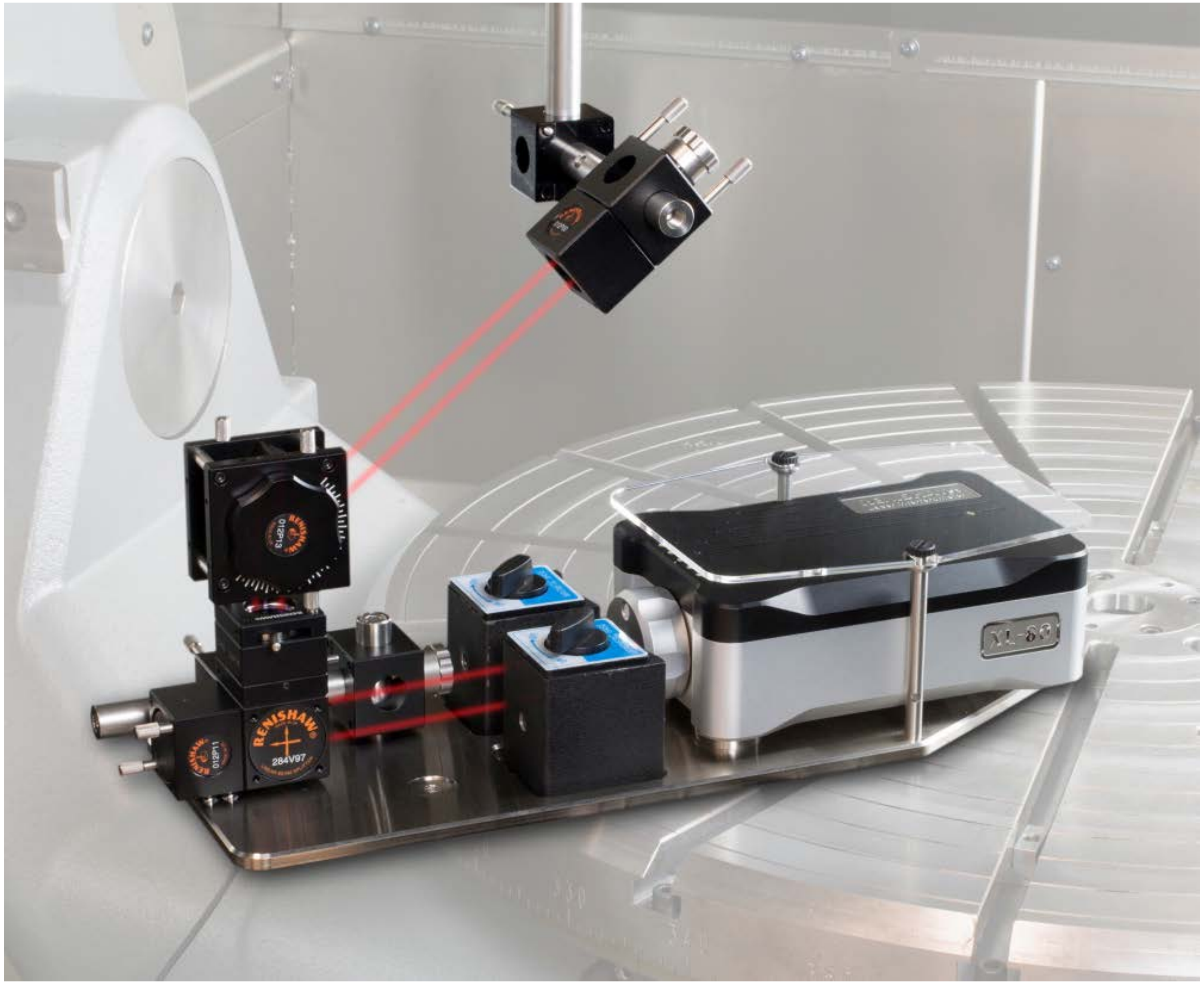
Laser
diagonal testing

H-5650-2056-01-B



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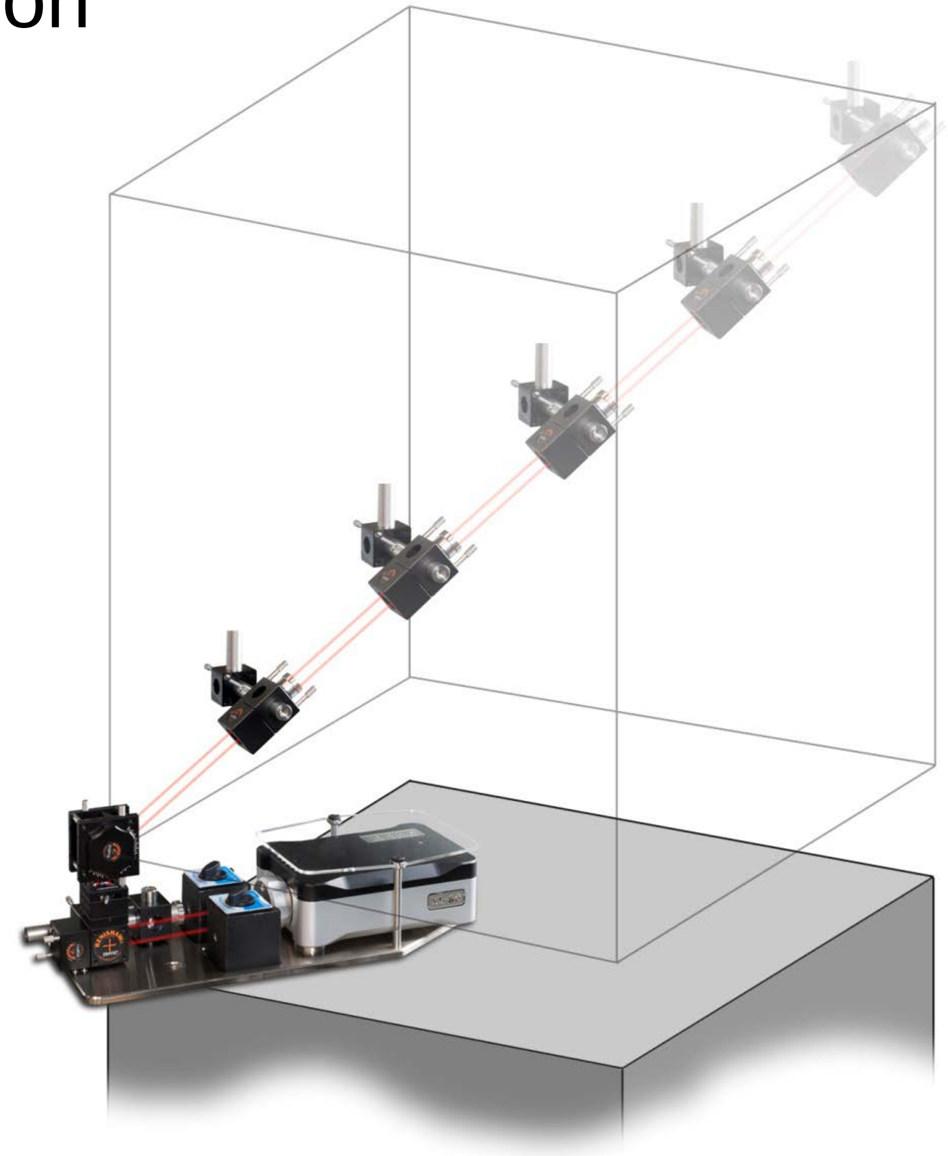
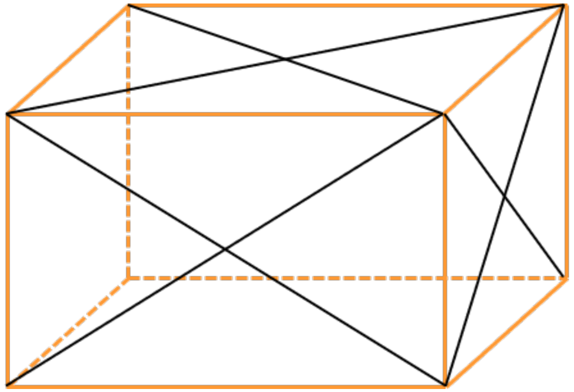
Introduction



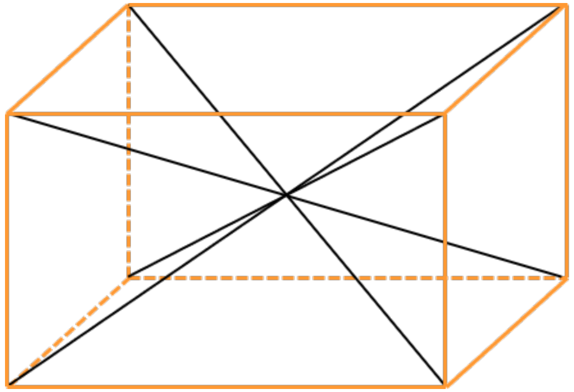
- This presentation explains how Renishaw laser calibration systems can be used to check machine positioning performance along machine diagonals, in accordance with the B5.54 and ISO 230-6 standards.
- It also explains the strengths and weaknesses of this method of machine performance evaluation.

Laser diagonal tests - B5.54 and ISO 230-6

- Laser diagonal tests for machining centres are described in both ASME B5.54 (2005) and ISO 230-6 (2002) standards.
- In these tests, a laser interferometer is used to measure the linear positioning accuracy of the machine as it moves along face or body diagonals of the machine's working volume.



6 face diagonals*

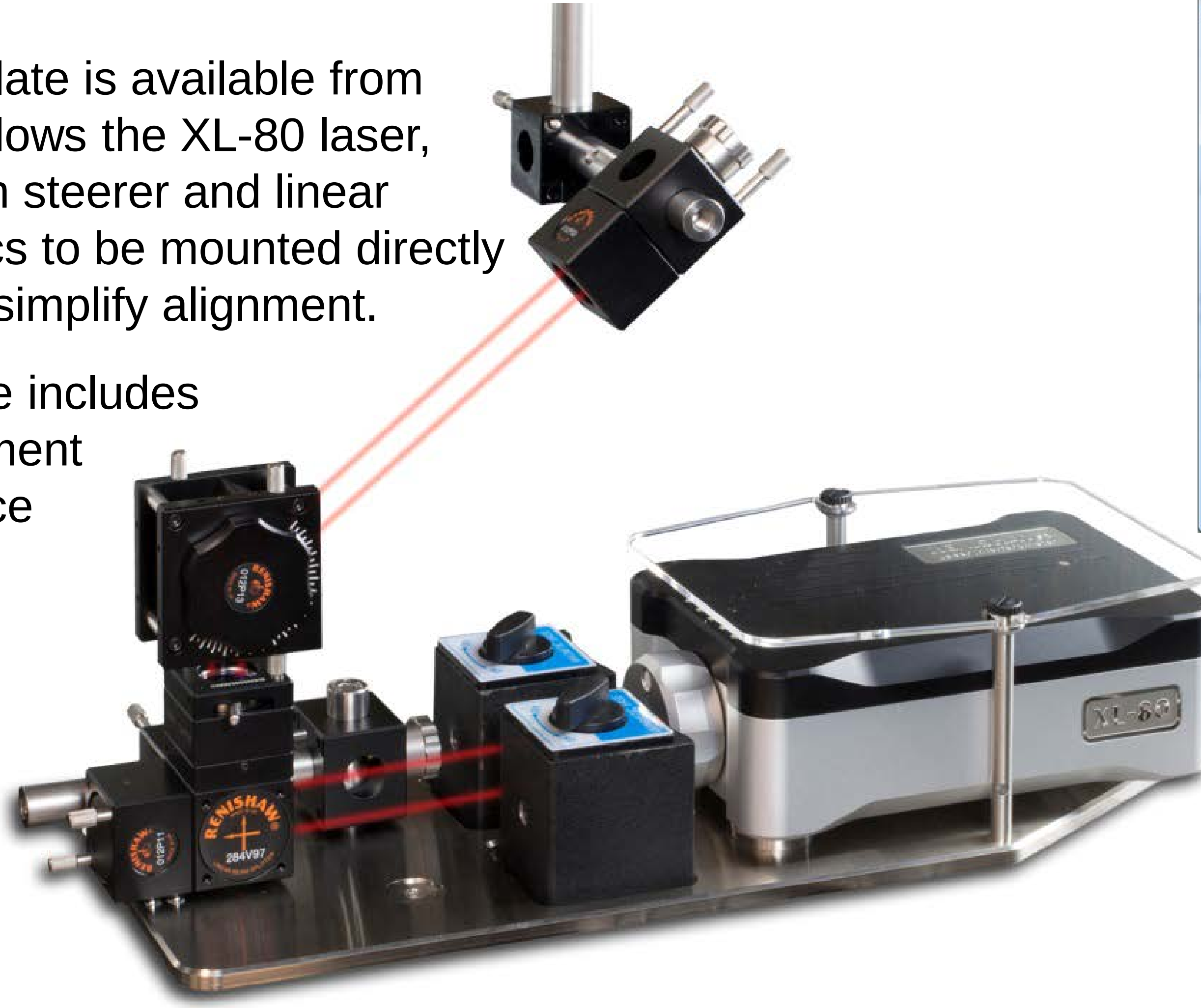


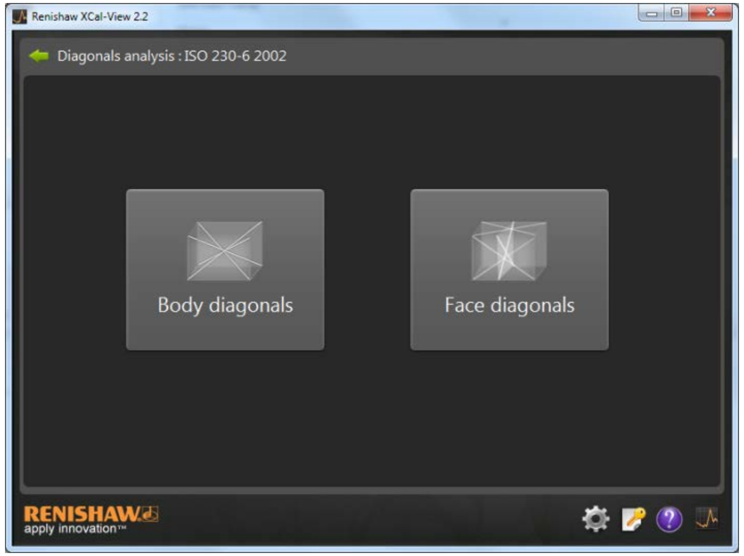
4 body diagonals

*Face diagonals may also lie within the machine volume, but parallel to the XY, YZ or ZX plane

Diagonal measurement equipment and software

- A laser mounting plate is available from Renishaw which allows the XL-80 laser, swivel mirror, beam steerer and linear measurement optics to be mounted directly on the machine to simplify alignment.
- XCal-View software includes diagonal measurement analysis of both face and body diagonal data in accordance with ISO 230-6 and B5.54*.

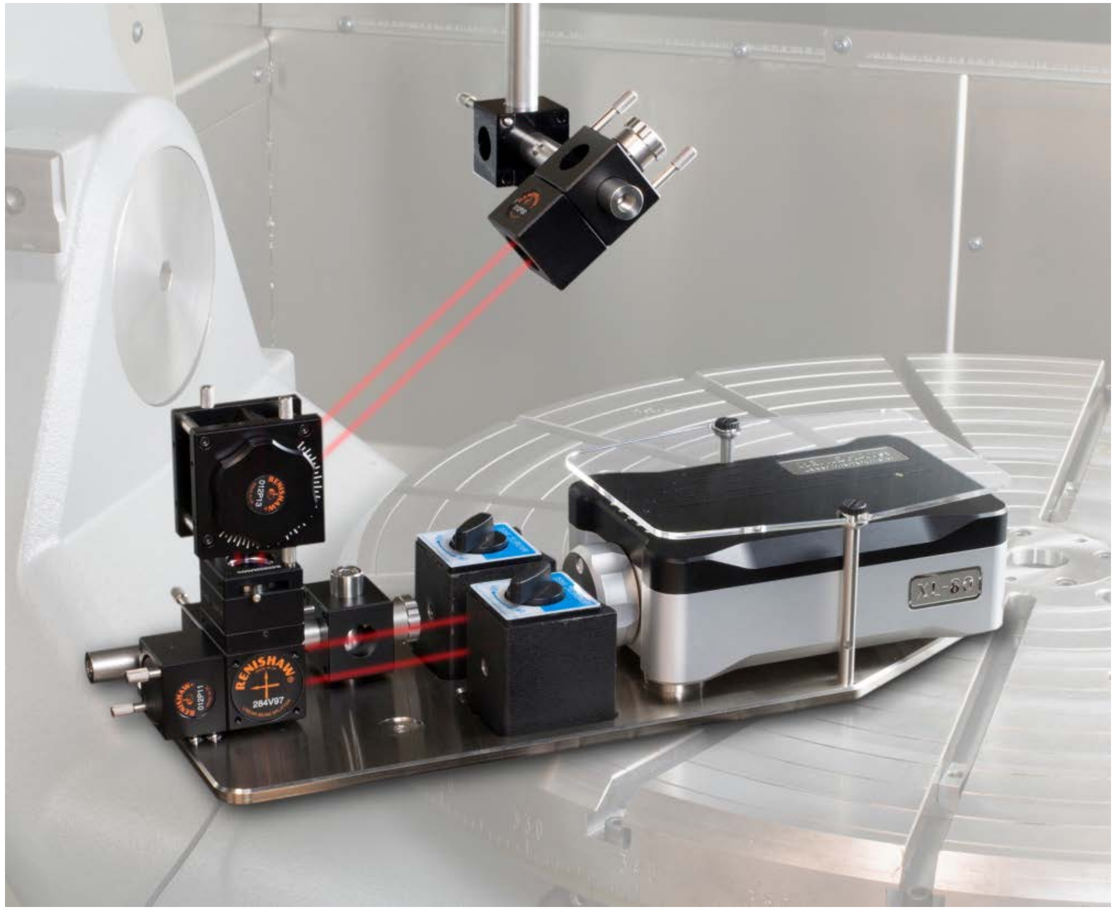




* B5.54 analysis requirements are the same as ISO 230-6

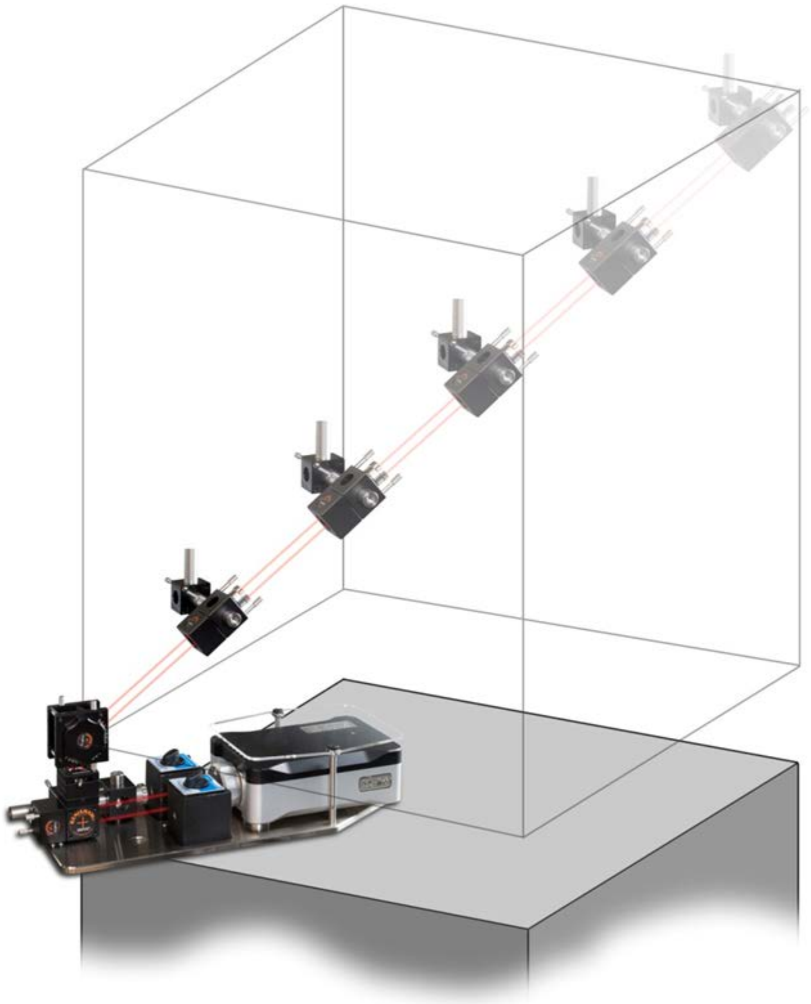
Test set-up

- The XL-80 laser can be mounted directly to the machine using the mounting plate.
- The laser beam is aligned to the face or body diagonal using the swivel mirror and laser beam steerer.
- The figure shows the laser system aligned to a machine body diagonal.
- Mounting the laser on the machine's rotary table allows easy realignment to each of the four body diagonals, or to the internal face diagonals.



Data collection

- A number of equi-spaced target positions are defined along each body diagonal.
- The machine is programmed to move along the diagonal from one target position to the next.
- The laser measures the linear positioning error at each target position.
- Measurements are taken in forward and reverse directions using 5 bi-directional runs.
- These measurements are repeated along each diagonal in turn.

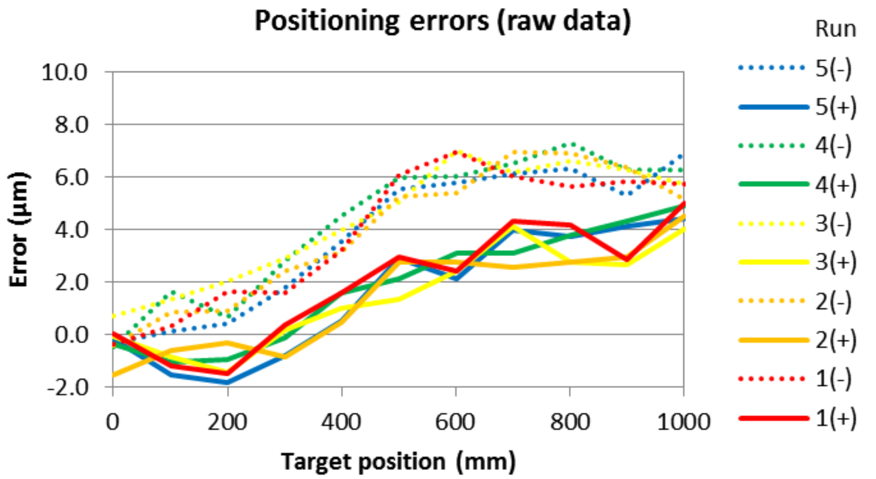


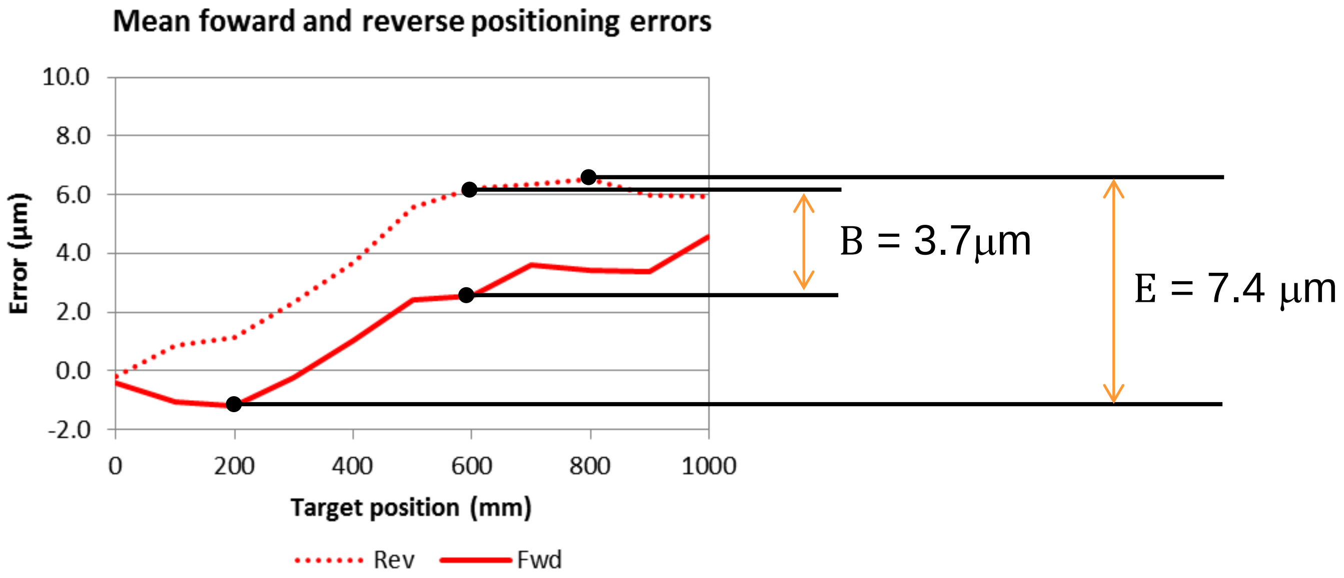
Equi-spaced target positions along a body diagonal

Data analysis - stage 1

- The data gathered for each diagonal is analysed separately in accordance with ISO 230-6 to give a bi-directional systematic positioning error E, and a reversal error B for each diagonal, as follows;
  - The mean forward ($\bar{X}_i\uparrow$) and mean reverse ($\bar{X}_i\downarrow$) positioning errors are calculated at each target position along the diagonal.
  - The bi-directional systematic positioning error (E) of the diagonal is:
    $E = \max\,[\bar{X}_i\uparrow; \bar{X}_i\downarrow] - \min\,[\bar{X}_i\uparrow; \bar{X}_i\downarrow]$
  - The reversal error (B_i) at each target is:
    $B_i = \bar{X}_i\uparrow - \bar{X}_i\downarrow$
  - The reversal error (B) of the diagonal is:
    $B = \max\,[\,\mathrm{abs}(B_i)\,]$
- These results can be represented graphically, as shown on the next slide.

Data analysis - stage 1 - graphical representation





E = The bi-directional systematic positioning error of the diagonal

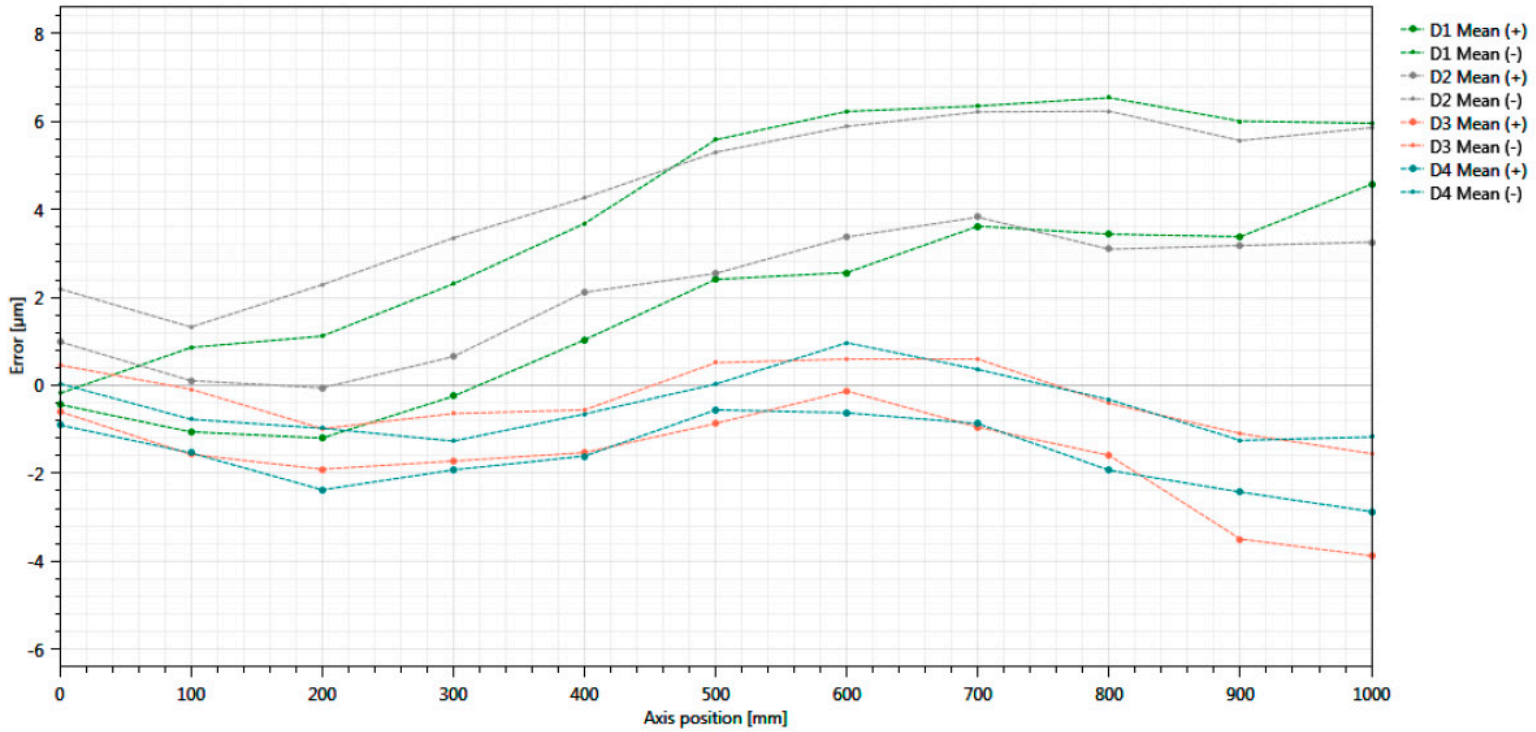
B = The reversal error of the diagonal

Data analysis - body diagonals - stage 2

- In the case of body diagonal measurement, the previous analysis will yield four values for the systematic positioning error (E_1,E_2, E_3, E_4) and four values for the reversal error (B_1,B_2, B_3, B_4), one for each diagonal.
- The worst case results for E and B are selected to give the overall result for the machine.
  - Diagonal systematic deviation of positioning for the machine is $E_d = \max(E_1,E_2,E_3,E_4)$
  - Diagonal reversal value for the machine is $B_d = \max(B_1,B_2,B_3,B_4)$
- ISO 230-6 recommends that, in addition to quoting results for E_d and B_d, the final report should include results for E_1,E_2,E_3,E_4 and B_1,B_2,B_3,$B_{4,}$ and the positioning error graphs each diagonal.
- The next slide shows part of the ISO 230-6 report from Renishaw’s XCal-View body diagonal analysis software.

Data analysis - body diagonals - final report

ISO 230-6 2002: Body diagonals



Name	Value (µm)
Sys dev (E)	7.7
Reversal	3.7

Test	Reversal (µm)	Sys dev (E) (µm)
Diagonal 1.RTL (D1)	3.7	7.7
Diagonal 2.RTL (D2)	3.1	6.3
Diagonal 3.RTL (D3)	2.4	4.5
Diagonal 4.RTL (D4)	1.7	3.8

Data analysis - face diagonals - stage 2

- In the case of face diagonal measurement, the previous analysis will yield two values for the systematic positioning error ($E_{1(ab)}$,$E_{2(ab)}$) and two values for the reversal error ($B_{1(ab)}$,$B_{2(ab)}$), on each face, where (ab) represents the plane of test (XY, YZ or ZX)
- The results for each face are quoted separately by selecting the worst case results for E and B on each face.
  - Diagonal systematic deviation of positioning for the three faces are:-
    $E_{d(XY)} = \max(E_{1(XY)},E_{2(XY)})$
    $E_{d(YZ)} = \max(E_{1(YZ)},E_{2(YZ)})$
    $E_{d(ZX)} = \max(E_{1(ZX)},E_{2(ZX)})$
  - Diagonal reversal value for the faces are:-
    $B_{d(XY)} = \max(B_{1(XY)},B_{2(XY)})$
    $B_{d(YZ)} = \max(B_{1(YZ)},B_{2(YZ)})$
    $B_{d(ZX)} = \max(B_{1(ZX)},B_{2(ZX)})$
- The next slide shows part of the ISO 230-6 report from Renishaw’s XCal-View face diagonal analysis software for the XY plane.

Data analysis - face diagonals - final report

ISO 230-6 2002: Face diagonals

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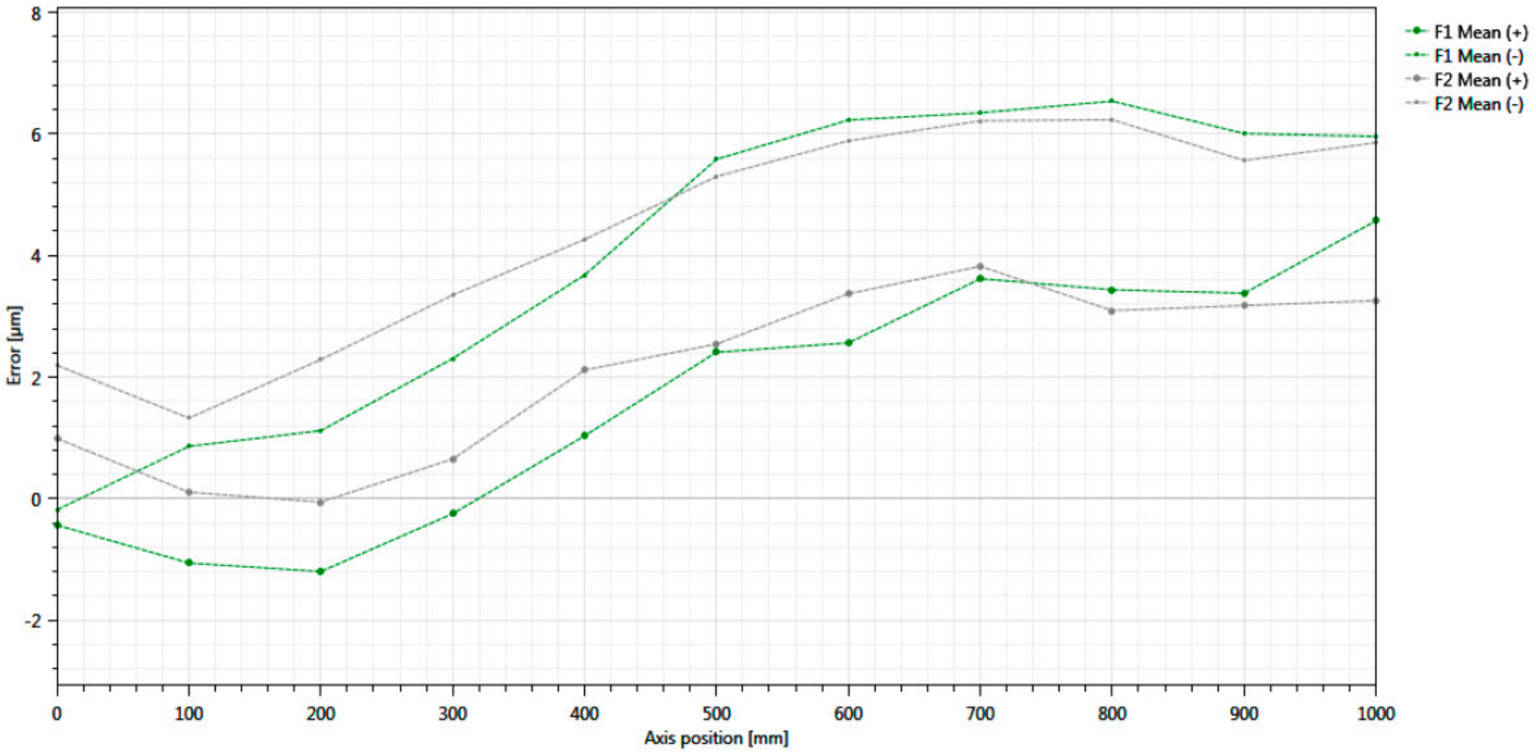


Plane: XY

Name	Value (µm)
Sys dev (E)	7.7
Reversal	3.7

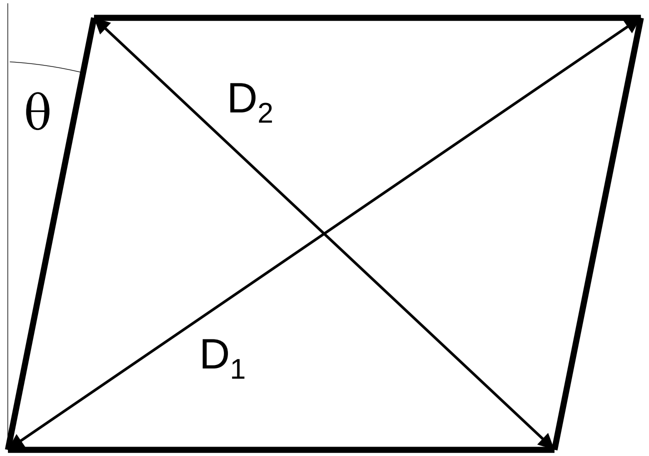
Test	Reversal (µm)	Sys dev (E) (µm)
Diagonal 1.RTL (F1)	3.7	7.7
Diagonal 2.RTL (F2)	3.1	6.3

Squareness analysis

- ISO 230-1 2012 (in section 10.3.2.6) states that it is also possible to calculate the non-squareness between axes using face diagonals*.

Considering a test in the XY plane as an example:

- If X and Y are the programmed travel lengths along the X and Y axes, then the squareness (in radians) is given by:
  - $\theta = D_0 (D_1 - D_2)/(2XY)$
  - 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:
  - Squareness = $(D_1 - D_2)/ D_0$
- It is also possible to calculate squareness from body diagonal lengths with suitable equations*.

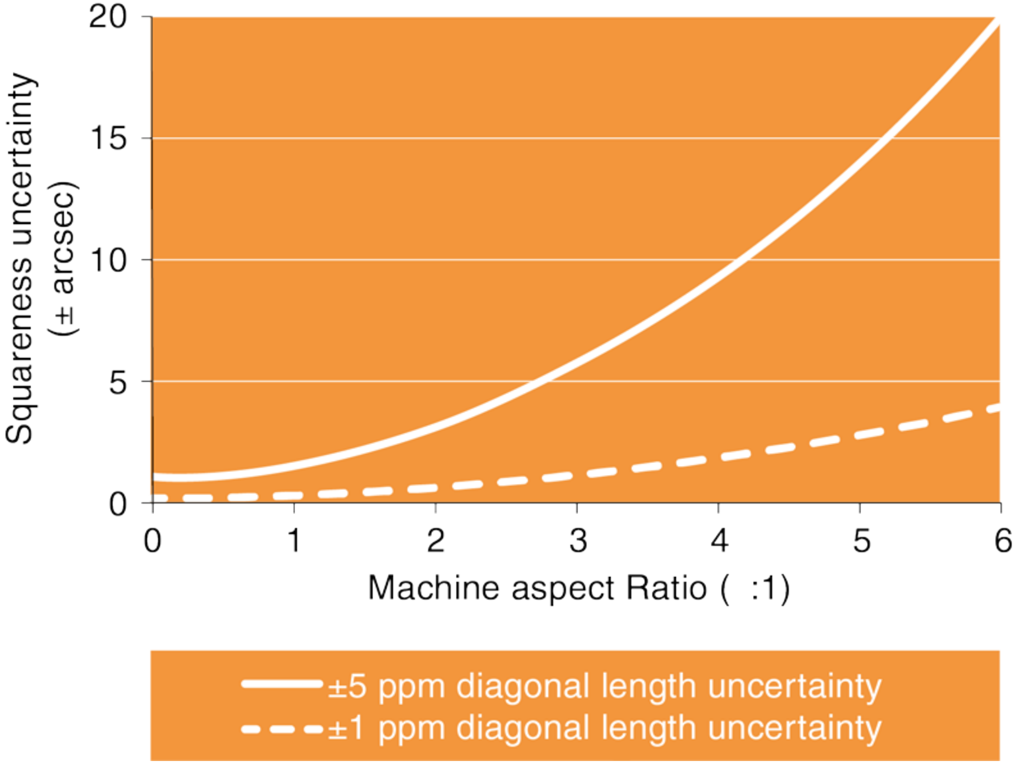


* Note: Renishaw XCal-View software does not provide this functionality.

Squareness analysis

- The accuracy of the squareness result is improved if:
  - The machine’s axes are of similar lengths (improves sensitivity and accuracy).
    - The graph shows effect of ±1 ppm and ±5 ppm shifts in laser reading on the accuracy of squareness results for various aspect ratio machines.
  - The test is performed quickly to minimise any thermal changes between measurement of each diagonal. Only a single reading is needed at either end of each diagonal.

Squareness uncertainty versus measurement uncertainty and machine aspect ratio



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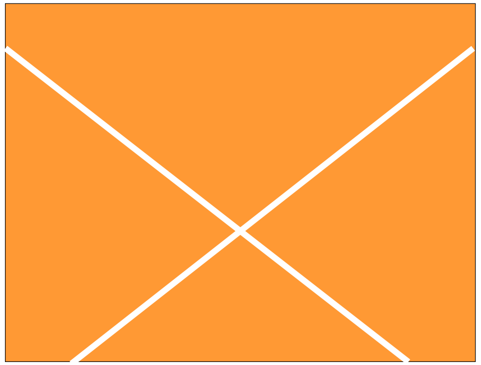
Squareness analysis

- Accuracy of the squareness result is also improved if:
  - The diagonals start and finish at identical X, Y or Z co-ordinates as shown opposite. This ensures that the effects of other machine errors are eliminated.
  - Backlash is eliminated by moving in the same direction before each reading.
- Under good conditions it is possible to measure machine squareness within ±1 arcsecond.
- The technique is especially useful on large machines where access to a large mechanical reference square may be problematic.



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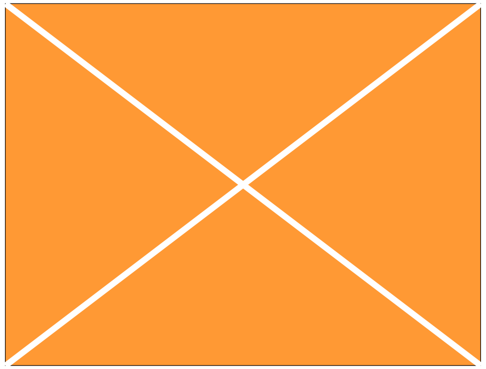

Correct

Strengths and weaknesses

The following section describes some of the strengths and weaknesses of laser diagonal measurements

Strengths and weaknesses

- ISO 230-6 2002 states:

  > “Diagonal displacement tests allow estimation of the volumetric performance of a machine tool. Complete testing of the volumetric performance of a machine tool is a difficult and time-consuming process. Diagonal displacement tests reduce the time and cost associated with testing the volumetric performance.”

- In 1992 ASME B5.54 in section 5.9.2 stated:

  > “Volumetric Performance Using Laser Diagonal Displacement Measurements. The volumetric accuracy of a machine may be rapidly estimated by measuring the displacement accuracy of the machine along body diagonals.”

- But section 7.7 of the more recent ASME B5.54 2005 includes a revised statement:

  > “Diagonal displacement tests are used to determine displacement accuracy of the machine along body or face diagonals. To obtain an estimate of the volumetric positioning capability of the machine, one has to combine the results of these tests with those of linear displacement tests.” [i.e. parallel to the machine’s axes]

- Views on the correlation between laser diagonal test results and volumetric positioning accuracy have changed.

Strengths and weaknesses

- The strength of body diagonal testing is that this simple, quick test is sensitive to a wide range of different machine errors using minimal equipment.
- **However, this wide range of sensitivity is also a weakness.**
- If multiple machine errors are present they can combine in ways that can increase or decrease the diagonal test result.
- The simultaneous presence of multiple machine errors can destroy the correlation between body diagonal results and volumetric accuracy.
- In 2003 Renishaw published a paper[1] on this topic in the Journal of Precision Engineering.

Machine error	Sensitivity
Linear displacement errors	Yes
Reversal errors	Yes
Angular (roll, pitch & yaw)	Yes
Straightness	Yes
Squareness	Yes

1) M.A.V. Chapman, "Limitations of laser diagonal measurements", Precision Engineering 27 (2003)

Weaknesses

- This technical paper demonstrated the following:
  - Estimates of volumetric machine performance, which are based on diagonal tests alone, are unreliable.
  - The results of a diagonal test, in isolation, cannot be used as a reliable machine comparison index.
- The reasons for this are summarised on the following slides.

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Precision Engineering 27 (2003) 401–406

PRECISION ENGINEERING

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Limitations of laser diagonal measurements

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Received 11 March 2003; accepted 14 March 2003

Abstract

The introduction of B5.54 and ISO230-6 machine tool performance measurement standards is increasing the popularity of laser interferometer diagonal, step diagonal and vector methods for the evaluation and compensation of machine tool errors. This is due to the potential reduction in calibration time, these methods can provide over the more conventional laser interferometer-based linear, angle and straightness measurements taken along lines parallel to the machine's X, Y and Z axes.

This paper highlights limitations in the results produced by diagonal-based measurements and by the more recently introduced vector or step diagonal methods. The purpose of this paper is to alert potential users of these methods to their limitations so they can make informed decisions as to whether the reduction in calibration time they can provide outweighs the loss of accuracy and detail in the results. It also indicates some of the dangers in using laser diagonal data alone for the compensation of machine tool errors.

Keywords: Laser interferometer; Machine calibration; Laser diagonal; Step diagonal test; Vector diagonal; B5.54; ISO230-6; Volumetric accuracy; Machi
error compensation

1. Laser diagonal measurement

In laser diagonal measurements (as described in B5.54 and ISO230-6 Standards), a laser interferometer is used to m
sure the positioning accuracy of a machine tool
along each of the machine's four bod
These four body diagonals are
The American B5.5
etric accu

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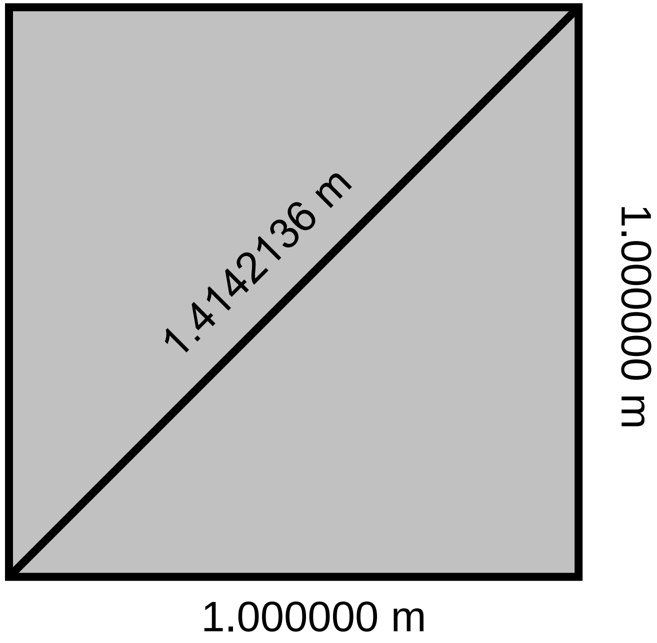
2 m × 1

Laser diagonal tests - 2D example

- The weakness of the diagonal test is most easily understood by considering a simple 2D example first.
- Consider a perfect 1 metre square planar machine. The travel of the X and Y axes are both exactly 1 metre, and the machine contains no other positioning or geometric errors.
- The length of both diagonals are given by Pythagoras' theorem.
- Diagonal length

  $= \sqrt{(1^2 + 1^2)}$

  = 1.4142136 m

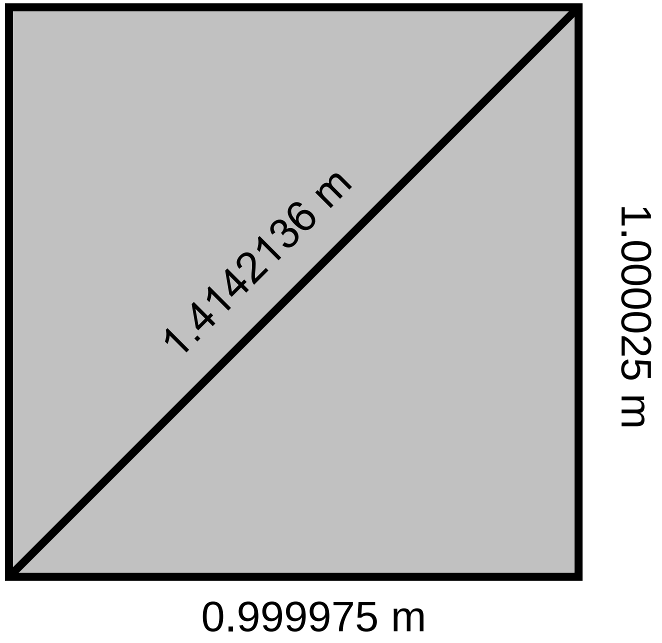


Laser diagonal tests - 2D example

- Now imagine that the machine is distorted such that the X axis over-travels by 25 μm/metre, and the Y axis under-travels by 25 μm/metre. (Linear positioning errors of this magnitude are common in machines due to inaccuracies in the feedback system e.g encoder tensioning and thermal effects).
- The length of the diagonals of this distorted machine are again given by Pythagoras' theorem.
- Diagonal length

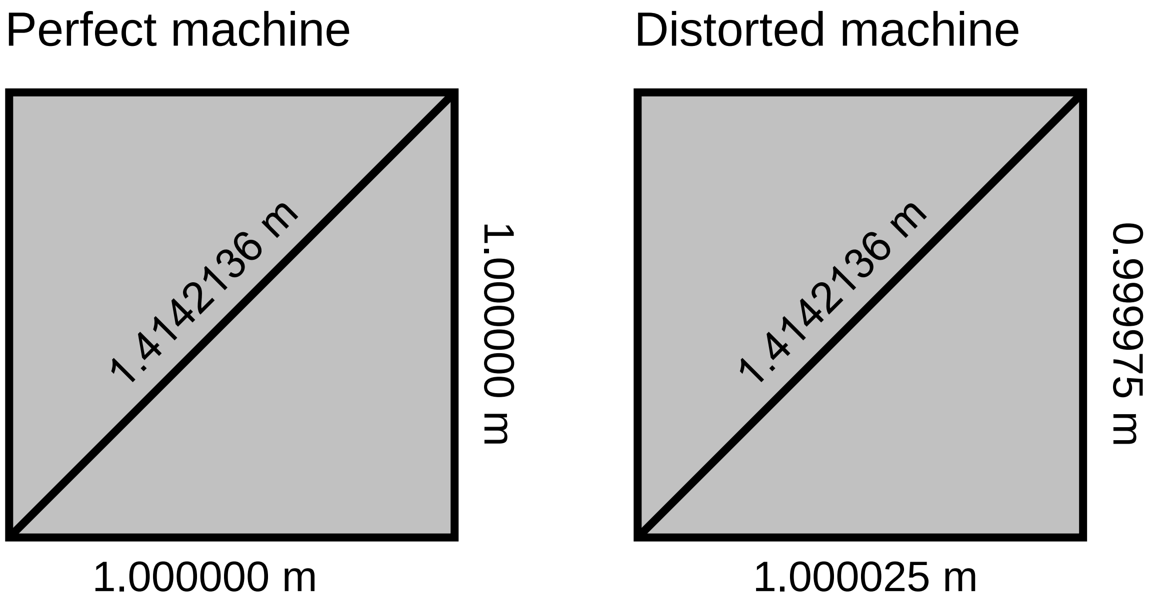
  $= \sqrt{(1.000025^2 + 0.999975^2)}$
  $= 1.4142136$ m

- **Note that the diagonal lengths appear unchanged**



Laser diagonal tests - 2D example

- Diagonal lengths of perfect machine = 1.4142136 m
- Diagonal lengths of distorted machine = 1.4142136 m
- The diagonal lengths are all the same (within 0.001 μm)
- Both the perfect and the distorted machine show effectively identical results on a diagonal test even though the distorted machine contains positioning errors of over 25 μm.



Laser diagonal tests - 2D example

- It might be thought that this is a very special case, which only occurs on a 2D machine if the error in the X axis motion is exactly equal and opposite to the error in the Y axis motion.
- This is not the case!
- If any axis (or axes) shows an over-travel error whilst any another axis (or axes) shows an under-travel error, their combined effect on the body diagonal length will, to some extent, cancel.
- These types of errors are common on machine tools.
- The problem also occurs on 3D machines as shown by the table on the next slide.

Laser diagonal tests - 3D example

- The table shows the simulated performance of three nominally identical machine tools with cubic 1 m^3 volumes.
- Each machine has a different combination of linear positioning errors in its axes.
- Compare the diagonal test results with the volumetric accuracy.

Error	Machine A	Machine B	Machine C
X axis linear error (µm/m)	50	50	100
Y axis linear error (µm/m)	50	0	-50
Z axis linear error (µm/m)	-100	0	-25
Diagonal test result Ed (µm)	0	29	14
Volumetric accuracy * (µm)	122	50	115

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* Volumetric accuracy is defined as the length of the worst case error vector between the target and the actual machine position anywhere within the machine volume.

Laser diagonal tests - 3D example

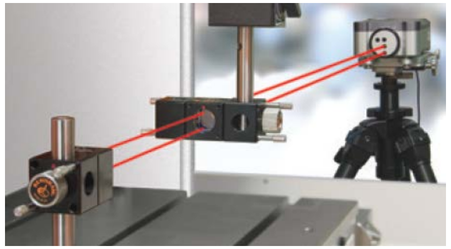
- Note the complete lack of correlation between the volumetric accuracy of these machines and their diagonal test results.
  - Machine A has the worst volumetric accuracy, but shows no error on the diagonal test.
  - Machine B has the best volumetric accuracy, but shows the worst diagonal test result.
- It is clear that laser diagonal test results do not provide a reliable estimate of volumetric accuracy and so should not be used (in isolation) to provide a reliable comparison index between machines.

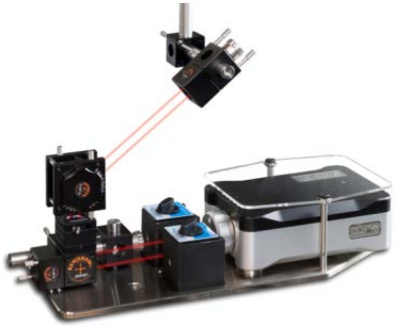
Error	Machine A	Machine B	Machine C
Diagonal test result Ed (μm)	0	29	14
Volumetric accuracy* (μm)	122	50	115

* Volumetric accuracy is defined as the length of the worst case error vector between the target and the actual machine position anywhere within the machine volume.

Machine comparison

- Because of this limitation ASME B5.54* now recommends the following tests to quickly estimate the performance of a three axis machine:
- **Recommended minimum test set**





1. **Contouring performance test** using circular tests in 3 planes using, for example, a telescoping ballbar.
2. **Linear positioning accuracy and repeatability** test of each axis, using, for example, a laser interferometer.
3. **Diagonal displacement tests** along 4 body diagonals using a laser interferometer.
4. **Precision contouring machining tests** including, for example, the classic “circle diamond square” test.

* Refer to Appendix A3 of 2005 version

Conclusions

Conclusions

- Laser diagonal tests can be used to measure the diagonal systematic deviation of positioning and reversal errors in accordance with B5.54 and ISO 230-6 standards.
- Renishaw can provide suitable mounting hardware and software to simplify the process.
- Laser diagonal tests are sensitive to many types of machine errors.
- With care, laser diagonal results can be used to accurately determine the squareness errors between axes.
- However, laser diagonal tests cannot be used in isolation to estimate volumetric accuracy of a machine or to grade machine performance.
- Laser diagonal tests should be combined with:
  - Linear accuracy and repeatability checks parallel to each axis
  - Telescoping ballbar tests in 3 planes
  - Cutting tests
- Tests of angular & straightness errors can provide further information.