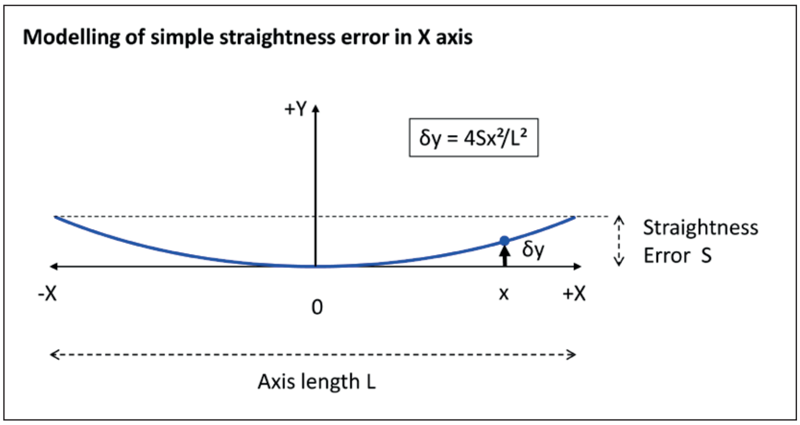

Figure 28

This simple straightness error can be modelled by a quadratic equation of the form $\delta y = Kx^2$, where δy is the straightness deviation in the Y direction at position x along the X axis, and K is a constant. Substituting for $\delta y = S$ and $x = L/2$ and rearranging gives $K = 4S/L^2$. The equation relating the X axis straightness error in the Y direction, to X axis position is therefore;

$\delta y = 4Sx^2/L^2$ …………………………………… Equation 1

Now consider what happens if a straight Y axis is mounted on top of the machine's bent X axis, as shown (in red) in Figure 29. In the absence of other constraints, as the X axis moves, the angle of the Y axis with alter according to the local yaw angle of the X axis. This *"associated yaw angle"* θ, can be found by differentiating Equation 1 with respect to x, giving $\theta = 8Sx/L^2$. The associated yaw error causes a small displacement δx in the X direction which will vary according to the position along the Y axis. If θ is expressed in radians and ignoring second order terms, this displacement can be closely approximated by $\delta x = -y\theta$. Note that if the machine also has a global squareness error θ_0, then this is added to θ before calculating δx, giving $\delta x = -y(\theta_0 + \theta)$. Substituting for θ gives;

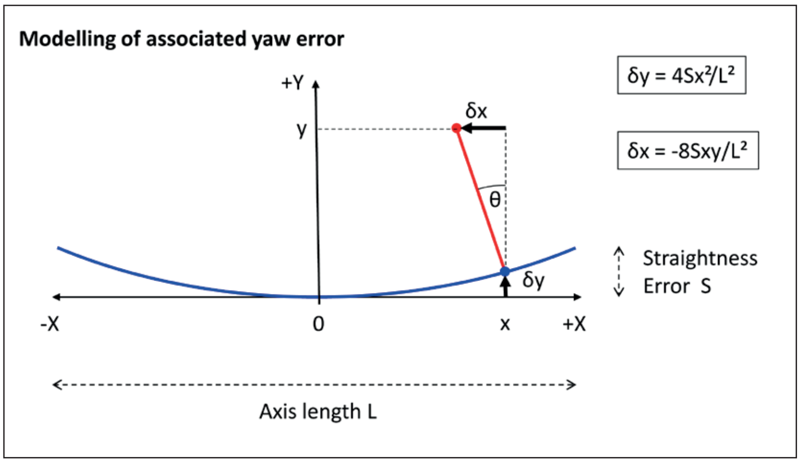

Figure 29

$\delta x = -y(\theta_0 + 8Sx/L^2)$ …………………..…………… Equation 2

Equations 1 and 2 allow the small errors, δx and δy, in machine position to be calculated for any general x,y location. If the machine is commanded to move to position [x,y] then the actual position achieved will be [(x+δx),(y+δy)]. Substituting for δx and δy gives;

Actual position = $[(x - y(\theta_0 + 8Sx/L^2)),(y+4Sx^2/L^2)]$ ………. Equation 3

Equation 3 is the general equation used to calculate the positioning error at any x,y location for a machine with an XY squareness error and a straightness error in the X axis which causes an associated yaw distortion. Because straightness errors do not always cause associated yaw error distortions (it depends on the machine's construction and kinematic chain) the $8Sx/L^2$ maybe zero. Under these conditions Equation 3 becomes;

Actual position = $[(x - y\theta_0),(y+4Sx^2/L^2)]$ ……………….……… Equation 4

The equations used to model the effects of a straightness error in the Y axis and any associated yaw errors are derived in a similar same way. (Note in this case there is no need to account for the squareness error again). In combination these equations allow the positioning errors of all the machines modelled in this paper to be calculated.

Simulation of each squareness test method involves generating an appropriate sequence of command positions (according to the test method), calculating the machine's positioning errors at each, and then applying the appropriate algorithm to calculate the squareness.

Appendix II – Volumetric compensation of machine squareness errors

The following points should be considered when carrying out squareness compensation or adjustments.

Because straightness, pitch and yaw errors can cause variability in squareness test results according to the test method, location and orientation it is recommended that straightness, pitch and yaw errors are measured and compensated for first. Once these errors have been minimised, the measurement of squareness (and incidentally linear) errors become largely independent of test location and test method, thereby improving the reliability of the squareness result and making it easier to apply.

Considerable care should be taken when compensating for the measured squareness error to ensure that the compensation is applied in such a way that alignments to other reference lines/features on the machine are maintained, or improved. The following are examples of alignments to be considered.

- Parallelism or perpendicularity of the compensated axis movements to the axis of rotation of the spindle
- Parallelism or perpendicularity of the compensated linear axis movements to the table surface
- Alignment of the compensated axis movements to reference points of 4th and 5th axes.

The potential pitfalls are best illustrated by considering a simple example. Suppose the squareness error between the X and Z axes of a lathe has been measured as 40μm/m using one of the test methods described in the paper. This is illustrated in Figure 30a. In the figure, the Z axis is shown correctly aligned, parallel to the axis of rotation of the spindle, but the X axis is out of alignment. Based on an XZ squareness measurement in isolation the user cannot tell whether the X or the Z axis (or neither) is

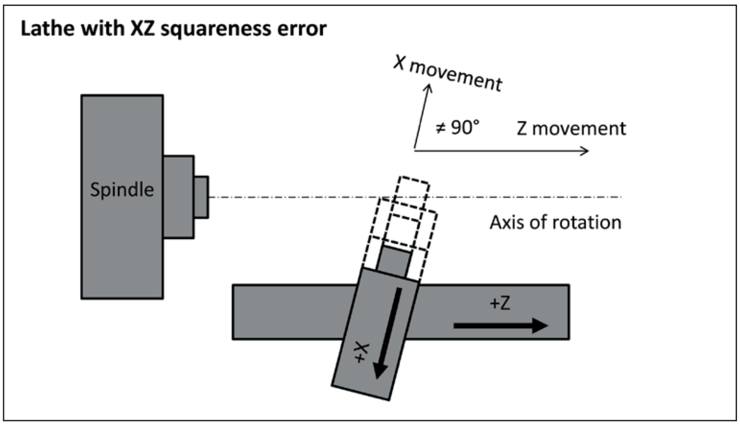

Figure 30a

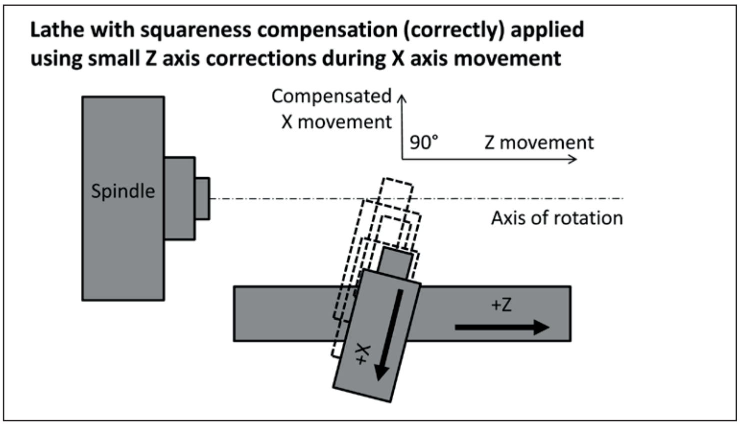

Figure 30b

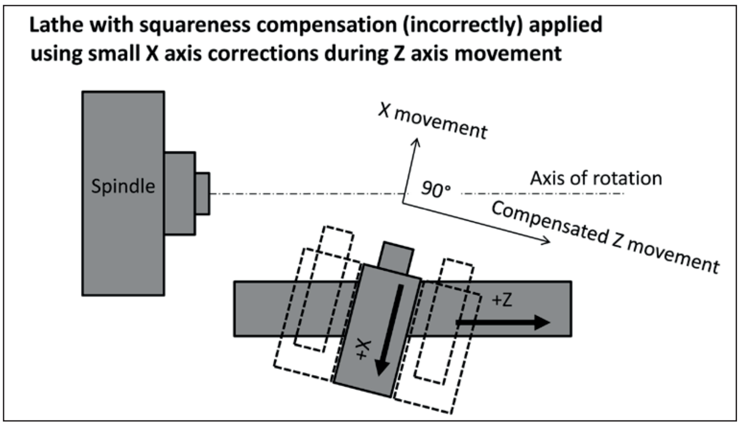

Figure 30c

correctly aligned to the spindle, therefore there is a danger that squareness compensation could be applied incorrectly. The user has a choice of correcting the squareness error by applying cross axis compensation to the X or the Z axis (or any combination of the two).

Figure 30b shows the effect of (correctly) using the Z axis to apply small (40µm/m) δz corrections during X axis movement. Note that the compensated X movement of the tool is now at 90 degrees to the Z axis (hence the X and Z axes now appear “square”) and the Z axis has remained parallel to the spindle’s axis of rotation.

Figure 30c shows the effect of (incorrectly) using the X axis to apply small (40µm/m) δx corrections during Z axis movement. Note that although the compensated Z axis movement of the tool is at 90 degrees to the X axis (the X and Z axes still appear “square”), the compensated Z movements are not parallel to the spindle’s axis of rotation.

In both figures 30b and c compensation has ensured the compensated X and Z movements are square to one another, but in the case of 30c, the compensation has caused a misalignment of these movements to the axis of rotation of the spindle. This example clearly illustrates why it is important to ensure other machine alignments are considered before making software compensations for machine squareness. This is particularly important when compensating for large XZ or YZ squareness errors. In such cases it is suggested that mechanical adjustments are used first to remove the majority of any squareness and parallelism misalignments between the X, Y and Z axes, the axis of rotation of the spindle, and the machine table. Volumetric compensation can then be used to make the final adjustments.

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