Chapter 2
Laser Instrumentation and Calibration

"Shall I, the gnat that dances in the ray, dare to be reverent?"
Coventry Patmore
(British poet—and an Associate of the
Pre-Raphaelite Brotherhood)
[1823–1896]
(In Pysche's Discontent)

2.1 Introduction to Lasers

On a CNC machine tool, any basic or intricate machining process inevitably has some pre-requisite for some form of actual measurement. Both the accuracy and precision requirements for machined products are continuously increasing—see Fig. 1.14. As a consequence, this accuracy/precision level of machined components can be directly related to the machine tool's performance as it is utilised on a production line. Today, any form of competitiveness in the manufacture of products, coupled to an effective production line, will demand constant inspection of a machine tool's overall performance. Consequently, the CNC machine tools geometrical accuracy and precision is a foundation for the evaluation of such plant—according to their production and quality performance requirements. Of significant importance is the measurement and verification of a machine, via its periodic calibration.[1] In order to calibrate a machine tool, one well tried-and-tested but highly accurate and precise technique is by calibration utilising specially designed laser measuring systems. Lasers have been utilised for many years, mainly for the

[1]**Calibration**—the formal definition by **The International Bureau of Weights and Measures** (Paris, France) is an: "Operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties [of the calibrated instrument, or secondary standard] and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication".

G.T. Smith, *Machine Tool Metrology*, DOI 10.1007/978-3-319-25109-7_2

assessment of a diverse range of physical properties but principally for precise distance-measurement. As a result, an accurate and precise measurement can be achieved using laser beams, with lasers using interferometric-measurement being applicable for such machine tool and metrology equipment calibration.

Some basic facts concerning the application of a laser light source, will be that they are:

- **coherent**—having all the photons of a laser beam being in-phase with each other;
- **directional**—with all the photons being both parallel and directed;
- **monochromatic**—all photons have the same energy with the laser beam colour, depending upon the energy source that is utilised for the stimulation of atoms.

Accordingly, a laser can be considered as a concentrated beam of light, which normally possesses an enormous amount of energy. The term laser has already been mentioned in Chapter 1, but it is worth just re-emphasising once again, namely that the acronym **LASER** is derived from **L**aser **A**mplification by the **S**timulated **E**mission of **R**adiation, relating to energy from a stimulated source of light. Low-powered lasers are expressly utilised for laser measurements, due to the fact that a powerful laser source is unnecessary and could prove to be potentially destructive. Furthermore, such powerful lasers are somewhat dangerous if employed for any form of machine and instrument measurement/calibration. Laser measurement is fundamentally based on the principle of optical interferometry—of a basic beam and its return beam, which carries certain dimensional information. This return beam is normally reflected from a specially manufactured matched-optic such as an accurately positioned reflective mirror which is placed on an observed object, via an interferometric optical source—more will be said on this topic later in this chapter. The main problem during laser measurement assessment is one of laser beam stability. From the time when laser beam wavelength is utilised as a measuring-gauge, the influence of the environmental conditions, such as ambient temperature; humidity; thermal air-flow; plus other contributory factors; must be effectively and consistently controlled.

2.1.1 Why Is Calibration so Important?

Calibration can define the accuracy, precision, as well as the quality of measurements being recorded utilising specific plant and equipment. Hence, over time, there is a tendency for these results and its attendant-accuracy and precision to drift. This drifting is particularly noticeable when utilising certain levels of high-technologies, or measuring particular parameters such as exacting dimensional measurements, in association with changes in the local ambient temperature, humidity and to a lesser extent, by air-movement—typically by drafts and/or thermal air-currents. Accordingly, to be confident in the metrological results being measured, there is an on-going need to both service and maintain the calibration of equipment throughout its lifetime for reliable, accurate, and repeatable measurements. The express goal of any form of calibration is to minimise any potential measurement uncertainty by ensuring the accuracy/precision of the test equipment, but in this case, by utilising the laser interferometer. Laser calibration when undertaken—see Fig. 1.47—will then have the capability to obviously quantify and control these undesirable error-sources, or uncertainties within measurement processes, maintaining them at an acceptable level.

One might ask the pertinent question, "What are the major objectives of calibration?" In essence, there are three foremost reasons for having both the industrial plant and metrological instruments calibrated, characteristically to:

1. **ensure** readings from the plant/instrument are consistent with other measurements;
2. **determine** the accuracy and precision of the plant/instrument readings;
3. **establish** the reliability of the plant/instrument—so that it can then be trusted.

2.1.2 Calibration of Laser Interferometers

Laser interferometer systems are widely employed in the manufacturing and metrology industries for direct precision measurement of length and displacement, particularly in relation to CNC machine tool and co-ordinate measuring machine (CMM) calibration.

Many technologically based countries have their own National Metrology Laboratories—see an abridged list of them at rear of this book, that can offer an end user/customer a laser calibration service, such as that provided by The NPL within the UK, or for certain industrial/metrology companies which are suitably accredited to undertake such calibration, or periodic re-calibration—see Fig. 1.47. Typically within the UK, The NPL offers a routine-service for the verification of interferometer system accuracy, which includes the following:

- calibration of a stabilised laser source wavelength;
- verification of displacement measurement—to 30 m;
- calibration of environmental compensation transducers;
- compensated system calibration—to 2 parts in 10^7;
- UKAS accreditation/ISO 9000 compliance.

Such essential periodic laser interferometer calibration confirms the traceability measurement chain to the absolute standard for the metre, as basically depicted in Fig. 1.2.

Typically, laser interferometers of the homo, or heterodyne-types, are frequently utilised by manufacturing industry at large, and in calibration laboratories for displacement-measurements in a very wide-range, from just 0.1 nm up to that of 50 m distance. The accurate and traceable operation of a laser interferometer requires calibrations and checks of several specific factors (i.e. see Table 2.1).

Table 2.1 The typical and maximum observed errors of either an representative industrial uncalibrated and unadjusted laser interferometer system

Quantity	Sensitivity/m	Typical error	Max. error
Wavelength	1	3.2×10^{-8} (relative)	7.1×10^{-8} (relative)
Pressure	−0.27 μm/hPa	1.7 hPa	−12 hPa
Air temp	0.96 μm/°C	0.16 °C	0.5 °C
Mat. temp	11.5 μm/°C	0.03 °C	0.3 °C

Source Centre for metrology and accreditation (MIKES), Espoo, Finland (2013)

Refractive Index of Air Compensation

A normal metrological practice is to establish the refractive index of air equation of a device, or by appropriate software, by comparing the calculated values to the values obtained from a commonly utilised updated Edlen equation

[Re: Bönsch, G., Metrologia, Vol. 35, 133–139 (1998)]

This specific value for the Edlen equation, for the reading of a commercial laser interferometer can be expressed as follows:

$$L_{20\,^\circ\mathrm{C}} = \frac{(D+\phi)\lambda_0 / 2}{n(t_{\mathrm{air}}, h, p)[1 + \alpha(t_{\mathrm{mat}} - 20\,^\circ\mathrm{C})]}$$

where:

'D' is the integer amount of interference fringes;
'ϕ' is the fractional phase of the interference signal;
'λ_0' is the vacuum wavelength of laser light;

function '$n(t_{air}, h, p)$', is for refractive index of air calculation with measured air; with: temperature, 't_{air}'; humidity, 'h'; and pressure, 'p'; are by corresponding sensors. Often commercial systems are also equipped with one, or several material temperature sensors, 't_{mat}', for thermal expansion compensation with expansion coefficient; 'α', of the material.

Realisation of the Metre and Vacuum Wavelength Calibration

The practical realisation of the definition of the metre, at the majority of countries National Standards Organisations, typically, such as at 'MIKES' in Finland, is obtained by:

- **an optical frequency combination, referenced to an atomic clock**—which is utilised to measure the absolute frequency of an iodine-stabilised He–Ne laser at 633 nm, this being operated according to the current international recommendations;
- **the vacuum wavelength of the iodine-stabilised laser**—which is calculated from the measured frequency and from the value for the speed of light in a vacuum.

As a result, the realisation of the metre is transferred to lasers utilised in interferometers, by calibrating their vacuum wavelength in beat-measurements with that of an iodine-stabilised (red) He–Ne laser.

Calibration of Sensors

As well as the actual laser interferometer, its associated-sensors (e.g. such as for temperature and material) will also need to be periodically calibrated, usually in the following manner:

- **air temperature sensors**—are compared against calibrated reference Pt100-sensors, inside a climate chamber;
- **pressure sensors**—are calibrated against a reference sensor typically utilising a piston cylinder to produce adjustable pressure;
- **humidity sensors**—are calibrated inside a climate chamber as a comparison to a reference humidity sensor;
- **material sensors**—of the instrument and reference Pt100-sensors, are attached to a steel block and inserted inside a climate chamber.

As a consequence of such a testing/calibration regime, if these sensors deviate considerably from the reference, then a correction is applied, or an adjustment is performed to them.

The Benefit of Calibration

In Table 2.2 is shown the radical improvement of uncertainty due to calibration for a characteristic commercial laser interferometer set-up. At this time, the uncertainty-calculation is undertaken for a typical commercially available interferometer system, although with the application of superior temperature-sensors then somewhat lower values of uncertainties could be achieved. This laser calibration will also provide traceability to the realisation of the metre, which guarantees conformity with other high-accuracy/precision dimensional measurements.

In summary, the periodic calibration of laser interferometers is:

- essential for accurate/precise and reliable measurements;
- necessary to achieve conformity with SI-metre (Standard), which definitely requires traceability that can only be achieved by its systematic calibration.

2.1.3 Laser Calibration—Potential Error and Uncertainty Sources

The main sources of error/uncertainty arising from the use of laser calibration systems is well known and documented and must be minimised if valid readings are to be obtained from the machine or equipment under test. The laser and interferometric measurement optics can provide remarkably high levels of linear resolution and precision. Nonetheless, it is the laser system's environmental compensation unit

Table 2.2 The uncertainty of a laser interferometer just prior to and after its calibration—with certain notable adjustments

Quantity system	Sensitivity coefficient		Uncalibrated system		Calibrated and adjusted system	
			Errors	Uncertainty contribution $(k = 1)$/µm	Errors	Uncertainty contribution $(k = 1)$/µm
$D + \phi$ (fringes)	1	n/a	5.0 nm	0.005	5 nm	0.005
λ_0 (wave-length)	1.6×10^6	L	0.02 pm	0.03L	0.003 pm	0.005L
n (refr. index)	1	L	1×10^{-7}	0.10L	3×10^{-8}	0.03L
t_{air} (air temp.)	-9.6×10^{-7}	1/K L	0.30 K	0.29L	0.05 K	0.05L
p (pressure)	2.7×10^{-9}	1/Pa L	170 Pa	0.46L	20 Pa	0.05L
α (coeff. exp.)	0.289	m K L	6×10^{-7}1/K	0.17L	6×10^{-7}1/K	0.17L
t_{mat} (mat.temp.)	-1.15×10^{-5}	1/K L	0.15 K	1.73L	0.025 K	0.29L
Combined standard uncertainty: Q(0.005; 1.8L)					Q(0.005; 0.34L)	

Where L is the measured distance in metres
Source Centre for metrology and accreditation (MIKES), Espoo, Finland (2013)

(i.e. often termed its weather-station) that is primarily responsible for the system's measurement accuracy and precision. This so-called weather-station, automatically compensates for the linear displacement readings from the laser on behalf of any variations in both the air refractive index[2] and material temperature.[3]

[2]**Refractive index of air**: because of the significance of refraction in both Optical-design and Metrology, the refractive index of air has been extensively-reported. Typically, the variations in atmospheric pressure, temperature and relative humidity, will alter the wavelength of a red 0.633 µm wavelength Helium Neon (He–Ne) laser, whose differences are normally quoted in parts per million (ppm). What is precisely known, is that the refractive index of a vacuum is exactly 1. The refractive index of what is termed Standard air (Standard air can be defined as: "The air with a pressure of 1013.25 mbar, at a temperature of 20 °C and, with a relative humidity of 50 %".), as seen by a He–Ne laser, is: ≈1.0002714. Consequently, a laser's wavelength in Standard air is: ≈271 ppm shorter than its actual vacuum wavelength.

[3]**Material temperature compensation**: in many situations this can be impractical and the dimensions have to be measured in situ. So that this can be successfully achieved, in for example, Renishaw's XL-80 laser interferometer system (i.e. see Figs. 2.1 and 2.2), which includes the capability to compensate for these linear readings, hence, by using a manually-entered Material expansion coefficient, plus the temperature from up to three material temperature sensors, this is successfully achieved and the process is termed: Material expansion compensation. The objective of the process here, is to estimate the linear laser readings that would have been obtained, if the measurements had been undertaken at the agreed: International Reference Temperature—of 20 °C.

Fig. 2.1 Portable laser measurement and calibration instrumentation (courtesy of Renishaw plc)

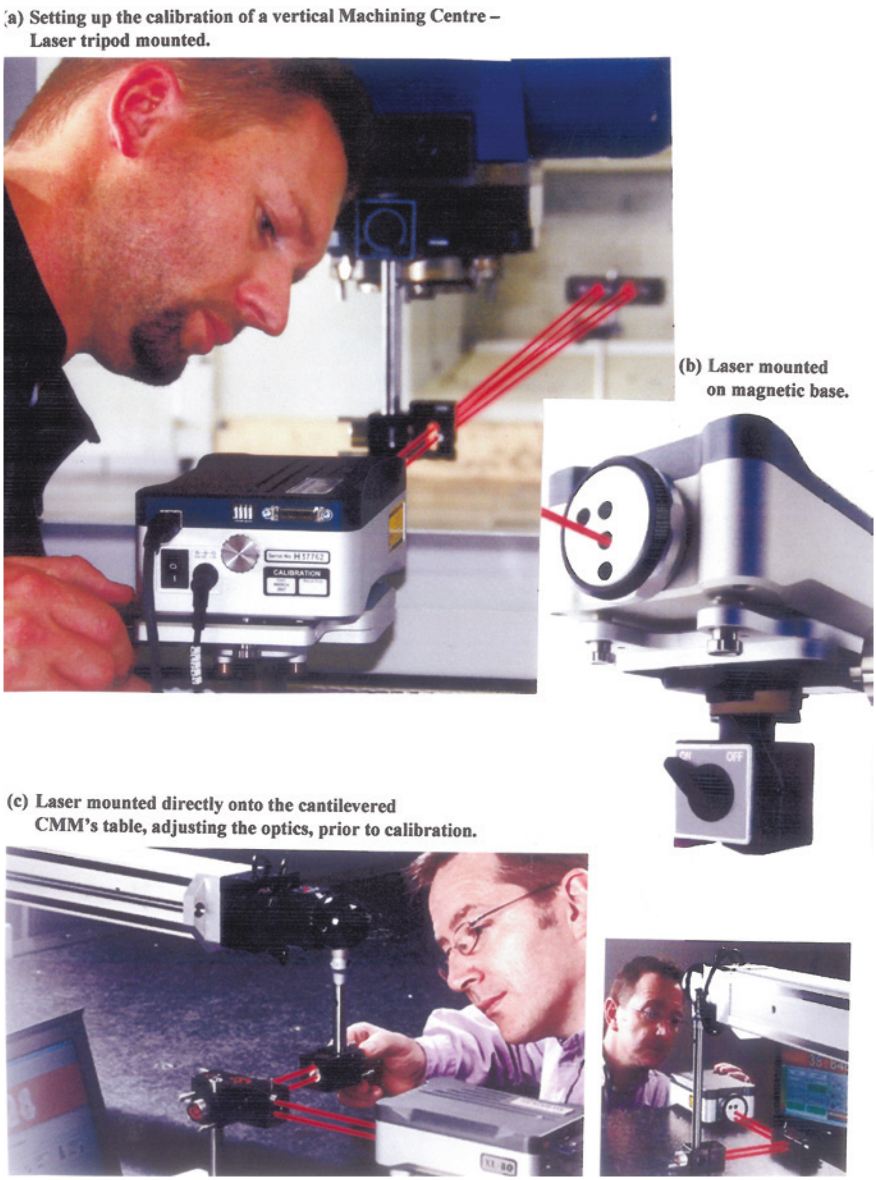


Fig. 2.2 Typical laser mounting configurations, prior to machine tool and CMM calibration trails (courtesy of Renishaw plc)

Just some of these significant values of uncertainty incurred when setting-up and utilising laser systems on machines, are the:

- **Cosine error** – this will be present if say, the machine tool's travel is not identical to that of the interferometer's beam (i.e. see Fig. 1.48a);
- **Abbé offset error**[4]—this is when the position of the laser measurement is shifted-away (i.e. offset), from the position of, say, the actual axis cutter's travel (i.e. see Fig. 1.48b);
- **Deadpath errors**[5]—are influenced by ambient conditions in the same manner as the displacement part of the beam. So, the interferometer reasons that the path length is the distance moved by the mirror, but in actuality this path length is affected by ambient conditions, thus being the distance from the interferometer block to the matched mirror (i.e. see Fig. 1.48ci, cii and ciii).

The equation, which is applicable to both air and material expansion compensation relating to linear laser readings, can be expressed as;

$$L = (1 - \alpha T) \,.\, \lambda_{\text{air}} \,.\, N/2$$

where:
'L' is the laser readout; 'N' is the number of laser fringes counted after the system was datumed; 'α' is the material expansion coefficient manually entered by the user; 'T' is the difference between the average material temperature and 20 °C; while, 'λ_{air}' is the current air refractive index—calculated using either the: Edlén-, or Ciddor-equations—from the air temperature, pressure and humidity.

[4]**The Abbé principle** was named after Dr E.K. Abbé, who stated that: "The measuring instrument is always to be so constructed that the distance being measured is a straight-line extension of the graduations on the scale that serves as the reference. … Should the measuring axis and that of the scale belong to two different axes, which are separated by a certain distance, then … the length being read off will be identical to the length being measured in general only when the moving system undergoes pure parallel motion, with no rotation. If the system undergoes a rotation between the initial and final settings, then the scale reading and the measured length are different".
Alternatively if this is somewhat too complex and confusing, then this **Abbé Offset**, can be simply stated as when: "The line of measurement is not coincident with the measuring plane". Dr Ernst Karl Abbé (Born: 23 January 1840 in Eisenach, Saxe-Weimar-Eisenach, Germany—died: 14 January 1905 in: Jena, Germany) was a notable German Physicist and Optical-scientist. Abbé was awarded his Ph.D. in Physics from The University of Göttingen, Germany—in 1861. In conjunction with both Otto Schott and Carl Zeiss, he laid the much toward the foundations of today's modern optical-developments and principles. Abbé was co-owner of Carl Zeiss AG, a respected German manufacturer of Research-microscopes, Astronomical-telescopes, Planetariums and for many other Optical-systems [source Galyer and Shotbolt (1990) and Smith et al. (2002)].

[5]**Deadpath errors**: in order for the equation (i.e. see the expression for 'L'), to effectively compensate linear measurements taken in unstable environments, it is important that 'N' (i.e. the fringe-count) nominally-reflects the separation between the optics in the measurement arm of the interferometer. For example, if the separation doubles, then 'N' should nominally double too and, when '$N = 0$'—the optics should be close together. This is easily achieved if the laser is datumed (i.e. with 'N' being set to '**0**') when the optics are close together. If these linear optics are not close together when the laser system is datumed and the environment subsequently changes, then the laser reading will show a small-drift in the datum position. This actual drift will often be comprised of two distinct components, these are: (i) an air deadpath error and, (ii) a material deadpath error.

Air Dead Path Error (E_{ADP})

With regard to the deadpath error (see Fig. 1.48ci) in the laser setup on the machine, effectively the system does not perceive that there is additional air in the measurement arm and as a result will not compensate for changes in the wavelength of the laser in that portion of the beam. As a consequence, the general equation for the air dead path error (E_{ADP}) is provided as follows;

$$E_{ADP} = D.(\lambda_{air} - \lambda_0) / \lambda_0$$

where:
'E_{ADP}' is the air dead path error; 'D' is the separation between the optics at datum (i.e. the dead path); 'λ_{air}' is the current laser wavelength; while, 'λ_0' was the laser wavelength—when the system was datumed.

For example, by utilising this equation and assuming alterations relative to Standard air, it is conceivable to estimate the dead path error per metre of air dead path. This alteration can be considered as follows:

- 0.27 µm error per mbar change in air pressure since datum;
- 0.96 µm error per °C change in air temperature since datum;
- 0.1 µm error per 10 % change in relative humidity since datum.

These specific readings clearly highlight that Air Dead Path Errors (E_{ADP}) are typically quite small and if the measurement arm optics are positioned such that 'D' is <10 mm when the system is datumed, then the air dead path error is negligible.

Material Dead Path Error (E_{MDP})

When considering once again the example shown by Fig. 1.48ci, the laser system is datumed where the encoder readout is 0.000 mm, but with a dead path separation as shown between the measurement arm optics. At this position the fringe count of '$N = 0$' is as expected, having the laser position readout at 0.000 mm. If one currently supposes that the temperature of the actual machine has now changed by +1 °C and then postulate that the material has an expansion coefficient of ≈10 ppm/°C, these effects will modify the measurement process. Moreover, this material expansion causes the measurement arm optics to move further apart by ≈10 ppm × D which instigates a 10 ppm increase in the number of waves that can now fit into the gap 'D' between the measurement optics. Accordingly, the fringe count 'N', will increase and the laser's position readout will drift-away from zero by 10 ppm × D. It should also be emphasised that this material dead path error is normally 10 times larger than the air dead path error produced by a 1 °C change in air temperature. Even if the environmental compensation unit has correctly calculated a new environment factor (EF), applying material expansion compensation will barely have any effect, since the fringe count is almost zero (i.e. instead of being 2D/EF). So in effect, the laser's system setup will not be able to distinguish that there is extra material in the measurement arm, consequently it will not compensate for its thermal expansion or contraction.

The general equation for Material Dead Path Error (E_{MDP}) is represented as follows:

$$E_{MDP} = D \, . \, \alpha \, . \, T$$

where:
'E_{MDP}' is the material dead path error; 'D' is the separation between the optics at datum (i.e. the dead path); 'α' is the linear coefficient of expansion of the material in the dead path; 'T' is the change in temperature of the material since the system was first datumed.

By way of practical example, if the material expansion coefficient is 10 ppm/°C, then the dead path error will be 10 µm per metre of material dead path per °C change in material temperature since its datuming. Clearly, this has exposed that these material dead path errors are potentially much more significant than its associated air dead path errors. This results from the materials in the dead path perhaps not being identical as the item being measured, so these temperatures may independently vary, ensuring that here, a simple software-correction is not a practical solution. In consequence, the optimum methodology herein—to lessen these undesirable conditions—is to apply good metrology practices, by minimising:

- **the material dead path**—by situating the setup of the laser's optics as closely and directly as possible to the point of metrological-interest;
- **any changes in material temperature during measurement**—by initially stabilising the temperature and/or promptly completing the measurements;
- **the optics separation (i.e. when the system is datumed)**—this should be made by utilising either a preset reading, or by employing a beam-splitter as the moving optic.

2.1.4 Introduction to Laser Machine Calibration

General Comments—Concerning CMMs and Machine Tools

The reliability of machine tools and CMMs has seen a marked-improvement, in particular, with respect to their inherent accuracy and precision, and of note, are the actual deviations in the machine tool accuracy/precision and subsequently how they affect the geometry of the machined workpiece, which may be due to a variety of technical reasons. Probable sources for this variation in these machines may include errors in the machine's geometry, due in part to the tolerances in their manufacture, construction and build/assembly of the separate machine parts, exacerbated by any deformation resulting from loads—whether they are either static or dynamic, or indeed both, via some form of thermal-deformation being present.

Laser Instrumentation and Equipment

Since the 1970s, laser interferometer systems have been employed for wide-ranging accuracy and precision calibration procedures, typically for a large range of CNC machine tools, co-ordinate measuring machines (CMMs) and other position-critical systems. Typical of the latest-type of highly portable laser interferometer systems, is the one being illustrated in Figs. 2.1 and 2.2. Here, the major benefits of utilising these high-quality laser interferometers can be derived from their notable-characteristics, which are listed below, where they can exhibit:

- **high levels of consistent accuracy**—the system accuracy of ±0.5 ppm, is maintained throughout the laser system's operating range of: 0–40°C;
- **traceable interferometry**—having all the laser measurements, including straightness, angularity, etc., being interferometric in nature; these measurements are based upon the Internationally traceable Standard of the wavelength of laser light;
- **quick and secure alignments using a tripod-mounted laser**—with all alignments, these can be undertaken comfortably and safely outside the machine's envelope, so there will not be any loss in axis travel, nor will the instrument suffer from the effects of factors such as its cable-drag during the actual measurement process;
- **laser's optics designed for the workshop-hardened user**—because all of the optical-housings are manufactured from hard-anodised aluminium. Furthermore, when these optics are then coupled with a novel-designed beam-steerer[6] (i.e. see Fig. 2.1, bottom), this facilitates quick and assured laser beam alignments;
- **long range measurement**—this particular laser system facilitates linear measurements to be undertaken on any axes up to 80 m in length, or simultaneously measuring parallel axes—for dual-drive machines;
- **rotary axis calibration**—the combination of the laser with its associated Rotary Axis-calibrator (see Figs. 2.13, bottom and 2.14) can provide a fully automatic-technique of rotary axis calibration—on both multi-axes machine tools and for CMMs—the latter being equipped with a rotary table;
- **comprehensive laser software**—with Renishaw's bespoke-packages—which can support reporting to International Standards for its machine verification, along with other notable features such as linear position error correction and dynamic motion analysis.

This particular company's laser-products (Figs. 2.1 and 2.2) produce an extremely stable laser beam with a wavelength that is traceable back to National and International Standards, having the laser-frequency stability specified as: ±0.05 ppm over 1 year, or alternatively, ±0.02 ppm over just 1 h. This high-quality laser's performance is accomplished by dynamic thermal control of the laser-tube

[6]**Beam-steerer** (i.e. illustrated in Fig. 2.1, bottom): utilises simple-levers to rapidly align the laser beam in both the horizontal and vertical planes. This Beam-steerer was designed to enable both new and experienced users to speed through its: linear; angular; and straightness measurements—for laser interferometer calibration of machine tools and coordinate measuring machines (CMMs), plus other similar precision devices which may also require calibration. So, simply by the action of sliding horizontal, or vertical control levers, this steers the laser beam for rapid setup and alignment in both horizontal and vertical planes. This Beam-steerer can provide an angular beam sweep of: ±2° (i.e. ±35 mm m^{-1})—in both planes—for linear-axes up to 5 m long.

length—to within a few nanometres. Moreover, the laser's linear measurement accuracy is: ±0.5 ppm over the whole environmental range (i.e. from a temperature range of: 0–40 °C and across atmospheric pressures ranging from: 650 mbar to 1150 mbar). At this juncture, the laser readings are obtained at: 50 kHz, thus allowing a linear measurement speed of 4 m s^{-1} (maximum) with a linear resolution of 1 nm. This product's compact laser head is supplied with an independent compensator system—see Fig. 2.1a. Furthermore, it features an auxiliary analogue signal with quadrature output. Accordingly, the same socket will also accept a trigger-signal input for data-capture synchronisation, plus LED status-lights, which will indicate laser-status and its signal-strength, providing back-up to the software's on-screen indicators. This comprehensive laser specification, also includes a switchable long-range operational mode (i.e. ranging from 40 to 80 m in length).

Laser Sensor Integration

In association with the laser head (depicted in Figs. 2.1 and 2.2) are its complementary and purpose-built compensator unit, which is a crucial factor in the system's measurement accuracy and precision. This compensator features some intelligent-sensors that can process the readings at source, with the compensator having the ability to accurately measure: air temperature; air pressure; plus the relative humidity. Once these readings have been established, the compensator will then modify the nominal value of the laser-wavelength producing a true value. This newly established value is automatically undertaken and then refreshed—every 7 s—and at that moment it is then utilised in subsequent displacement-calculations, virtually eliminating any measurement errors resulting from these variations. Up to three material temperature sensors can also be attached to its accompanying compensator, thereby enabling linear measurements to be normalised to a standard material temperature of 20 °C. At this time it should be noted that both the air and material temperature sensors can be considered as intelligent, with integral-microprocessors to analyse and process these sensors' output, before sending its digital temperature values to the compensator—thus providing secure measurements.

Table 2.3 below shows the integrated laser-sensor's performance for this particular company's current commercial laser system, when they are coupled-up to the compensator unit and ultimately to that of the accompanying laser head—for controlled and accurate calibration readings.

Table 2.3 Typical values obtained for laser-sensor performance—for a representative commercial system

Sensor performance	Range	Accuracy
Material temperature	0–55°C	±0.1 °C
Air temperature	0–40 °C	±0.2 °C
Air pressure	650–1150 mbar	±1 mbar
Relative humidity (%)	0–95 %	±6 %RH

Courtesy of Renishaw plc

2.2 Methods of Machine Acceptance Tests—The Basis for Verification

In order to certify a high-degree of machine accuracy and precision, several measurement systems and processes have been produced, together with their appropriate published International Standards (see Appendix 1) governing machine tool acceptance tests. Procedures for machine acceptance consist of basically two types. These are either: (i) indirect; or (ii) direct processes; to identify a machine's properties. In the case of indirect machine accuracy identification, the trial workpieces are defined by the manufactured geometrical and formal characteristics utilising the machine tool to be tested drawing out deductions concerning machine accuracy/precision, these being based upon the deviations between the required and actual geometries. Here, these indirect processes are more easily matched to final functional tests to determine the accuracy/precision of a machine tool and as a result, are today considered as being the preferred method employed in acceptance tests. When these indirect acceptance criteria are not satisfactory, then direct processes will normally be applied for more detailed examinations. At this time, the direct determination of a machine's properties allows for the identification of so-called error-impacts. Consequently, these parameters are established directly on the machine, with the aid of suitable measurement instruments. Currently, tests of individual criteria, or discrete degrees of freedom can be undertaken, responding to more demanding machine accuracy/precision requirements. Where machine tools are configured with Serial cartesian kinematics, the results of test-measurements can be utilised to re-adjust the machine's performance. This theoretical re-adjustment is possible, as there is an indisputable-connection between the actual confirmation of each axis of the system coordinates for the workpiece and the corresponding actuation-axis of the machine tool.

The parallel kinematic machine tools (see a typically configuration, in Fig. 1.26) are calibrated after machine-assembly in a procedure which, in general, is considered as significantly more complex. With this kinematic-arrangement, it comprises of both the machine's parameter identification and error compensation. Moreover, such parameter identification serves the purpose of accurately determining the geometric parameters of these parallel kinematic machine tools (e.g. such as the actual leg-lengths, or its joint-positions) so the algorithms for the transformation of actuation and workpiece coordinates in such a machine control can be modelled with much greater-precision. Parameter identification serves the purpose of identifying, as directly as possible, the connection between the cause-and-effect of machine-errors, while also finding the decisive reasons underlying this actual error.

2.2.1 ISO 230 Machine Tool Standards—Previous and Current Calibration Procedures

Some of the earliest techniques for the calibration of machines (see the schematic diagrams shown in Fig. 2.3a, b) were quite time-consuming and somewhat

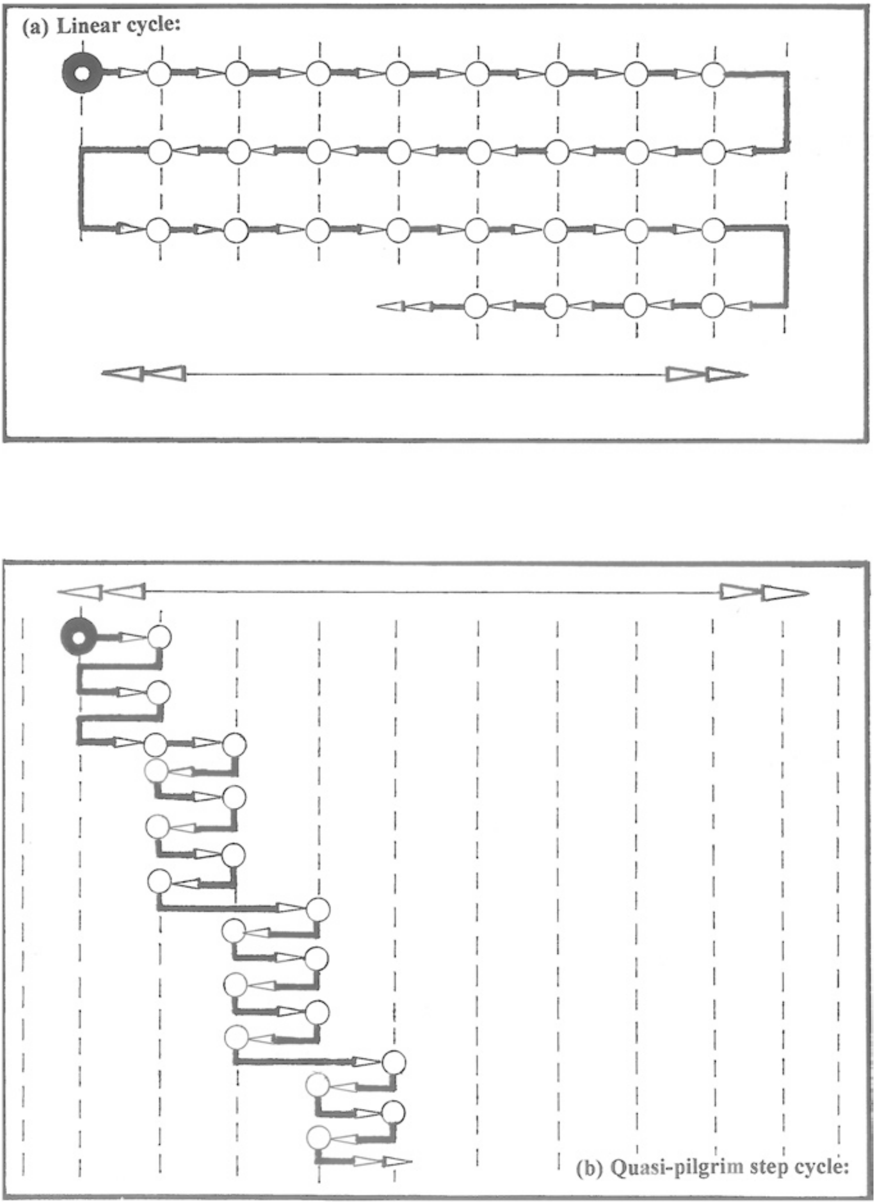


Fig. 2.3 Two types of *static step cycles* for machine tool calibration—previously employed

inefficient; this made them open to some degree of uncertainty in the readings obtained from such procedures. Here, in order to take static readings (i.e. by stop-and-go readings) along a particular axis—typically for straightness measurement—the original standard suggested that the linear motion for the target positions—utilised in slide-calibration—moved either with the Linear cycle (i.e. Fig. 2.3a), or Quasi-pilgrim step cycle (i.e. Fig. 2.3b). By moving in this repetitive stop-start progressive manner over five bi-directional runs, the potential backlash would be effectively eliminated and its accompanying target-readings would by this procedure be averaged-out. Historically, of the **ISO 230-2** readings at that time, these two differing-techniques—for obtaining machine calibration—would have produced slightly differing results, so each linear-cycle was designated marginally differently, with the linear-cycle being denoted by the suffix 'L' and the quasi-pilgrim step cycle by suffix 'P'. Of note, was that this early standard did indeed state how when, as well as where, it was appropriate to take the calibration readings on a machine tool.

Today, the International Standards such as **ISO 230-series** have evolved from these previous standards that were already in use, in conjunction with the knowledge of current working-practices and with the awareness of the development in new technologies. Over the last several decades the **ISO 230-1 to 11** (parts) has been internationally adopted as the means to calibrate and validate vertical-spindled CNC machine tools, while **ISO 13041-1 to 8**[7] (parts) considers the testing of horizontal spindled machines—typified by that of turning Centres. For Co-ordinate Measuring Machines (CMM's) the equivalent standard here is **ISO 10360-1 to 6** (parts) which has also seen similar international-approval. Returning once again to the relevant **ISO 230-series** for machine tools equipped with vertical spindles, they can be simply described, in the following manner:

- **ISO 230-1: 2012 Part 1: Geometric accuracy of machines operating under no-load, or finishing conditions**—specifies methods for testing the accuracy of machine tools, operating either under no-load, or under quasi-static conditions, by means of geometric and machining tests. The methods can also be applied to other types of industrial machines. This Standard also covers power-driven machines, which can be used for machining metal; wood; etc.; by the removal of chips; or swarf material; or indeed by plastic deformation. However, it does not cover power-driven portable hand-tools. This **ISO 230-1** relates to the testing of geometric accuracy, but it is not applicable to the operational-testing of the machine tool for its: vibrations; stick-slip motion of components; etc.; nor to the checking of characteristics—such as speeds and feeds. Furthermore, it does not cover the geometric accuracy of high-speed machine motions—where its machining-forces are typically smaller than the acceleration-forces;

[7]**ISO 13041-1** for example, specifies with reference to: **ISO 230-1:1996**: the geometric tests on numerically controlled (NC) Turning machines and Turning Centres, of normal accuracy, with horizontal work-spindle(s). This Standard specifies the applicable-tolerances corresponding to the tests mentioned above; and goes on to explain different concepts, or configurations and common features of CNC Turning machines and Turning Centres. Moreover, the Standard also provides a terminology and designation of controlled axes. Here then, this **ISO 13041** also deals with verification of the accuracy of the machine. It does not apply to the operational-testing of machines (e.g. vibration, abnormal noise, stick-slip motion of components), nor to the machine's characteristics (e.g. speeds, feeds) as such, these checks are generally undertaken before testing the accuracy. For more information on the other parts of: **ISO 13041-series** of tests—see Appendix 1.

- **ISO 230-2: 2006 Part 2: Determination of accuracy and repeatability of positioning CNC machine tools**—the Standard specifies methods for testing and evaluating the accuracy and repeatability of the positioning of numerically controlled machine tool axes, by direct-measurement of individual axes on the machine. These methods apply equally to both its linear and rotary axes. However, when several axes are simultaneously under test, the methods do not apply. Here, **ISO 230-2** can be utilised for: type-testing; acceptance tests; comparison testing; periodic verification; machine compensation; etc. In this Standard, the methods involve repeat-measurements at each position. The related parameters of the test are defined and calculated, with their uncertainties being estimated—as described in: **ISO/TR 230-9:2005, Annex C**;
- **ISO 230-3: 2007 Part 3: Determination of thermal effects**—defines three distinct tests for the determination of thermal-effects on machine tools: (i) an environmental temperature variation error (ETVE) test; (ii) a test for thermal-distortion, caused by rotating-spindles; (iii) a test for thermal-distortion, resulting from moving linear axes. The test for thermal distortion caused by moving linear axes is applicable to computer numerically controlled (CNC) machines only and is expressly designed to quantify the effects of thermal expansion and contraction, together with the rotational-deformation of its structure. Hence, for practical reasons, it is applicable to machines with linear axes up to 2000 mm in length. If such tests are utilised for machines with axes longer than 2000 mm, then it will be necessary to choose a representative length of 2000 mm, but in the normal-range of each axis for the tests. These tests will correspond to that of drift-tests-according to **ISO/TR 16015** and then define the evaluation and the detailed procedure for such machine tools;
- **ISO 230-4: 2005 Part 4: Circular Test for CNC Machine Tools**—here, it specifies methods of testing and evaluating the bi-directional circular-deviation, as well as the mean bi-directional radial deviation, according to the circular-deviation and the radial-deviation of circular paths that are produced by the simultaneous movements of two linear axes. Thus, the standards objective, is to provide a method for the measurement of the contouring-performance of a CNC machine tool;
- **ISO 230-5: 2000 Part 5: Determination of the noise emission**—this part explains how, where, plus when noise-emissions are undertaken and the levels of acceptable-noise, also with the techniques and equipment utilised to establish these noise-levels;
- **ISO 230-6: 2002 Part 6: Diagonal displacement test**—specifies the actual diagonal displacement tests which allow the estimation of the volumetric-performance of a machine tool. The complete testing of the volumetric-performance of a machine tool is both a difficult and time-consuming process. Subsequently, diagonal displacement tests have been developed, that can reduce the time and cost associated with testing for the machine's volumetric performance. A diagonal displacement test is not in itself a truly diagnostic test, although conclusions of a diagnostic nature may sometimes be possible from these test results. In particular, when face diagonal tests are included, a direct

measurement of the axes squareness is also possible. Diagonal displacement tests on the body diagonals may be supplemented by tests in the complementary face diagonals, by tests parallel to the machine axes in accordance with **ISO 230-2**, or by the evaluation of the contouring-performance in the three coordinate planes, as defined in **ISO 230-4**. These types of diagonal displacement tests may be utilised for acceptance-purposes and as reassurance of machine performance—where parameters of the test are utilised as simply a comparison-index;

- **ISO 230-7: 2006 Part 7: Axes of rotation**—this Standard is primarily aimed at standardising methods of specification and test for the geometric accuracy of axes of rotation utilised in machine tools. Spindles, rotary heads and rotary and swivelling tables of machine tools will constitute axes of rotation, all of these having unintended-motions in space, as a result of multiple-sources of errors. Here, **ISO 230-7** encompasses the following properties of spindles axis of rotation error motion, together with speed-induced axis-shifts. The other additionally important properties of spindles will include, such factors as: thermally induced axis-shifts and environmental temperature variation-induced axis-shifts, both of which are dealt with in: **ISO 230-3**;
- **ISO 230-8: 2010 Part 8: Determination of vibration values**—this Standard is primarily concerned with the different types of vibration that can occur between the tool-holding part as well as the workpiece-holding part of a machine tool. (NB For simplicity, these features are generally referred to as simply the tool and workpiece, respectively.) These are vibrations that can adversely -influence the production of both an acceptable surface finish and an accurate workpiece. Here, the Standard is not aimed predominantly at personnel who have specialist expertise in vibration analysis and who would routinely undertake such work in research and development environments. However, the standard does not therefore replace relevant textbooks on the subject, but is normally intended for manufacturers and users alike, with general engineering knowledge—in order to enhance their understanding of the causes of vibration, by providing an overview of the pertinent background theory. **ISO 230-8**, will also provide basic information on measurement procedures for evaluating certain types of vibration problems that can beset a machine tool, such as:
  - vibrations occurring as a result of mechanical-unbalance;
  - vibrations generated by the operation of the machine's linear slides;
  - vibrations transmitted to the machine by external forces;
  - vibrations generated by the cutting process including self-excited vibrations—specifically chatter;
- **ISO 230-9: 2005 Part 9: Estimation of measurement uncertainty for machine tool tests according to ISO 230, basic equations**—this Standard will provide information on a possible estimation of the measurement uncertainties—for measurements according to **ISO 230**;
- **ISO 230-10: 2011 Part 10: Determination of the measuring performance of probing systems of a CNC machine tool**—is where it specifies test procedures to evaluate the measuring performance of contacting-probing systems

(i.e. utilised in a discrete-point probing-mode) being integrated with a numerically controlled machine tool. Moreover, it does not include other types of probing-systems, such as those used in a scanning-mode, or non-contacting probing-systems. Here, it should be noted that the evaluation of the performance of the machine tool being utilised as a coordinate measuring machine (CMM) is considered to be outside-the-scope of **ISO 230-10**;

- **ISO 230-11 [Standard in development: PD ISO/TR 230-11]: Part 11: Measuring instruments and their application to machine tool geometry tests**—this Standard's aspect will be concerned with that of measuring instruments. This standard in development is categorised in boring and milling, dividing and tool-workpiece holding devices, electrochemical machines, general, grinding and polishing, lathes, machining centres, manufacturing engineering, measurement; vibration and shock, numerically controlled machines, other specific equipment.

[Abridged details, courtesy of the ISO (2015)]

2.2.2 ISO 230—Laser Calibration Procedures on CNC Machine Tools

Before considering any laser calibration procedure on a CNC machine tool, it has already been mentioned that probably the greatest-uncertainty in most laser-measurements results from variations in its attendant environmental-conditions (e.g. these include air-temperature, air-pressure, also humidity) when compared to nominal values. Even relatively minor-variations in the ambient conditions will modify the laser-wavelength and consequently the resulting data-measurement reading. By the way of a practical example of this potential alteration in test conditions, if the following changes occurred, then they will increase laser wavelength by 0.25 ppm, such as 0.26 °C air-temperature increase, or a 0.93 mbar air-pressure decrease. Whenever such variations occur of temperature, humidity, plus pressure—from the nominal values—which are then combined, they can create a 20–30 ppm uncertainty in measurement (i.e. even if the test conditions remain stable during the whole test time-period). In order to mitigate against the undesirable variation in potential testing conditions, an Environmental compensation unit is normally included within the system, having some very accurate and precise environmental sensors, which will then compensate for these effects of the laser-wavelength. In the case of laser interferometer company's products, they will make great-efforts ensuring that their merchandise, such as their Compensation system and sensors—are highly accurate and precise across the entire operating-range of the system. It is this exacting-level of compensation that can typically maintain ±0.5 ppm linear measurement accuracy/precision from 0 to 40 °C ambient temperatures and, over the full air-pressure range, which thus ensures that reliable and traceable results are obtained from their sensors and instrumentation.

For many years the industry standard method of measuring CNC machine tool, or CMM performance, has been by utilising a free-standing laser, on a tripod, in combination with remote (i.e. separate) interferometer and reflector optics, these usually being mounted directly onto the machine table and into the spindle (i.e. see Figs. 2.1bi and 2.2a). The linear, angular (i.e. pitch and yaw), or straightness measurements between table and spindle, can then be separately commenced interferometrically, by utilising the appropriate choice of the system's interferometer optics. More recently, alternative systems have been introduced that depart from the above technique in one, or two significant areas, with these alternative calibration strategies being that they use:

1. **a linear interferometer optic that is combined with the laser-head** (i.e. either internally, or externally)—with the laser-head—in this case, being mounted directly onto the machine—rather than on its more-usual, separate tripod;
2. **remote electronic targets** (i.e. not interferometers)—these are utilised to measure: pitch; yaw; and straightness errors. With some laser systems, they can provide simultaneous 5-dimensional (i.e. 5D) measurements.

These alternative systems appear to suggest the benefits of easier set-up, increased portability and significantly reduced measurement time (i.e. particularly, if electronic targets and a linear interferometer are utilised to provide simultaneous linear, angular and straightness readouts). However, these more recently devised alternative techniques are often at the expense of both the machine's measurement accuracy and stability.

Comment will be made in the following extended-discussion on each type of measurement-mode, explaining the benefits of obtaining measurements interferometrically, but here, with a tripod-mounted laser system and by employing remote interferometer optics. Furthermore, these specific comments will then go on to consider the importance of the environmental compensation system—for its accompanying linear measurement accuracy.

There are number of distinct advantages in utilising a tripod-mounted laser with only the remote interferometer-optics mounted directly onto the machine, these being that the:

- **heat generated by the laser is isolated from the interferometer optics**—this allows the linear interferometer and reference arm to form the reference point from which all machine movement is measured. So any changes in the interferometer position or in the reference arm length, caused by thermal expansion/contraction, will degrade the accuracy of this measurement. In order to ensure that such changes are kept to an absolute minimum the laser system mimics good metrology principles, by ensuring that the heat of the laser source is distanced from that of the measurement-optics. Laser systems that employ an interferometer inside the laser-head, or have it mounted onto the front of this laser-head, do not follow these principles and as a result are likely to suffer from significant thermal-drift, both during laser warm-up as well as when ambient environment changes. Such thermal-drifting can have a magnitude of several orders of micrometres;

- **heat generated by the laser is remote from the machine under test**—typically, a Helium–Neon laser-head will dissipate >5 W of heat—with even more if it contains its integral power supplies. By situating a heat-source on, say, a small but high-accuracy machine, this action may cause a combined thermal-expansion and distortion of that machine. However, these effects are generally quite small but they can degrade the accuracy of results—at the micrometre-level of measurement. Consequently, by mounting the laser on a tripod, away from the machine, this will eliminate such heat-induced potentials;
- **laser-head does not obstruct axis movement**—if the laser-head is placed on the machine, its relative-size can often reduce the available range of travel of the axis under-test. Conversely, when the laser is mounted on a tripod, the only associated-items situated on the machine are its small interferometer optics, which will provide less-restriction in its axis-range of motion;
- **beam alignment adjustments can be undertaken outside the machine's envelope**—equally, if the laser is mounted inside the machine, all such laser-beam alignment adjustments have to be made inside the machine. A further restriction is that the machine's geometry and its machine guards, for any form of alignments, may make adjustments difficult to achieve. Certain laser systems allow adjustments to be made externally, by either utilising the tripod's stage-controls to move the laser, or internally—utilising a Beam-steering optic (see Fig. 2.1, bottom); this novel optical device being mounted directly onto the interferometer. Thus, a tripod-based laser allows the end user to choose the easiest method for calibration-testing—for the machine under-test;
- **there are no trailing cables inside the machine**—here, the laser-head requires power and signal cables, but in the case of the interferometer optics it does not. Subsequently, by mounting the laser on an external tripod with just the optics inside the machine, this avoids the need to route both the power- and signal-cables into the moving machine, preventing the expected problems of snagging, or dragging of these cables, which may cause either some damage, or a measurement error to occur.

Provided that any thermal drift has been eliminated (i.e. see first point above) then the accuracy of linear laser measurements will primarily depend on the performance of its integrated weather-station and not the laser-head. As a consequence, the accuracy of the weather-station sensors' over the full range of operation is a critical factor.

When undertaking either a full calibration, or verification procedure on a CNC machine tool, certain tests must be undertaken in accordance with the various **ISO 230—Parts**-see Sect. 2.2.1, these critical factors will be very briefly mentioned below:

- **linear positioning accuracy and repeatability of an axis**—the laser can measure the actual displacement moved along an axis and compare it against the displacement shown by the machine's axis encoders. This is the basis for error-compensation of machine tool CNCs—**see Appendix 3a**;
- **straightness of an axis**—both horizontal and vertical straightness of motion along an axis can be measured. Straightness-errors have a direct influence on

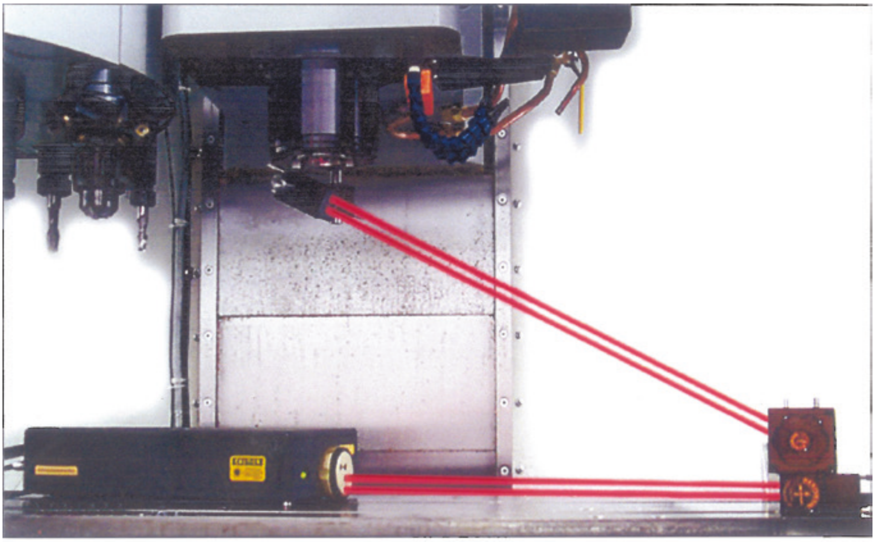
the machine and influence the cutter's path accuracy but, they are unlikely to be uniform along the entire axis of a machine's slide—**see Appendix 3b**;

- **squareness between axes**—these orthogonal axes of a machine tool need to be square to each-other, as well as accurate along their length. By utilising, say, a previously calibrated Optical-square and combining the two straightness-measurements, the squareness of two axes can be calculated precisely—**see Appendix 3c**;
- **flatness of a surface**—flatness of reference-tables (i.e. such as the machine tool's table) can be critical—as they are datum-surfaces for any potential measurement. This flatness-measurement enables a 3-D picture of its surface-form to be built-up—**see Appendix 3d**;
- **angular pitch and yaw of an axis**—these problems are common causes of positioning-errors. Even just a small error at the machine's spindle can cause a significant effect at the extended-position of the tool's tip, meaning that any interferometric-measurement must be fully traceable to International Standards—**see Appendix 3e**;
- **rotary axis/table angular positioning**—rotary axes are now becoming increasingly common features on multi-axis machine tools. Typically, a Rotary Axis Calibrator can provide for automatic data collection when utilised with a laser-head and its matched angular-optics—**see Appendix 3f**.

2.2.3 Laser Diagonal Displacement Test

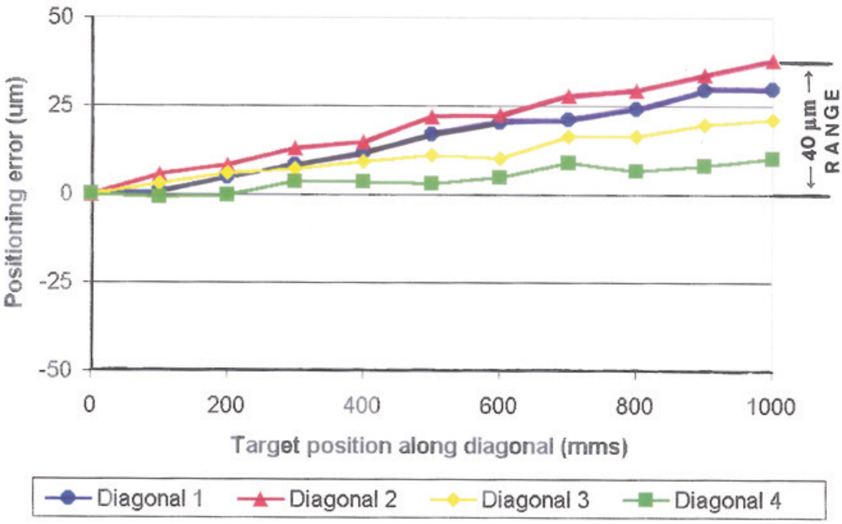
The International **ISO 230-6** Standard specifies diagonal displacement tests—see Figs. 2.4, 2.5, 2.6 and 2.7 which allows the estimation of the volumetric-performance of a CNC machine tool. However, in some supplementary-topical work[8] on such testing, it was highlighted that under certain conditions, a machine can achieve a good result from the **ISO 230-6** and **B5.54 Diagonal Tests** even if this plant has a poor volumetric-performance. This positive-outcome is because changes in the lengths of the body-diagonals created by one source of error in the machine can be subsequently cancelled-out by the changes due to yet another source of error. This effect is illustrated by considering a volumetric capacity of $2 \times 1 \times 0.5$ m on an orthogonal machine tool. If the machine has no errors, then the body-diagonal measurement will show that, to the nearest micrometre, all four body-diagonals are exactly 2.291288 m long—this is derived from Pythagoras' theorem (see below). If one now supposes that this identical machine tool has a 25 μm m^{-1} over-travel error (i.e. a positive linear-error) in the motion of the *X*-axis, with a 100 μm m^{-1} under-travel (i.e. a negative linear-error) in the *Y*-axis motion but no error in the *Z*-axis, then under these set of conditions, the laser

[8] Chapman (2003).



Laser diagonal test setup on a vertical Machining Centre.

[Courtesy of Renishaw plc]



Typical B5.54 diagonal test results from a machine.

[Courtesy of Renishaw plc]

Fig. 2.4 The laser diagonal test on a machining centre and some typical test results

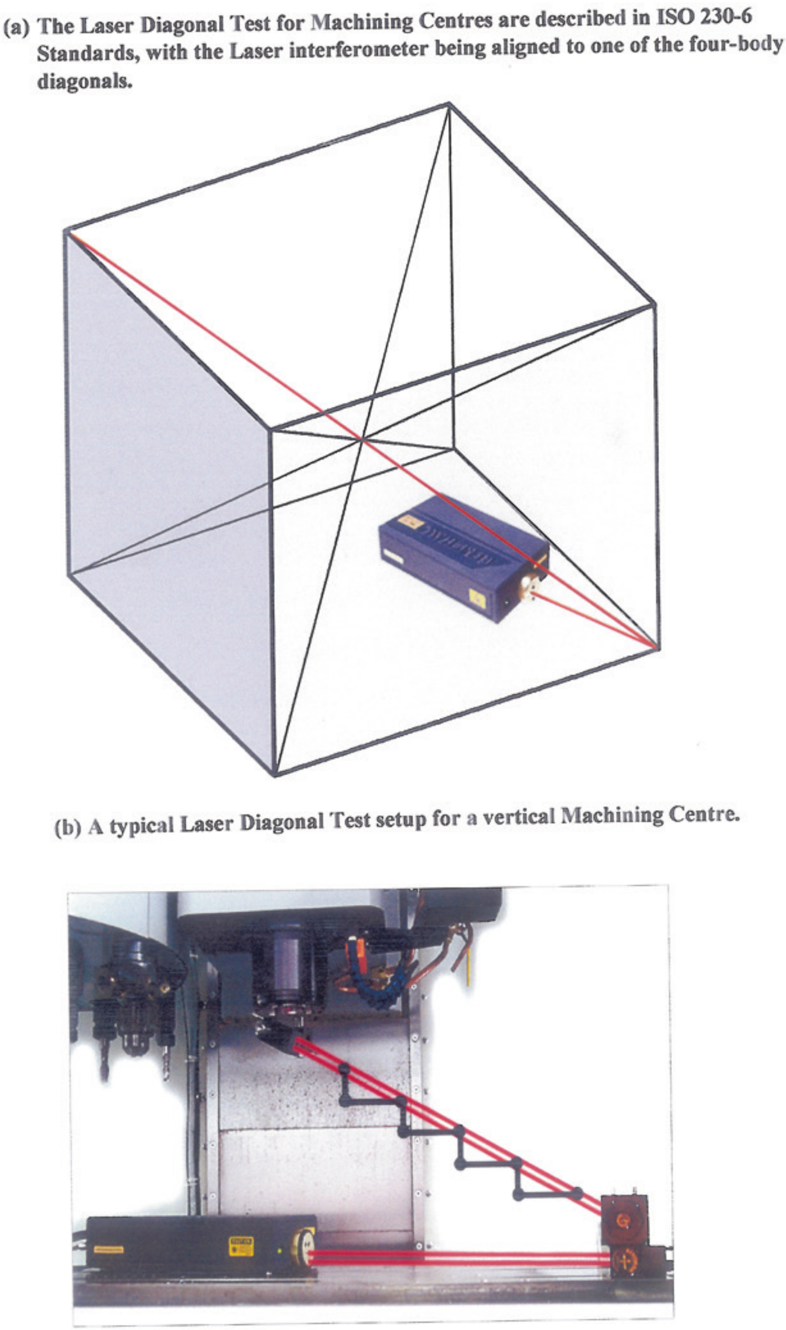


Fig. 2.5 The laser diagonal calibration setup for a typical machining centre (courtesy of ISO standards/Renishaw plc)

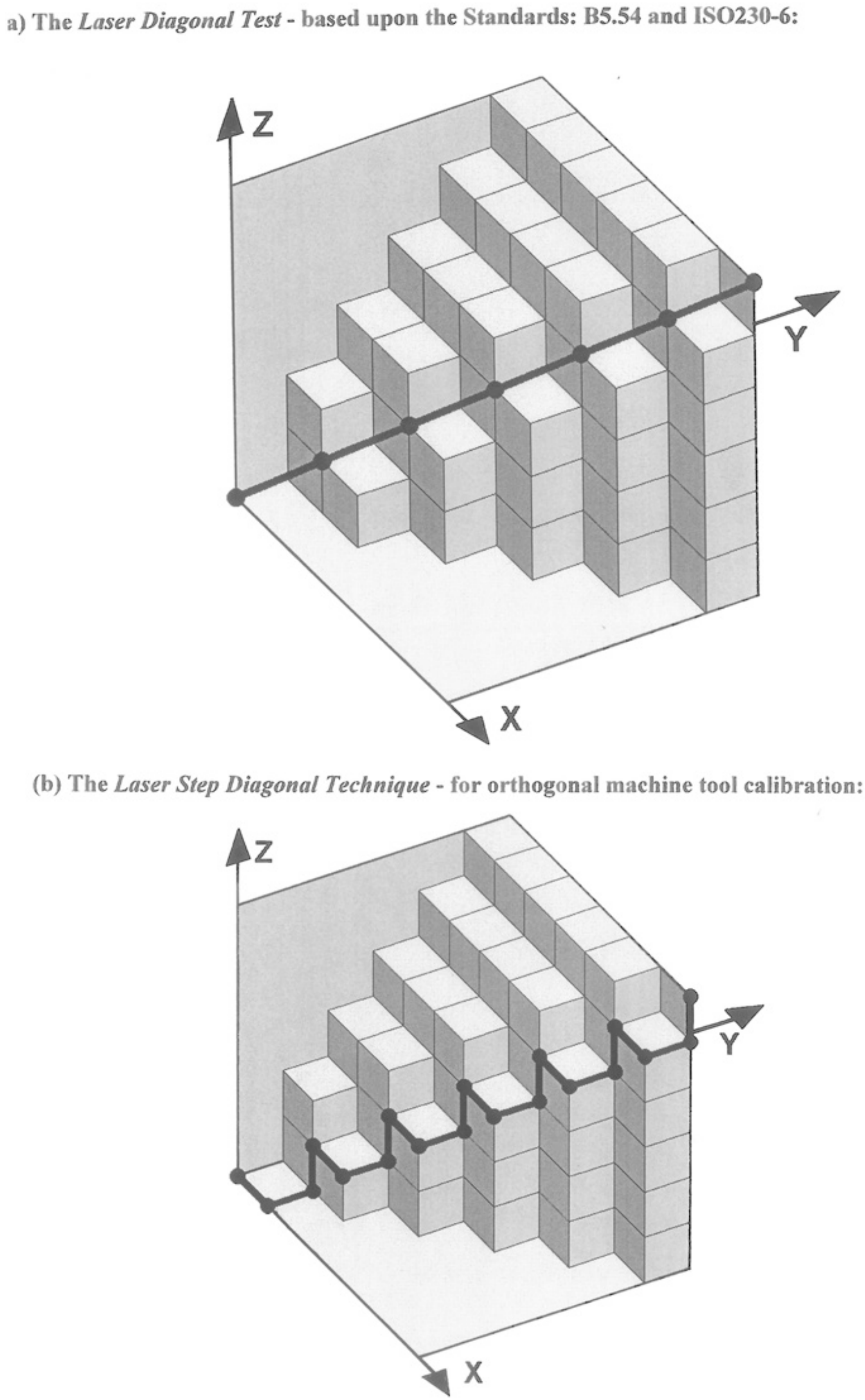


Fig. 2.6 Typical laser diagonal tests for orthogonal machine tools (courtesy of Renishaw plc)

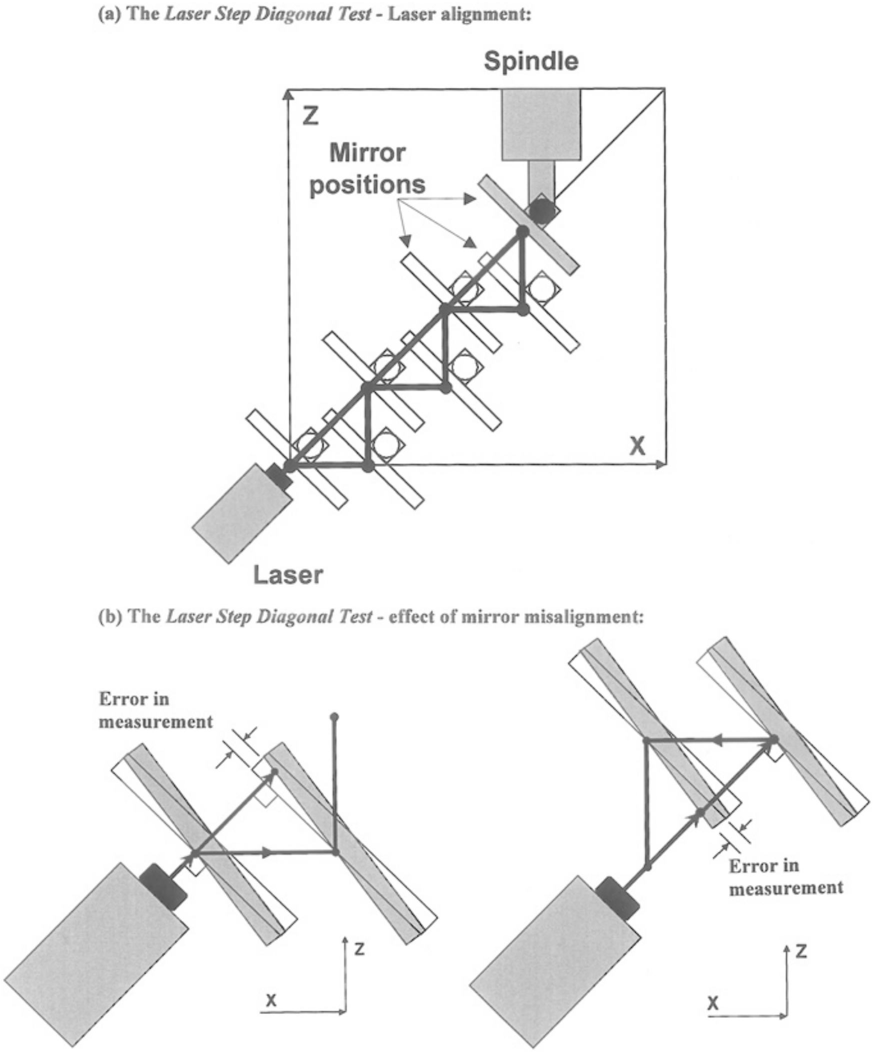


Fig. 2.7 Practicalities of the laser step diagonal testing arrangements (courtesy of Renishaw plc)

diagonal test will show that these diagonal lengths have changed by less than 0.1 μm and so, to the nearest-micrometre, they are still in effect 2.291288 m long—also derived from Pythagoras' theorem:

$$2.291288 = \sqrt{(2.000052 + 0.99992 + 0.52)}$$

Both the Standards **B5.54** and **ISO 230-6 Diagonal Tests** will indicate that the machine is still acceptable, even when this is undoubtedly not the case. The machine has a volumetric-error of >100 μm. It should also be noted that the volumetric-error is defined in this situation as follows, "The length of the worst-case error vector between the target and the actual machine position anywhere within the machine volume". Laser measurement of overall diagonal-lengths and the results of these laser **B5.54** and **ISO 230-6 Diagonal Tests**, do not always give reliable-indication of volumetric-performance, so they should be interpreted with some caution. The act of undertaking any Diagonal-tests should not be utilised in isolation when comparing the actual volumetric-performance of machines. In order that reliable results are obtained, it is important to also undertake some supplementary tests,[9] such as for: linear accuracy; as well as pitch and yaw tests that are parallel to the *X*-, *Y*- and *Z*-axes. These additional tests are all succinctly defined in the **B5.54** and **ISO 230-Series** of Standards, although they are occasionally disregarded—to minimise actual calibration test-times.

Specific **Laser diagonal Tests** for Machining Centres are precisely described in **B5.54** and **ISO 230-6 Standards**. With such tests, a laser interferometer is utilised to measure the linear positioning accuracy of the machine as it proceeds along each of its four body diagonals in turn—see Figs. 2.4 (top) and 2.5a. The illustration (i.e. Fig. 2.4, top) shows a laser that is aligned (i.e. via a mirror) to one of four body-diagonals. A number of equi-spaced target positions—see Fig. 2.6a—are defined along each body-diagonal. Accordingly, the machine is then moved along this diagonal, from one target position to the next. Here, the laser will measure the linear-positioning errors at each target position. Moreover, measurements are taken in both the forward and reverse directions, and then they are averaged. Further measurements are then similarly repeated along each body-diagonal in turn. These laser diagonal test results can then be presented graphically—as depicted in a typical test run shown in Fig. 2.4 (bottom). In this **B5.54** test procedure, the diagonal positioning accuracy is quoted from the diagonal with the largest range of error-values where it is shown to be, in this example, 40 µm. By way of illustration and subsequent comprehension of these two important internationally applied standards, the following comments can be subsequently compared:

1. **American Standard B5.54: 1992**, states that, "The volumetric accuracy of a machine may be rapidly estimated by measuring the displacement accuracy of the machine along body diagonals";
2. **International Standard ISO 230-6: 2002**, states that, "The Diagonal displacement tests allow the estimation of the volumetric performance of a machine tool and, that these Diagonal displacement tests may be used for acceptance purposes and as reassurance of machine performance where parameters of the test are used as a comparison index".

[9]**ISO 230-6 Standard**: suggests additional tests to supplement the Body Diagonal Tests with such: tests on face-diagonals; tests parallel to the machine's axes; by either the well-known Circular test (i.e. see reference to Knapp, W.), or by Telescoping ballbar tests—see the Chap. 4 for details of this latter testing-regime.

In some contemporary applied research work at the company Renishaw plc and by others,[10] it has been shown that any estimates of volumetric, or machine performance which are based on these diagonal tests in isolation, may be considered as somewhat unreliable. To expand on this important unreliability-theme in some more detail, the results of a diagonal-test alone cannot be used as a reliable machine comparison-index. The potential weakness with this testing strategy—which has been reported for this diagonal test on a machine—can be comprehended more simply by considering a simple 2-D example, if one were to consider a perfect 1 m^2 planar machine, with the axes travel of the '*X*' and '*Y*' being both exactly 1 m and the machine which contains either no other positioning or geometric errors. So, simplistically, the length of both diagonals is given by Pythagoras' theorem,[11] as follows;

$$\text{Diagonal length} = \sqrt{\left(1^2 + 1^2\right)} = 1.4142136\ \text{m}$$

Now, let one imagine that the machine is somehow distorted, such that the *X*-axis over-travels by 25 $\mu\text{m m}^{-1}$ and the *Y*-axis under-travels by 25 $\mu\text{m m}^{-1}$, of note is that these linear-positioning errors of this magnitude are relatively common in many machine tools, usually due to inaccuracies in the feedback-system (e.g. possibly the result of the original installation for the Ballscrew-tensioning/-preload and, possibly, resulting from any associated thermal-effects). Consequently, the length of the diagonals of this distorted-machine, are once again derived from Pythagoras' theorem, thus:

$$\text{Diagonal length} = \sqrt{\left(1.000025^2 + 0.999975^2\right)} = 1.4142136\ \text{m}$$

NB: here, the diagonal length appears unchanged, accordingly, for this test of a machine:

- diagonal length of perfect machine = 1.4142136 m;
- diagonal length of distorted machine = 1.4142136 m;
- thus, the diagonal lengths are the same ($\leq 0.001\ \mu\text{m}$);

[10] Ibaraki and Hata (2010). Plus, these findings confirmed once again the initial data obtained by: Chapman (2003).

[11] **Pythagoras' theorem**: in mathematics, the well-known **Pythagorean theorem** is an exacting-relationship in **Euclidean geometry**, being based upon the simple relationship of three sides of a right-angled triangle. It is a frequently applied geometric relationship, which simply-states: "That the square of the hypotenuse [i.e. the side opposite the right angle] is equal to the sum of the squares of the other two sides". This completely-reliable geometric-theorem was obviously-named after the Ancient Greek Mathematician: Pythagoras—who was Born on: Samos (Greece) in 570 BC, then died: in Metapontum (Italy) in 495 BC.

Table 2.4 Demonstrates the performance of three nominally identical 1 m^3 machine tools. Each machine tool has a different combination of linear-positioning errors in their respective axes (courtesy of Renishaw plc)

	Machine A	Machine B	Machine C
X axis linear error (um/m)	50	50	100
Y axis linear error (um/m)	50	0	−50
Z axis linear error (um/m)	−100	0	−25
B5.54 diagonal test result (um)	0	29	14
volumetric accuracy[a] (um)	122	50	115

[a]Volumetric-accuracy, can be defined as: "the length of the worst case error vector between the target and the actual machine position anywhere within the machine volume"

- that both the perfect and the distorted machine show identical results on a diagonal test, even though the distorted machine contains some distinct and mindful positioning-errors of >25 μm.

At this point, it might be considered that this test is somewhat of a special-case, which only occurs on, say, a 2-D machine tool if the error in the *X*-axis motion is exactly equal and opposite to the error in the *Y*-axis motion, but this is not the case; explaining this apparent-dilemma as follows: if any axis (or axes) shows an over-travel error whilst any another axis (or axes) shows an under-travel error, then their combined-effect on the body-diagonal length will normally cancel-out. These types of positional-errors are particularly common on machine tools. However, this problem will also occur on other orthogonal 3-D machine tools, as shown in Table 2.4.

From this Table 2.4 we note that there is a complete lack of correlation between the volumetric-accuracy of these machines and their diagonal test results. In the two extreme cases, machine A has the worst volumetric-accuracy, but displays no error on the diagonal test; while machine B has the best volumetric-accuracy, but shows the worst result for its diagonal test. Therefore, contrary to the statements in both **B5.54** and **ISO 230-6**, it now seems obvious that these laser diagonal test results do not provide a reliable estimate of volumetric accuracy, or performance—so cannot be utilised as a reliable comparison index between machines. However, what can be implied concerning these laser diagonal tests is that they do not provide a reliable method of measuring a machine's volumetric-accuracy but they can provide a good technique of measuring the squareness between any two axes.

In order to obtain the most accurate test results, it has also been suggested that to measure a face rather than the body diagonals will reduce the test time and as a result, will improve sensitivity. For example, if the two face diagonal lengths are designated as '$d1$' and '$d2$'—which are slightly distorted—then the machine squareness error (in radians) is given by:

$$\theta \approx \left(1 + m^2\right)(d1 - d2)/[m(d1 + d2)]$$

where: 'm' = machine aspect-ratio.

The relative accuracy of a squareness result (i.e. angle) can be improved if:

- **the machine's axes are of similar lengths**—as this will improve sensitivity;
- **the test is quickly performed**—to minimise any thermal changes between measurement of each diagonal length;
- **results plotted graphically**—as it would show this squareness-effect of ±1 and ±5 ppm shifts in laser reading on the accuracy of squareness results for various aspect-ratio machine tools.

In addition, the accuracy of the squareness result (i.e. angle) is also enhanced if the diagonal-measurements both start and finish at identical '*X*', '*Y*', or '*Z*' coordinates. This measurement-strategy will ensure that the effects of other machine-errors are effectively eliminated. Furthermore, any potential backlash present, can be eradicated by always moving the axis in the same direction—before taking each reading. Under such ideal-conditions, it is possible to measure machine squareness within ±1 arcsecond. The technique is especially useful on much larger machine tools, where obvious access to an enormous mechanical reference square may prove to be distinctly restrictive.

In conclusion, one can make the following observations concerning such diagonal-testing applications … that these:

- **Laser Diagonal Tests**—can provide a quick and efficient technique of measuring a machine, as it moves-along a machine's diagonals;
- **Laser Diagonal Results**—can, with some care, be utilised to accurately establish the squareness errors between axes;
- **Laser Diagonal Measurements**—are sensitive to multiple machine error sources, nonetheless, it is possible for the effect of one error source on the diagonal to cancel another, thus, giving laser diagonal results that do not relate to the volumetric accuracy of the machine;
- **Laser Diagonal Testing**—when utilised in isolation, does not provide a reliable method of measuring machine volumetric-accuracy;
- **Laser Diagonal Testing Regimes**—offer a more reliable evaluation of machine performance, which should invariably be supplemented with other tests, typically by, Telescoping ballbar—Circular tests, together with conventional laser-calibration, by linear; angular; plus straightness tests; which are parallel to the machine's axes;
- **Machine Testing Techniques**—which are currently defined in both the American **B5.54** and **B5.57 Standards**, as well as in the **ISO 230-series** of International Standards.

2.2.4 Laser Step Diagonal Test

In relatively recent years, it has been proposed in a that the original Laser Diagonal Test can be suitably enhanced by using a Special Step-sequence to move between target positions on the body diagonals. This announced and modified testing-technique is often known as either a step diagonal, or the vector method. In the original laser diagonal tests (i.e. as appropriately described in both the **B5.54** and **ISO230-6** Standards), the machine progresses movement of its *X*-, *Y*- and *Z*-axes simultaneously, to move in a straight-line between the target positions along each of its body-diagonals—see Figs. 2.4 (top), 2.5a and 2.6a. This compound-angled linear-motion is simply illustrated in Fig. 2.6a, which shows the target positions (i.e. here being depicted simply as black dots) along just one of the body diagonals. This laser-data is then recorded at each target-position, by utilising a laser linear interferometer, which is aligned along the diagonal and striking an aligned retro-reflector optic. A number of equi-spaced target-positions are defined along each body-diagonal. The machine is then moved along this diagonal, from one target position to the next. Simultaneously, the laser will then measure the linear-positioning error at each target-position. Measurements are taken in both the forward- and reverse-directions and these results are averaged. This measurement-strategy is then repeated along each of its body-diagonals in turn—as depicted in Fig. 2.5a. Results are typically presented graphically (i.e. as shown in the graph in Fig. 2.4, bottom). In **B5.54**, the diagonal-positioning accuracy is quoted from the diagonal with the largest-range of error-values—shown here (Fig. 2.4, bottom), where in this example, it was found to have a 40 μm range. Conversely, in the case of the step diagonal test, or vector test, the *X*-, *Y*- and *Z*-axes are moved individually (i.e. separately—one-axis-at-a-time)—as shown once again by the black-dots (i.e. see Figs. 2.5b and 2.6b) with laser-data recorded after the movement of each axis. This particular type of Stepped 3-D motion, will generate up to three times as much positional-data when compared to that of the Laser Diagonal Test. This motional-action being illustrated in Fig. 2.6b, which shows the effect of these additional target-positions.

It has been claimed by some investigators (i.e. see Footnote 10) that in addition to the original diagonal-displacement error results, the step diagonal method can also provide results for the: linear-accuracy; straightness; plus squareness; of the machine tool's *X*-, *Y*- and *Z*-axes. In order to undertake this specific test, the laser system is usually operated with a plane mirror reflector mounted onto the machine's spindle (i.e. see Fig. 2.5b). This laser-setup configuration of the mirror held in the machine's spindle, ensures that the laser-beam is always returned into the laser's return port as the machine zig-zags along the machine's diagonal (i.e. see Fig. 2.6b). However, in some more recent detailed analysis of the technique, it has been highlighted that there may be some fundamental flaws with this Laser Step Diagonal technique. The fundamental reasons for this deduction—concerning some specific flaws in this Step Diagonal Method, are suggested and listed below:

- **maintaining alignment of the laser beam**—so, as the machine moves along the stepped diagonal path, the laser is directed onto an angled plane mirror fixed to the machine spindle;
- **successive positions of the mirror**—are shown in Fig. 2.7a, as it is moved along the diagonal;
- **2-D schematic view**—here in Fig. 2.7a, is shown for simplicity;

- **laser beam**—is shown as having a straight path in Fig. 2.7a;
- **machine movement path**—is shown as a zig-zag black line (i.e. *X*, and *Z* linear motions);
- **laser beam and mirror are aligned perfectly**—thus, indicating that here, there are no: pitch-; yaw-; and roll-errors; in the machine, then the theory of operation is stated as follows:
  – when the *X*-axis moves, then the laser will measure the combined effect of errors in the linear and straightness motion of the *X*-axis;
  – when the *Y*-axis moves, then the laser will measure the combined effect of errors in the linear and straightness motion of the *Y*-axis;
  – thus, when the *Z*-axis moves, then the laser will measure the combined effect of errors in the linear and straightness motion of the *Z*-axis;
  – once data has been taken along all four body-diagonals, the individual contributions from the linear- and straightness-errors of each axis and the squareness-errors between the three orthogonal axes can, in theory, be calculated.

Nevertheless, there appears to be two fundamental complications here with the Step Diagonal Method, they are …:

1. when the vast-majority of orthogonal-based machine tools do have any significant types of: roll-; pitch-; and yaw-errors. These errors will influence the results, by introducing additional error terms which the proposed-calculation method does not unfortunately resolve;
2. when significant errors occur in the alignment of the plane-mirror and laser beam, which will introduce additional errors that cannot be separated-out from the linear-displacement errors in the *X*-, *Y*- and *Z*-axes of the machine tool.

In the following text, the problem with mirror alignment is explained in more detail in the circumstances of its actual usage. In Fig. 2.7b (left) the side-view of the laser-aligned to a body-diagonal of a 1:1:1 aspect ratio machine tool is shown. Here, the movement of a misaligned-mirror (i.e. presented in the diagram as a shaded-mirror) is compared with that of a perfectly aligned mirror (i.e. shown as simply a solid outline). Moreover, this mirror has been misaligned by a small angle about the *Y*-axis. Note, that in this schematic-diagram the mirror-misalignment has been somewhat exaggerated—for clarity. At this juncture, one can comprehend how this mirror-misalignment introduces an error into the laser-measurement. Consequently, as the machine moves along the *X* axis, the laser-beam will travel across this angled-mirror surface. Thus, the laser-reading is therefore affected by this mirror alignment, as well as by any linear- and straightness-errors in the axis. Furthermore, it might be thought that this specific error is very small; unfortunately this is not the case, because the error-accumulates. By way of a practical-example, if the plane mirror is misaligned by an angle of just 40 arcseconds, or 0.2 mm m^{-1}—this being a typical alignment-tolerance—and the *X*-axis step-size is set to 50 mm, then the laser will record an extra 7 μm of displacement during the *X*-axis step-movement. In isolation this induced-error may seem to some extent rather small, but because it occurs every time the *X*-axis moves, therefore it can accumulate to a considerable error of 140 μm per metre—of *X*-axis travel! As a consequence, even a small amount of mirror-misalignment can accumulate—giving a very large measurement-error.

It has also been proposed—see Footnote 10—that because this error is constant it can be removed by appropriate software (e.g. by say either linear regression, or by slope-removal techniques, etc.). However, there are two specific-faults that have been reported with this approach, such that:

1. the error will only be constant if the angle of the mirror does not change—as it moves along the axis. On the other hand, if the machine contains any pitch- and yaw-errors, then the angle of the mirror will change, so that even with small changes in mirror alignment of a few arc seconds, this will have an unwanted and significant effect;
2. it is not possible to determine whether the error in laser readings is caused by mirror-misalignment or by a genuine progressive-linear over-travel in the axis motion. For that reason, the process of slope-removal will remove the effects of both and accordingly, it will eliminate one of the machine-errors the system is proposing to measure.

At this time one might take the view that by reversing the axis-movement sequence, it should be possible to separate the errors caused by mirror misalignment from any linear-travel errors in the machine's axis, but unfortunately this is not the case. Examples will follow showing the laser records additional movement despite the fact that the sequence has been reversed and the laser-beam has travelled onto the opposite side of the mirror—see Fig. 2.7b. Even though the Step diagonal technique cannot reliably measure the linear-positioning errors in a machine's axis, it can provide regular diagonal-displacement accuracy results in accordance with th: **B5.54** and **ISO230-6** Standards. Nonetheless, the technique has three distinct disadvantages, when compared utilising a regular linear laser interferometer and its accompanying retroreflector, such as:

1. an inaccurate alignment of the laser beam with the machine-diagonal combined with any misalignment of the mirror will cause small measurement-errors—where this effect is much smaller than that described-previously;
2. the test takes longer, because of the more complex machine tool part-programming routine and the additional target-positions required by such a testing-regime. This longer test time makes the actual test more prone to any environmental-fluctuations that may occur between the measurements of each diagonal;
3. the large angled-mirror assembly—when fitted to the machine-spindle limits the available *Z*-axis travel.

It should now be apparent from this previous discussion, that the Step Diagonal method does not give reliable linear positioning accuracy data for the machine's axes. Nonetheless, the technique can give reliable diagonal-displacement accuracy results, in accordance with **B5.54** and **ISO 230-6**—see Fig. 2.4 (bottom). It is therefore possible to estimate the diagonal length and squareness-errors and to undertake a compensation to ensure the diagonal results are improved. Where one assumes that the diagonals are different lengths, then machine squareness can be adjusted, or compensated for utilising the cross-axis compensation parameters, until all four body-diagonals are the same length, although they may all still be either too long, or short. Once this compensation has been completed, then it is possible to apply a single and simple scaling-correction to the travels of all three linear-axes—ensuring that its body-diagonal lengths are also corrected. This type of remedial-action, will improve the **B5.54** and **ISO 230-6** test results. Although the diagonal test results have been improved by this operation, one might also pose the question, "Is it true that the machine's positioning-accuracy must have been improved too?" The answer here is a definitive no! Regrettably then, the combined weaknesses of the Step Diagonal Technique and **ISO 230-6**, or **B5.54 Diagonal Tests** when utilised in isolation, mean that the machine performance may have been degraded. This degradation is because the:

- **Step diagonal method**—does not give reliable linear positioning accuracy data for the machine's axes—as previously mentioned;
- **ISO 230-6 and B5.54 Diagonal Test results**—cannot detect the presence of complimentary linear positioning errors in two, or more axes.[12]

This is a specific technical problem, which is more adequately explained by the following theoretical test example:

If one considers a machine tool with a volumetric envelope of 1 m^3, which has perfect *X*- and *Y*-axes, but here in this case, the *Z*-axis over-travels by 100 $\mu m\ m^{-1}$, where all three axes are perfectly square to one another and contain no other errors, then diagonal results will indicate that all four body diagonals are too long—each body-diagonal is 1.732109 m long, instead of being 1.732051 m, thus having an error of +58 μm. Yet, any calculations utilised to remove these errors due to mirror misalignment in the step diagonal method will also extinguish any information about which of the machine's axes was responsible for this fault. Accordingly, the step diagonal technique will therefore fail to identify that the *Z*-axis alone was responsible for the problem, making correct linear-compensation impossible. However … it is now possible to apply compensation in order to improve the **B5.54**, or **ISO 230-6 Diagonal Test-results**; this can be achieved by simply applying a single $-33.3\ \mu m\ m^{-1}$ scale-factor correction to all three axes. This corrective action will produce a good diagonal test-result, but it will not have alleviated the problem with this machine tool, as the *Z*-axis still comprises of a significant linear-error of $+66.7\ \mu m\ m^{-1}$. However, for both the *X*- and *Y*-axes—which were originally perfect—they will, as a result, have a linear error of −33.3 μm/m. After its compensation the machine's accuracy in the *X*-*Y* plane will now be seriously degraded, even though the **B5.54** and **ISO 230-6** body-diagonal

[12]**Complimentary linear positioning errors in two, or more axes**: this technical-information is more than adequately-described in some significant detail in the associated technical 'White-paper' company-documentation from Renishaw plc's—presentation, which is entitled: *Laser diagonal tests*.

results indicate that the machine tool has been improved. Therefore, these actual step diagonal tests have shown, that the:

- **sensitivity of the step diagonal method to mirror misalignment**—means that the method cannot be used in isolation to reliably determine the linear-positioning errors in a machine tool. Such errors should always be measured utilising conventional linear laser measurements, which are taken parallel to the machine's axes;
- **Step diagonal method**—can be utilised to give diagonal-positioning performance results, in accordance with **B5.54** and **ISO 230-6**. Moreover, this is not as accurate, or convenient as utilising a direct-diagonal measurement using a conventional linear interferometer and retro-reflector (i.e. as described in **B5.54**);
- **results from the Step diagonal test**—in isolation should not be used for linear-error compensation of a machine, even though the **B5.54**, or **ISO 230-6** results may show improvement, but the machine's positioning-accuracy may actually be worse.

Some additional and relevant comments on step diagonal testing have been provided by J.A. Soons—at NIST (i.e. The National Institute of Standards and Technology, USA) who has performed a detailed theoretical analysis of such tests. The results of this relevant work were presented at the LAMDAMAP 2005 International Conference within the UK and were published in its subsequent Proceedings, with the attendant abstract from this paper, stating that, "Our analysis confirms that setup errors in the alignment of the return mirror cause significant errors in the slope of the estimated positioning errors that cannot be detected from the (step-) diagonal measurements. Correction requires information on the slope of the positioning errors of two axes".

Step Diagonal Testing—Some Concluding Statements

It can now be justified—with some conviction—that there is some overwhelming-evidence that suggests that this step diagonal (vector) test method when utilised in isolation, cannot reliably-determine the linear-positioning errors in a machine tool. Moreover, any declarations to the contrary made by the originators of this step diagonal method in their previously published papers, are somewhat misinformed. Further, it has been adequately reported—see appropriate references at the rear of this chapter—that originators of the step diagonal (vector) test method have now developed some revised-software—to now address this previous problem. Accordingly, this recently modified-software will now allow the laser-user to take some additional but conventional linear laser measurements, parallel to two of the machine's *X*-, *Y*- and *Z*-axes, in order to determine the linear accuracies of all three axes. As a result, the requirement to take these additional linear measurements, which obviously now lengthens the time taken to calibrate a machine tool in this manner, has the effect of reducing somewhat one of the key benefits claimed (that it was a quicker testing procedure) for the introduction of step diagonal (vector) test method.

2.2.5 Potential Errors—In Three Axes Machine Tools

Introduction

Fundamentally, every machine tool-builder will list as part of a machine's specification, its accuracy and repeatability figures. What is generally not provided are the methods that were utilised to derive such test figures. The techniques used when defining a series of linear, straightness, squareness, rotary, etc. positioning methods within each Standard—was previously mentioned earlier in this chapter—but not all of these machine-builders will use the same standards. Not only do such machine tool-builders often use different Standards, but some do not consider all of the potential-errors that are likely to occur when considering their machine's accuracy and repeatability. Hence, the question one might readily ask is, "If this is so, what are these error-sources in a machine tool?" The following textural-dialogue attempts to expand on this error-based theme, briefly reviewing some of their significant causes in machine tools.

Types of Errors—Occurring in CNC Machine Tools

For a typical orthogonal horizontal Machining Centre, there are a range of problems associated with the actual position of a tool within its volumetric envelope, as depicted in the exaggerated diagram—shown in Fig. 2.8a. Not least of which, these types of errors will consist of:

- **positioning errors**—on each axis;
- **straightness**—of each perpendicular axes;
- **pitch, yaw** and **roll errors**—of each of the axes;
- **squareness errors**—between these orthogonal axes;
- **backlash errors** of each axis—except for the 21 kinematic errors[13];
- **contouring errors** of each axis—except for 21 kinematic errors (see Footnote 13).

In the previous section, it was argued that by utilising a conventional laser interferometer for measuring, say, the straightness—and squareness errors, it can require a prohibitive amount of calibration time—restricting the potential production usage of an expensive piece of plant (e.g. machine tool). This conventional laser technique, has led to the development of the body diagonal displacement method—which was also reviewed in Sect. 2.2.3, for a so-called speedy check, but having some attendant problems associated with it—as defined in the: **ASME B5.54**, or **ISO 230-6 Standards**—for this latter Standard, also see: Appendix 1.

[13]It has been previously-mentioned that a rigid body has 21 potential errors present—termed their degrees of freedom for a typical three-axes orthogonal machine tool (i.e. see Fig. 1.21). These potential errors will include three of each of the following error-types: linear displacement, vertical straightness, horizontal straightness, roll (angular), pitch (angular), yaw (angular), plus, squareness—between axes.

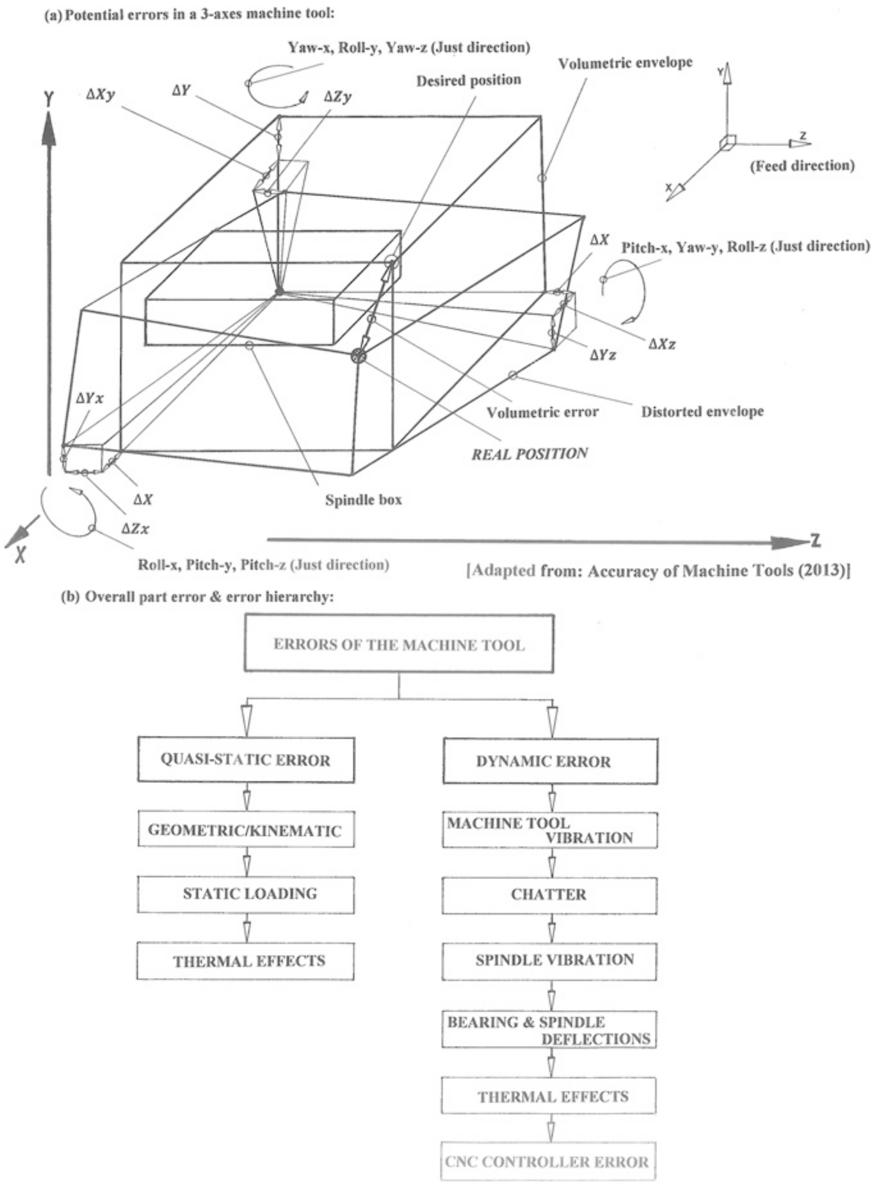


Fig. 2.8 Typical errors causing machine and tool positioning inaccuracies

Classification of Errors—For a CNC Machine Tool

For a CNC machine tool it is positioning for both accuracy and repeatability means that the machine is limited by a vast number of quasi-static errors and dynamic errors—as simplistically displayed in the flow-diagram, in Fig. 2.8b. Here, the range of errors is quite enormous and can contain the following levels of uncertainty for the quasi-static errors, such as: geometric/kinematic errors of all components, load-induced (i.e. static) errors, thermal errors. The dynamic errors will usually consist of a range of machine-induced errors, as well as computational-errors, although the machine's resolution is limited by the quality of its sensors, quality of the control-system, frictional-effects—stick-and-slip effect (i.e. stiction), as well as by any potential backlash present. As a result, one might ask, "What are these error sources on a machine tool?" In the following-text these potential positioning-uncertainties (i.e. errors) and some other important factors shown in diagrammatic-form in Fig. 2.8b will be briefly mentioned. First, is a description of the range of quasi-static error sources, etc. then secondly, consideration of the influence on the machine of a variety of its dynamic errors, etc.—also to be found within a typical orthogonal CNC machine tool.

Quasi-static Machine Tool Errors—See Fig. 2.8b (left)

In terms of quasi-static errors, the geometric/kinematic errors are those errors that are present in a machine tool from its basic-design and original-build quality. These are unintentional built-in inaccuracies, which occur during the machine's assembly and are a result of the components and partial-assemblies utilised in the actual-build of the machine. Due to this machine tool assembly process, such errors can potentially form one of the greatest sources of machine tool inaccuracy. These error-sources originate from the purported quasi-static accuracy of working-surfaces that can move relative to one another. Consequently, the quasi-static accuracy of machined and lapped surfaces that axially travel relative to one another might result from either the linear-, or rotary-motion of axes, or from both of these effects. In the case of the linear-motion axis, they can exhibit: pitch; roll; yaw; straightness (i.e. two components); as well as linear displacement. While, for the rotary-motion of axes, they can have: radial-error motion (i.e. two components in fixed coordinate frame, plus one component in rotating-frame); axial-error motion; tilt-motion (i.e. two components); plus an angular-motion about the axis of rotation. Looking into these rotary-motions in more detail, one will note that the:

- **radial-error motion**—which is the positioning error of the rotary stage in the horizontal-direction, when the table is oriented in the horizontal plane. Here, the radial-runout can be theoretically defined as, "The total indicated reading [TIR] on a spherical ball positioned 50 mm above the table and centred on the axis of rotation";
- **axial-error motion**—is the error of the rotary-stage axis of rotation in the vertical direction when the stage is oriented in the horizontal plane. In this situation, the axial-runout is defined as, "The total indicated reading [TIR] on a spherical ball positioned 50 mm above the table and centred on the axis of rotation";

- **tilt-error motion**—is the relative wobble, which is defined as, "The angular error between the actual axis of rotation and the theoretical axis of rotation"—measured in arcseconds.[14]

Geometric/Kinematic Errors—see Fig. 2.8b (left)

Of particular note, is that the machine's geometric errors can be of a smooth and continuous nature while also demonstrating either some form of hysteresis, or random behaviour. These geometric errors of the machine tool are affected by influences such as the machine tool's surface straightness, surface texture (i.e. its roughness), bearing pre-loads, together with certain other influences, with just some of these errors sources being listed below:

- **hysteresis error**—this being considered as a deviation between the actual and commanded position of the programmed point, being created by elastic forces in the motion system. Hysteresis will also affect bi-directional repeatability;
- **backlash error**—which is an error in positioning initiated by the reversal of the axis travel direction. Backlash is the portion of the commanded motion that produces no change in position upon initial reversal of its travel direction, generally being the result of clearance between main elements within the drive-train (e.g. gears). Accordingly, as these clearances increase, the amount of input necessary to produce this required linear motion is proportionally greater. This increase in clearance, results in an amplification of the machine tool's backlash error. Backlash will also affect an axis repeatability, as listed below, affecting the machine's;
  - **uni-directional repeatability**—which refers to the repeatability when approached from the same direction. Uni-directional repeatability does not consider the effects of backlash;
  - **bi-directional repeatability**—specifies the repeatability when required from any direction and includes the effects of backlash;

- **feedback inaccuracy**—which will result from any imperfections in the operation of the machine's encoders, such as non-uniform division of the grating scale, or any imperfections in the photodetector signal, interpolator errors, axis-hysteresis, plus the levels of friction present;
- **noise**—this could affect the positioning-capabilities of, say, the rotary stage – when present on the machine tool.

[14]**Second of arc**—alternatively termed an **arcsecond**, or **arcsec**: is $\frac{1}{60}$ of an arc minute, $\frac{1}{3600}$ of a degree, $\frac{1}{1{,}296{,}000}$ of a circle, also $\frac{\pi}{648{,}000}$ (about $\frac{1}{206{,}265}$) of a radian. By way of a simple but practical and valid example of this minute angular relationship, is that it is approximately the angle-subtended by a U.S. dime-coin at a distance of 4 km (i.e. ≈2.5 miles). While yet another example of an **Arcsecond**, for a very useful general Rule of thumb, concerning an arcsecond and its relative distance, is that: **one arcsecond** (i.e. 1/3600°), when tilted through this angle over a length of one metre, has an approximate vertical height at its free-end position of: ≈5 μm.

In the case of these machine tool's kinematic errors, there are a number of factors that must be dutifully considered. Typically, these errors that may arise because of the:

- **kinematic errors**—which are the result of the relative motion \errors of several moving-machine components, that need to travel with precise functional requirements. Kinematic errors are particularly important as the result from the combined motion of different axes. Such errors occur during linear, circular, or other types of interpolation algorithms, but are more noticeable during any actual machining, such as the motion-errors due to alignment, the component's geometric shape thus resulting from the application of improper offsets—each of which, are thus creating translational-axes problems;
- **errors in an axis's trajectory**—being instigated by any misaligned/improperly tolerance/sized components in the assembly; squareness and parallelism between axes; error motions in a closed kinematic-chain; together with any potential external load-induced errors:

Static Errors—See Fig. 2.8b (left)

Of note, are that these static errors are often the result of:

- **errors due to deformation of machine components**—which consider any gravity load-induced errors (i.e. static errors); cutting/probing force induced-errors; plus axis acceleration load-induced errors;
- **errors due to uneven distribution of table-loading**—where a particularly heavy fixture and/or workpiece is positioned on an extreme end of the table's working volume, creating uneven loads and resulting in unwanted axes displacements.

Thermal Effects—See Fig. 2.8b (left)

A machine tool's thermal errors will account for between 40 and 70 % of the total dimensional and shape errors of a machined workpiece, in any manufactured form of precision engineering. It is well known (i.e. see appropriate references) that there are six sources of thermal influence that have been identified which will occur on a machine tool, these are:

1. heat from the machining process;
2. heat generated by the actual machine;
3. heating, or cooling provided by the machine's cooling-system(s);
4. heating-, or cooling influence of the machine-shop room;
5. the heat effect from people, working in the machine's vicinity;
6. thermal memory, from any previous machining environment.

If these heat-induced effects are prevalent on machine tools, then the question to be raised is, "What problems do they contribute to the accuracy and precision of machined parts, as a result of such thermal influences?" These valid points will now be described. Unwanted heat, causes relative expansion of the various elements of the machine tool, leading to inaccurate positioning of the cutting tool, subsequently affecting the workpiece's machined-quality. Accordingly, errors due to spindle-growth, thermal expansion of the Recirculating ballscrews and thermal distortion of the machine's bed are invariably present. Consequently, as heat generation at the machine's contact-points is unavoidable; this source of error is one of the most difficult to effectively eliminate. In the manufacture of accurate and precise components, any error due to thermal-deformation of the machine elements will play a crucial role in limiting the accuracy and precision of the part produced by the machine. It is important to know both what and where the likely heat-sources are, that will contribute to the thermal errors on a machine tool within its operating-environment.

Just some of these thermal factors are the result of internal-heat sources caused by:

- a mean temperature other than 20 °C;
- thermal gradients in machine environment's, namely, resulting from its temperature variability;
- errors caused by thermal expansion of these vital machine tool elements, typically from: motors; bearings; the machining process; pumps; expansion of compressed fluids; plus temperature differentials in the actual coolant.

While some of the external heat sources that affect the machine tool are:

- mean temperature of the room/machine shop;
- solar-influences—typified by the sun shining through windows onto the exposed machine tool's elements;
- machine tool being situated in close-proximity to a hot-air vent;
- overhead-light sources, in the machine's vicinity;
- operator's body-heat.[15]

When machine tool builders design a new range of machines, their design strategies for this prospective plant, must address some important factors in order to alleviate these potential thermal influences. Typically, they would:

- isolate heat-sources and incorporate some form of temperature control system;
- maximise thermal-conductivity, or insulate against known heat-sources;
- combine at least one of above factors—by instituting machine thermal mapping in combination with its real-time error correction.

Accordingly, one might ask the pertinent question, "What are these thermal-sources?" Hence, these thermal effects must be known in order to mitigate against them within the machine tool. Characteristically, as the cutting speed increases

[15]**Body heat**: the actual amount of heat produced by a human-body will depend upon the individual, such as their respective: weight; plus their level of physical-activity. Accordingly, the total amount of heat produced over a period of time, is equal to the total calories-consumed, minus any useful mechanical-work being performed. For example, if a person consumes an average of 2400 kilo-calories per day, the average body heat produced is 100 kilo-calories per hour, or 116 W. So, ten people in a workshop, will produce the heat-equivalent of a typical single bar-element's output, from an electric-fire!

this creates heat, which impacts on both the machine's accuracy and repeatability. This simple fact, becomes more problematic with longer production cycle-times, plus it is exacerbated by higher speeds and feeds, but most notably, it is normally reduced by any high-speed machining (HSM) applications—due to the high passage of the cutter's edges through the yet-to-be-machined component's material stock. On the other hand, today, most techniques of thermal applications, will emphasise their efforts on keeping heat away from the workpiece, so that other areas—which are influenced by any likely thermal-distortion—are somewhat overlooked.

Thermal-stability can be maintained by an improved heat-dissipation throughout the machine's various components. Typical of this approach is in the machine's spindle's design, where:

- high-speed spindles can experience growth due to heat from friction, when rotating at high rpm's and may require longer saturation-periods before they stabilise;
- too much heat in the spindle will compromise accuracy and can potentially cause premature spindle-failure;
- one such notable spindle-builder, has designed a core-cooling system and an under-race lubrication system, that effectively cools the spindle from the inside-out—to minimise heat and growth for shorter saturation-periods of usage;
- the cooling system circulates in this (above) system, facilitating spindle oil through the centre of the rotating spindle. Hence, at high rotations, centrifugal force draws the lubricant outward through the spindle, by circulating through holes in the inner-bearing races—to both lubricate and chill these bearings.

While other notable thermal-sources on the machine tool are invariably from the Recirculating ballscrews,[16] where heat is present resulting from perhaps the high feedrate levels, this can be mitigated against by forcing chilled-oil through the ballscrew's core. Furthermore, the location and design of the machine's pumps, motors, hydraulics and magnetics, are key items in thermal heat reduction exercises. For example, on some Machining Centres they are designed so these ancillary—but vital—components are mounted at the rear of the machine within a so-called dead-air space, isolating them from the rest of the machine tool. To ensure this heat cannot impact upon the machine tool, a radiator cooling system is sometimes used to wrap-around the machining centre's column. The machine

[16]**Recirculating ballscrew/Ballnut—heat generated**: the moment for a ⌀40 mm Ballscrew having a 10 mm pitch was measured by Golz (Golz, Hans Ulrich, *Analyse, Modell-bildung und Optimierung des Betriebsverhaltens von Kugelgewindetrieben*, Dissertation: *University Karlsruhe*, Germany, 1990), for various preload-forces and rotational speeds. For example here, Golz found that with a typical preload of 3 kN, this results in a no-load, or frictional moment of between 0.5 and 1 N m. Meaning that the machine tool in a rapid traverse with a Ballscrew speed of 2000 rev min^{-1}, will produce between 100 and 200 W of frictional heat being generated by its associated Ballnut. Also see Fig. 6.18 (middle), for a thermographic snapshot image.

tool's actual workshop environment plays a significant role in the thermal characteristics within a machine shop. Although even with certain safeguards in place, the shop environment must be checked for external heat sources. Such hot-zones – as mentioned - can range from sunlight on the machine tool, to external heat on the shop floor, with any increase or decrease in temperature being appropriately dealt with in the working-environment. These unwanted ambient temperature fluctuations, can have a negative impact on machined component's accuracy and repeatability.

Dynamic Errors—In CNC Machine Tools—See Fig. 2.8b (right)

Once the machine tool is in motion and actually machining components, then the dynamic errors can be caused by either vibration/chatter, or by the control-processes, which can become significant. These particular problems along with other dynamic-factors relating to the CNC machine tool need to be considered, including:

- **vibration**—from the external environment, normally via the ground-based vibrational effects resulting from cutting processes and the influence of rotating masses;
- **control-system effects**—such as, algorithm-type induced programming-effects, stick-slip friction (i.e. stiction), varying-masses (i.e. rotating and linear motions) and its structural-stiffnesses—within the machine tool;
- **switching-amplifier's effects and servo-loop frequency changes**—which have the effect of exciting the natural mode of the machine;
- **calibration errors**—associated with mastering the actual machining process and the machine's sensors, influencing the intrinsic-accuracy of the machine tool, plus its linear-/circular-interpolation effects;
- **additional errors**—which could include, computational errors, namely, the errors introduced in the analysis-algorithms, rounding-off errors due to machine's hardware.
- **Cutting-force—Induced Errors**—See Fig. 2.8b (right)

The dynamic stiffness of all the components of the machine tool, typically the bed, column, etc., are within the respective cutting-loop that is responsible for errors caused as a result of cutting-action. The CNC machine tool stiffness is one of the major sources of error in metal/material-cutting machines—as the forces involved in the cutting action are considerable. As a result of these cutting forces, the relative position of the tool's tip with respect to the workpiece, varies on account of the volumetric distortion of the various elements of the machine—see Fig. 2.8a. Contingent on the structure's stiffness and under particular cutting conditions, the accuracy and precision of the machine tool could also considerably vary. For that reason, for a machine with a given stiffness, then it is obvious that a heavy-cut would generally produce more inaccurate components than if a lighter cut was programmed.

Errors Resulting From CNC Machine Tool's Motors—See Fig. 2.8b (right)

Of some note, are the dynamic errors induced by the machine's motors, which can result in a range of inaccuracies of programmed axes positioning and orientation; just some of these error-related factors are the result of:

- **positioning errors**—they are produced by errors in the position-detecting scale and the servo-system in the case of a closed-loop type system (i.e. having a linear-scale feedback type of CNC). While, for a semi-closed-loop type system (i.e. with a ballscrew/encoder feedback type of CNC) the errors are caused by the servo-control system and the ballscrew driving-mechanism (i.e. this effect being created by the ballnut/ballscrew and the coupling of the servo-motor assembly);
- **errors from motors**—as a result of the motor's angular-motion error, with the magnitude of this error being determined by the magnitudes of the moment, added to the sliders by gravity, the counterbalance force, ballscrew driving-force, plus the sliding-friction during the motion of these sliders. Moreover, the combination errors are also determined by the rigidity of the guideways that restrict the sliders. Furthermore, the inertial force should also be considered, when the acceleration of axis feed motion is very high.

Origins of Motion Errors—In CNC Machine Tools

There are a range of motion-induced errors that can occur on CNC machine tools, most notably the following list provides some of the major error-related motional-influences, like:

- **positioning errors**—resulting from any errors in the scaling-system;
- **uniform expansion**, or **contraction**—of the linear scale, cyclic error, also local error;
- **thermal expansion** and **distortion errors**—where temperature change causes the actual ballscrew to expand/grow, or via the temperature-gradient to distort the machine geometry, which also creates distinct positioning errors;
- **Ballscrew driving system**—significant errors can occur here;
- **Ballscrew uniform expansion**, or **contraction**—together with any attendant pitch error, ballscrew whirling-effects, lost motion, backlash, tilting of the thrust-bearing, errors in coupling assembly, transmission gears, or timing belts;
- **servo-control system**—can introduce some significant errors here;
- **'stiction'** (i.e. stick-motion) – often termed stick-slip errors, resulting from an inadequately defined pitch-error compensation, insufficient backlash compensation, reduction in the programmed-radius during circular-interpolation motion—due to response-lag (i.e. often termed servo-droop effects), mismatching of position loop-gain, as well as noise in the detectors';
- **straightness** and **squareness errors** of **guide ways**—these errors are caused when the guide way is not perfectly straight, usually resulting from the weight shifting (i.e. the machine's axis bending) or due to large-overhangs during extreme axis-travel (i.e. here, acting like a cantilever) which may lead to positioning errors;

- **angular motion errors**—resulting from straightness and parallelism errors of their respective guide-ways;
- **asymmetrical guide-way** and **ballscrew**—plus the effect of counter-balance, shift of weight, levitation of its slider.

Moreover, there are some additional error-categories that may also be present in the machine's positioning mechanism and in its feedrate errors, which can affect the CNC machine tool's operation, just some of these errors might include:

- **uniform expansion**, or **contraction**—(i.e. namely, of the first-order, and second-order)—of the ballscrews and the axes linear scales;
- **cyclic-error**—in a ballscrew; the linear-scale problems, presence of backlash/ backlash compensation; as well as through inaccurate pitch-error compensation;
- **profile errors of guide way**—these are based upon: squareness-errors between two axes; straightness-errors; rolling of vertical axis; pitching of vertical axis; yawing of vertical axis; yawing of vertical axis with pre-compensated geometry; yawing of horizontal axis; plus the machine's parallelism error;
- **feedrate dependent errors**—that can include: lost motion; stick-slip; mismatching of position loop gain; decrease in radius of circular-interpolation motion—due to response lag in the servo-system; together with the levitation of sliders—possibly due to dynamic pressure.

It has been mentioned previously, but is still worth re-emphasising here, that machine design is key to the CNC machine tool's volumetric-accuracy. This crucial design element in the development of new machine tools, is normally based upon the builder's long experience in this specialised-field. Some considerable attention and significant attendant costs must furthermore be made to the appropriate depth of foundations in place, prior to the machine's installation. This latter factor is vitally important, prior to the siting and levelling of a new machine tool. As a consequence of having adequate foundations present, the machine must still be precisely levelled (i.e. see Fig. 3.17, top)—by appropriate levelling-systems. This siting and levelling is a crucial aspect of the machine's original commissioning, which will directly impinge upon its prospective operational performance—while having a significant impact on the machine's volumetric-accuracy.

2.3 ISO 10360 for Coordinate Measuring Machine (CMM) Calibration and Verification

The International Standard **ISO 10360** Acceptance and reverification tests for coordinate measuring machines (CMMs)—was established (1994) see Appendix 1. This standard defines the detailed test-procedures for the various applications of a CMM, typically for: length measurement, form inspection, measurements with and without a rotary table. Previously, some CMM manufacturers published specifications for their own CMM's according to the preceding German Standard

VDI/VDE 2617, or to that of the USA Standard **B89**. However, it is actual normal practise today, to adopt specifications according to **ISO 10360**, as only then can the performance of different CMMs from a variety of countries for their respective CMM-manufacturers, be adequately compared.

2.3.1 Coordinate Measuring Machine (CMM)—Fundamentals

Today, the ubiquitous CMM has, to a greater-degree, superseded the traditional hard-gauging systems,[17] with both process control and quality assurance in manufacturing operations increasingly dependent upon the performance of CMMs. During the last four decades, these CMMs have replaced old-style inspection techniques that usually employed gauges and fixtures and in the process, which have reduced the time and manpower required for these vital quality-control operations. CMMs enable one to inspect standard geometrical and linear dimensions, together with intricate components having special and complex features, such as: gear teeth (e.g. their involute tooth forms), cam-profiles, or air-foil and turbine-blade contours. Consequently, in a conventional manufacturing environment, each of these non-uniform contours/geometries, would have been both time-consuming in inspection procedures and required expensive and special metrological-instrumentation rather than today, a single multi-purpose CMM metrological testing machine.

A product's quality does not only depend on the excellence of the machine tools utilised for their actual manufacture, but it also heavily relies on the accuracy/precision and inherent-repeatability of these measuring/inspection devices. By way of an example, if a low-cost/performance turning centre is employed for part production in combination with a high-precision CMM, this arrangement can still guarantee good product quality; this is because only workpieces that are within tolerance can successfully pass this CMMs inspection. Equally, if an expensive and high-quality Mill/Turn Centre is operated in combination with a low-cost/accuracy conventional inspection device, this arrangement cannot always guarantee quality products. It is worth labouring the point still further, in that a certain percentage of out-of-tolerance components will always pass using a low-accuracy CMM for inspection; similarly, a certain percentage of parts within the tolerance

[17]**Hard-gauging systems**: thus a **Hard-gauge** is an extremely accurate and precise machined measurement gauge. Beginning with: **Gauge Blocks**, this type of **Hard gauge,** is associated with the Primary Standard—of dimensional metrology **(i.e. see chart—in Fig.** 1.2). These artefacts are extremely accurate/precise and are utilised to perform verification on a range of hand measuring-tools and certain measurement equipment. Types of **Hard gauges** include: **Gauge Blocks—mentioned**; **Threaded, or Smooth Plug, or Ring Gauges (i.e. utilised as Limit-gauges for part-tolerances)**; **Pin Gauges**: **Angle Gauges**; **Bore Gauges**; also **Step Standards, plus many more variants**.

range will also be rejected.[18] Accordingly, selecting the correct CMM for the anticipated production output of parts is critical. CMM-uncertainties and accompanying test procedures have been more than adequately-described in **ISO 10360**—since 1994. In the case of **ISO 10360-2**, it specifies three types of uncertainties, they are for:

1. **volumetric length measuring uncertainty**—(MPEE);
2. **volumetric probing uncertainty**—(MPEP);
3. **volumetric scanning error**—(MPETHP).

Noting that the: MPE—is an acronym for: Maximum Permissible Error.

CMM Verification

For CMM verification, normally a set of five-calibrated gauge blocks—of differing lengths—is utilised to verify an MPEE—see Fig. 2.9a. These Gauge Blocks are then measured in seven different locations (i.e. for both their position and direction) within the CMMs measuring-volume for this so-called 'E-test'. Consequently, for each of these seven locations, the length of each of the five gauge blocks is measured three times, giving a grand total of 105 measurements. All of these 105 measurements must be within the stated-tolerance being specified by the CMM manufacturer. Furthermore, a precision calibrated sphere of between Ø10 and Ø50 mm—having its associated form and diameter certification utilised to verify a CMMs probing uncertainty (MPEP)—is colloquially termed a P-test—see Fig. 2.9b. The P-test consists of measuring 25 equally spaced points on this Calibration Sphere. Once this measurement task has been undertaken, the MPEP is computed by adding the absolute values of the minimum and maximum deviation from the radial form. Accordingly, the total measured form-deviation is the volumetric probing uncertainty, with the result being reported in micrometres (μm) and, all 25 probed points must be utilised in this calculation. While, the CMMs Scanning-performance—see Fig. 2.10a—is calculated by scanning a high-precision calibrated sphere on four exactly defined lines – as shown by the respective probing circles and partial arcs, but this is undertaken at a set speed of 10 mm s^{-1}. This probing-sequence will then produce the Total form deviation on all four lines, which is the MPETHP value—see Fig. 2.10b. Such an accurate and precise testing regime is very specific, both in terms of the CMMs definition and its actual execution.

[18]**Operating-characteristic**—is the result of a component production Sampling Plan. This type of Acceptance-sampling has utilised statistical-sampling to determine whether to accept, or reject a production-lot (i.e. batch) of material. It has previously been a common Quality Control technique utilised in industry and most notably for the military—for contracts and procurement. It is usually undertaken as products leave the factory, or in some cases even within the factory. Most often, a producer supplies a consumer a number of items and decision to accept, or reject the lot is made, by determining the number of defective-items in a sample from that lot. Thus, the lot is accepted if the number of defects falls below where the acceptance number occurs, or otherwise this lot is rejected. This is why inspection-strategies are critically-reviewed, away from tightened-inspection, to that of reduced-inspection procedures—whenever possible—to minimise quality-costs within the company.

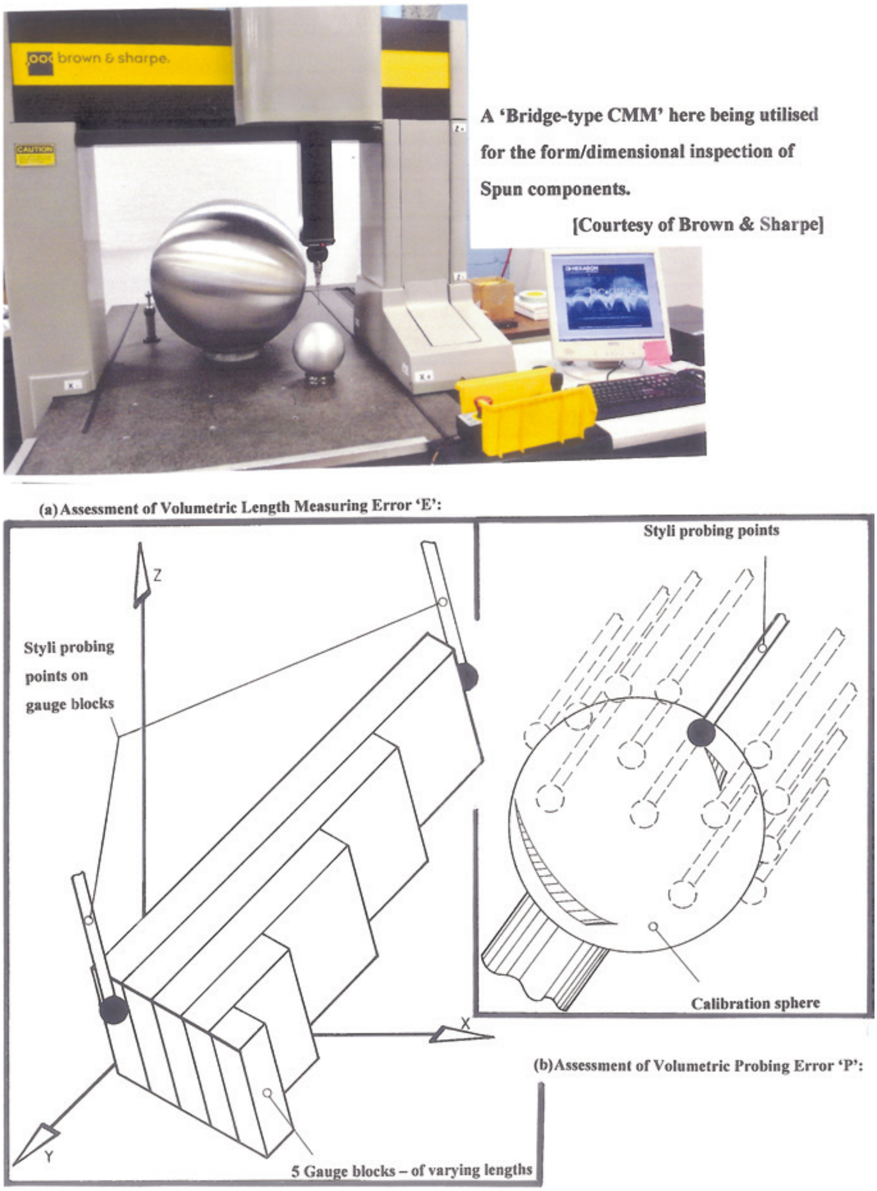


Fig. 2.9 Typical arrangement for assessing the volumetric probing errors '*E*' and '*P*' (adapted from: ISO 10360/Hexagon Metrology)

It is important to comprehend that a CMMs uncertainty under actual functioning circumstances could be larger than stated within the manufacturer's specifications. This difference in the CMMs performance, is because of a range of interrelated factors, such as the use of: probe extensions—either long, or slender

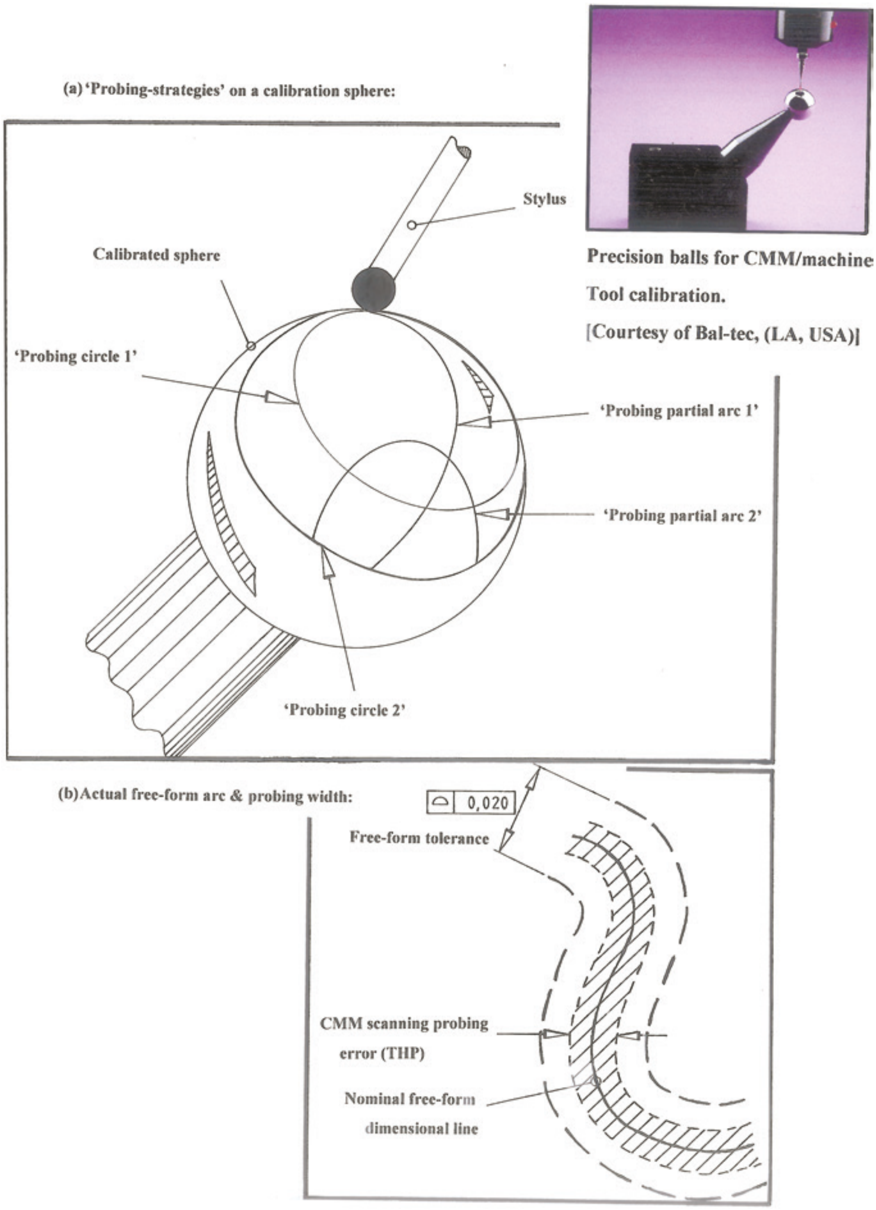


Fig. 2.10 Typical 'probing-strategies' when either 'qualifying a stylus', or 'scanning' a free-form profile (adapted from: ISO 10360/Hexagon Metrology)

probes; articulating probe heads; rotary tables[19]; ambient/CMM temperature changes; as well as any airborne contaminants within the working environment. By way of an example, MPEE and MPEP as specified, are actually determined by just one stylus fixed-directly into the probe head with no extensions and no rotation. Nevertheless, most intricate-geometry workpieces normally require some complex probe-configurations. Hence, a complex part geometry may necessitate the use of: several styli; probe-extensions; rotations of the probe; also possibly a probe-change during the inspection programme of critical component features. Since these probing-differences here are readily apparent, then the commonly accepted-practice is to apply a ratio of uncertainty to tolerance—when calculating a mandatory CMM specification. Therefore, this ratio may vary extensively, contingent upon the factors previously mentioned, also considering the complexity of the actual measurement task and the overall probing-process. Characteristic ratios of uncertainty can range from 1:3 to 1:20, but with values of between 1:5 and 1:10 being the most common. Accordingly, to maintain a 1:5 ratio of uncertainty to the part's tolerance, the CMM data-sheet specification, should be five times more accurate than that of the tightest tolerance inspected.

For just about all inspected parts, the CMMs must examine three-groups of features for: diameters/distances; positional tolerances; plus form tolerances. For this reason, an analysis of the mandatory-uncertainty must be accomplished for each of these three groups, hence:

1. **diameter/distance tolerances**—for example, must refer to the component drawing and location of the diameter for distances having the tightest tolerances. This is due to the length-dependency of its volumetric-uncertainty, where a greater tolerance on a very long feature may present more difficulty, than the opposite effect of a very tight tolerance on a small feature;
2. **positional tolerances**—these are usually defined by, say, a tolerance diameter, where only the radius is utilised to determine the deviation from the part's nominal-centre;
3. **form tolerances**—can include factors relating to the component's: roundness; flatness; straightness; cylindricity; as well as its profile form.

[19]**CMM—Rotary Table Calibration of the 4**th **Axis** (i.e. **ISO 10360—**Standard)**—**see Figs. 2.11 and 2.12, having the following - **Rotary table Errors**: Radial Error '**FR**'; Tangential Error '**FT**'; plus Axial Error '**FA**'.

CMM—Rotary Table Calibration—test procedure:

(i) fix spheres '**A**' and '**B**' on '**RT**'. (i.e. recommendation 'Δh' = 400, 'r' = 200 mm) (The errors of a rotary table generally increase with 'Δh', radius 'r' and table load.);
(ii) measure sphere '**B**' and set centre—point to zero (0,0,0);
(iii) measure sphere '**A**' in 14 positons, 7 positions from 0° to 720° and 7 positions from 720° to 0°;
(iv) measure sphere '**B**' in 14 positions, 7 from 0° to 720°, 7 from 720° to 0°, at the last position (28) measure sphere '**A**', one more time;
(v) calculate range of '**X**', '**Y**' and '**Z**' for '**A**' and '**B**';
(vi) Rotary table error: Radial '**FR**' = Max. range in '**X**' ('**A**', or '**B**');
(vii) Rotary table error: Tangential '**FT**' = Max. range in '**Y**' ('**A**', or '**B**');
(viii) Rotary table error: Axial '**FA**' = Max. range in '**Z**' ('**A**', or '**B**').

[Source: adapted from—Hexagon Metrology, GmbH (2014)].

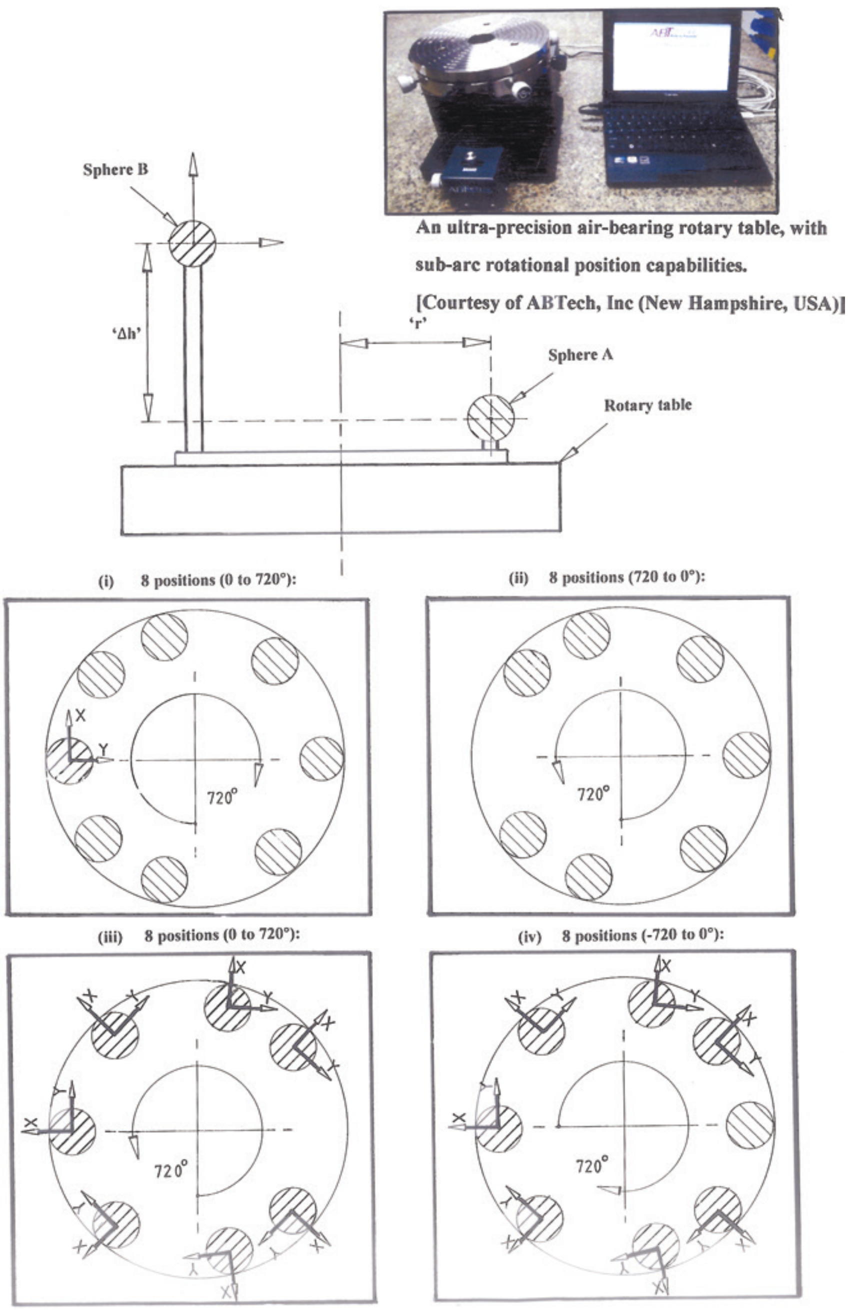


Fig. 2.11 A typical setup for the assessment of a rotary table (adapted from: ISO 10360/Hexagon Metrology)

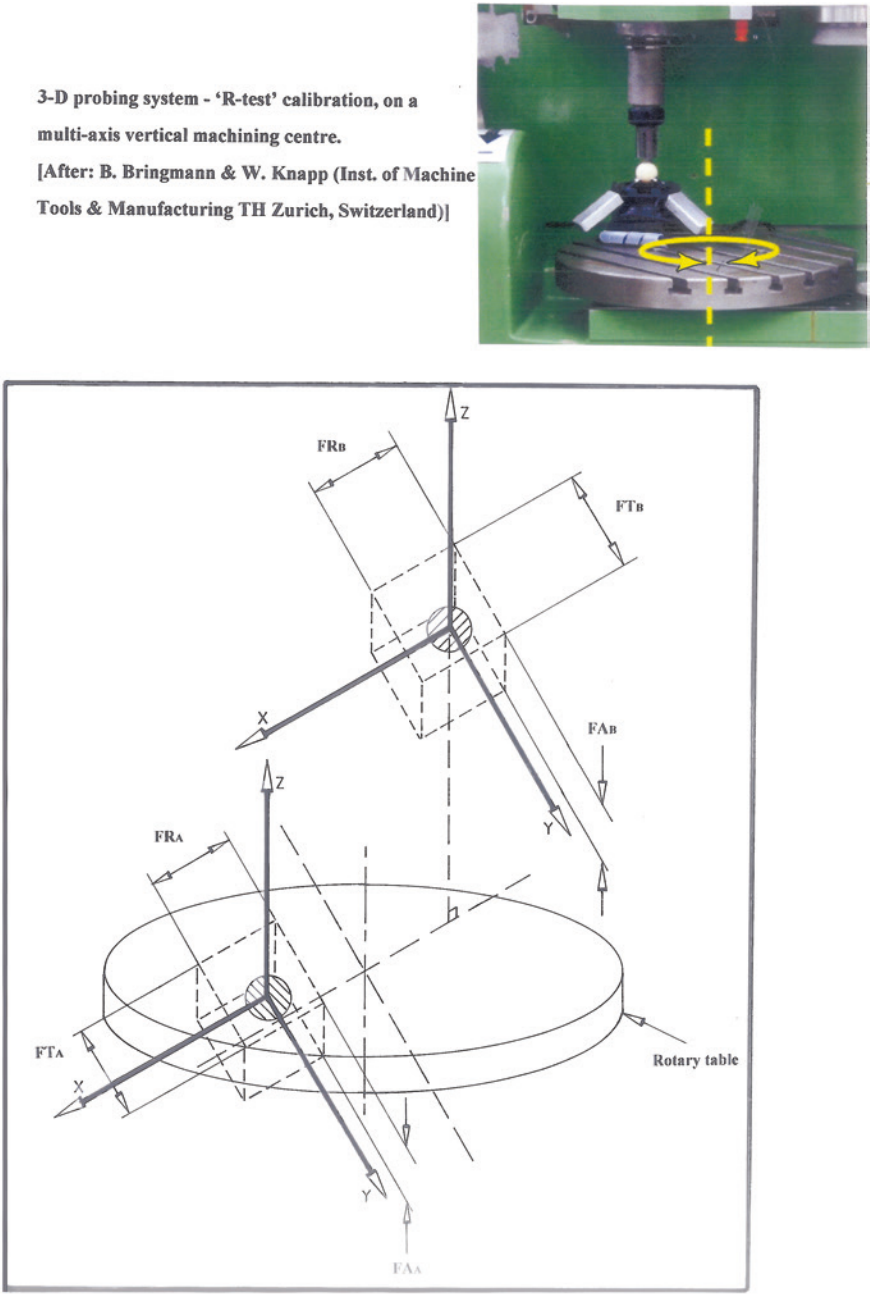


Fig. 2.12 General test procedure, with rotary table error (adapted from: ISO 10360/Hexagon Metrology)

2.3.2 CMM—Environmental Conditions

Metrological environmental conditions can have a serious effect on the prospective uncertainties of a CMM—in its present location. Accordingly, CMM-manufacturers normally stipulate the: temperature range; temperature variation per hour; temperature variation per day; also the temperature variation per metre; within which a specific CMM will ultimately achieve its performance specifications. These environmental variables must be considered when choosing its actual location site and ensuring that an appropriate CMM is supplied—being equipped with its necessary technical specification. Likewise, as also previously mentioned concerning adequate foundations—for machine tools—similarly, the CMM's floor-loadings must also be considered in a similar manner. Furthermore and additionally—in a CMM's case, the magnitude of anticipated floor vibration is an important consideration, to optimise its anticipated metrological performance. In addition, the majority of CMM-manufacturers supply details of the maximum vibration that such CMMs can withstand, while still meeting their stated technical specifications.

In certain situations, active or passive vibration damping-systems can be supplied that enable the CMM to be installed in distinctly challenging environments, enabling them to still perform to their published specifications. Of some note, is the often overlooked requirement of completing a Seismic vibration study—this being executed at the chosen CMM-installation site.

2.3.3 CMM Performance Standards

All current CMM-manufacturers can provide performance standards as the means to rate a CMM. Such standards are beneficial when equating different manufacturer's CMM products, to enable one to determine how well their current machine will inspect workpieces, while also ensuring that the machine operates correctly. There is a distinct range of different Standards of measurement for CMM calibration, although these opposing Standards can often create-confusion and a certain amount of misunderstanding for the CMM user. Of late, there are principally three primary standards that are invariably utilised to verify the accuracy and precision of a CMM's performance, these are **ASME B89.4.1**; **VDI/VDE 2617**; as well as the **ISO 10360-series**. The main differences between such Standards chiefly occurs in the number of tests utilised in evaluating CMMs and the manner in which performance specifications are written. For example, to evaluate the length-measuring performance, the **B89** Standard utilises multiple tests, while the **VDI/VDE 2617** utilises three tests; similarly **ISO 10360-series** also utilises three tests—but here, with one of these tests being for the probe. So, to represent a typical CMM performance-range of, say, the **B89**-specifications, this standard will consist of a single number. For example, a particular CMM could have a

B89—volumetric-performance specification of 0.010/325 mm. Here, the number after the slash represents the length of the ballbar measurement. This specification means that the range of measured lengths with the ballbar in its many positions is ≤ 10 μm. For the other CMM Standards, namely, the **VDI/VDE-** and **ISO**-specifications, they represent length-measuring performance as a formula. As a consequence, a CMM's volumetric performance, can be quantified in the **VDI/VDE** format, as follows:

$$U3 = 4 + 5L/1000.$$

where in this case the notation means that over the same measured 325 mm—length previously mentioned, there could be an error no larger than ±6 μm (i.e. actually 5.625 μm).

In all cases for the **VDI/VDE** and **ISO** Standards, they utilise measurements taken from a calibrated step gauge—see Chap. 5—or an equivalent set of calibrated gauge blocks (i.e. see Fig. 2.9a). Moreover, in the **VDI/VDE** Standard, this calibrated Step gauge is measured in three positions, which are:

1. **axial**—($U1$);
2. **planar**—($U2$);
3. **volumetric**—($U3$).

Hence, the differences between the measured lengths and the calibrated lengths of this Gauge are compared in the formula (i.e. for this **VDI/VDE**-specification), by:

$$U = a + b \times L/1000$$

where: the '*a*' term is a value representing the error—when measuring a component part of zero-length; the terms '*b*' and '*L*' are divided by 1000, to represent the increase in error—being based on the length-measured; thus, the formula represents a line for zero measured length, which is its '*a*' value. As an example of this, a 4 μm value—in the equation above (i.e. also, then see below), is where it goes up by a slope which is defined by the '*b*' term. Further, this '*b*' term is the number of micrometres that the error increases for every 1000 mm of '*L*' length. Accordingly, the means that the error formula will then become:

$$U3 = 4 + 5L/1000 \text{ (i.e. for volumentric accuracy)},$$

which for zero measured-length, is 4 μm and for every additional metre of length measured it will become 5 μm larger. Often though, the specification is more generally stated as simply:

$$U3 = 4 + 5L.$$

The measurement approach is the identical for the **ISO** Standard, but in this specific case the formula will change to:

$$\text{MPE}_E = a + L\big/k$$

where: here the value of ‘k’ is substituted for ‘b’ value—from the **VDI/VDE** formula, this being divided into 1000. Here, there are no individual axial- and planar-specifications, as they are included in the volumetric ‘E’ specification.

In the case of the **B89 Standard**, the basic test of a CMM’s performance, includes five critical-measurements, these are for:

1. **multiple measurements of the position of a fixed ball**—the range (i.e. the largest minus smallest) is the machine’s repeatability;
2. **measurements with a Step gauge, or by a laser**—in each axial direction, which determines the machine’s linear accuracy;
3. **measurements of a ballbar**—at multiple-positions and orientations, within the machine’s working-volume. This value is the machine’s volumetric performance;
4. **measurement of the ballbar**—in four diagonal positions—in vertical planes. In each position, the ballbar is measured with two right-angle probe offsets and the difference in their measured lengths is determined. The differences are compared with an offset-probe performance specification;
5. **measurement of the length of a short Gauge block**—in four orientations. The measurement is compared with a bi-directional accuracy-measuring capability specification.

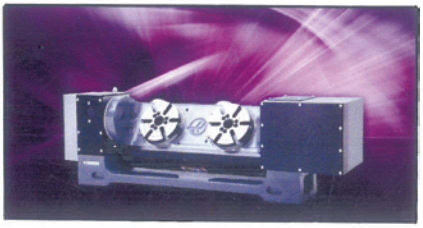
Probably, the most important topic being discussed at present—in both the USA-Committees and within the ISO-Standards Committees, is that while these performance tests provide an overall characterisation of a CMM’s quality, they do not provide the CMM-user with sufficient information about how accurately a CMM can measure an actual feature. As a result of this quandary, Technical Standards Committees around the world are seeking to determine how to characterise what is termed Task-specific measurement uncertainty as a method of describing how accurately the CMM can perform a real measurement task.

2.4 Calibration of a Rotary Table—With a Rotary Indexer

The diagrammatic representation of an exploded view of a typical auxiliary 4th-axis rotary table is shown, for auxiliary-fitment to a CNC machine tool (i.e. Figure 2.13, middle). In this example, it is depicted as having a large-diameter, aluminium-bronze worm-gear, that can precisely mesh with a ground alloy steel-worm (i.e. here being hardened to 60 H_{Rc}) which is lubricated by submerging it in a synthetic oil bath. The apparent high precision indexing-accuracy is achieved in this indexer, by machining the worm gear while it is attached to its spindle, rather than the alternative, of assembling the finished worm-gear to a separate spindle—as might be the case with some other rotary-table manufacturers. Each assembled

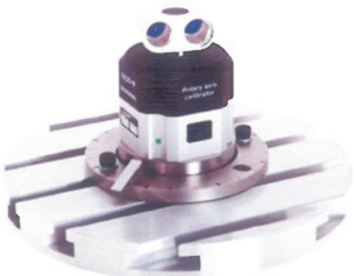
Dual-Spindle Tilting 2-Axis Trunnion Rotary Table, with scale feedback on the A (tilting) axis.

[Courtesy of Haas Automation (USA)]



Exploded view of a Rotary Indexer, showing: 1-main body, 2-turntable platter, 3-bearings, 4-worm gear, 5-worm drive shaft, 6-brake disc & 7-motor enclosure.

[Courtesy of Haas Automation (USA)]



Rotary Axis Calibrator & Laser**,**
plus its associated *Optics* can be used to *calibrate* a CNC *Rotary Indexer* for a machining centre, or *any* CNC machine tool's rotary axis. **[Courtesy of Renishaw plc]**

Fig. 2.13 A typical CNC rotary indexer and rotary axis calibrator spindle is individually 'trammed-in' on a CNC Gear-hobber, to an accuracy of ≤2 μm run-out, then the worm-gear is precision cut. This particular two-stage gear-hobbing and shaving machining process,[20] will ensure high-concentricity between the large-diameter ball bearings and the worm-gear—minimising and assuring a bind-free operation. Rotary tables of this level of accuracy and precision, still require periodic recalibration of their angular-indexing[21] ability. So, in order to achieve this vital rotary table calibration, it is necessary to either statically, or dynamically calibrates this table periodically. In order to achieve this rotary-calibration, a Rotary axis calibrator (Fig. 2.13, bottom) can be utilised in conjunction with a laser—see Fig. 2.14a—which can achieve the necessary high-precision rotary table calibration, providing ±1 arcsecond angular measurement accuracy. Here, as shown in Fig. 2.14, the wireless operation and modular mounting system ensures suitability for a wide range of rotary axes calibration applications across a diverse range of CNC machine tool configurations.

A typical rotary axis calibrator setup is shown in the Machining Centre configuration in Fig. 2.14a. An angular reflector is mounted on top of the rotary axis calibrator, which in turn is also mounted on top of the machine tool's rotary table axis—in this case, it is an integral rotary table which is presently being calibrated. As the machining centre's axis, under test, is rotated from one target position to the next, the rotary axis calibrator is driven in the opposite direction in order to maintain alignment with that of the angular-interferometer. When the axis under test stops at each target-position, then the positioning-error is calculated by comparing this target-position, with the arithmetic-sum of the angular-readings from the laser interferometer and from that of the rotary axis calibrator. This specific rotary-action allows the calibration of the axis over a full 360°, or even over multiple-revolutions.

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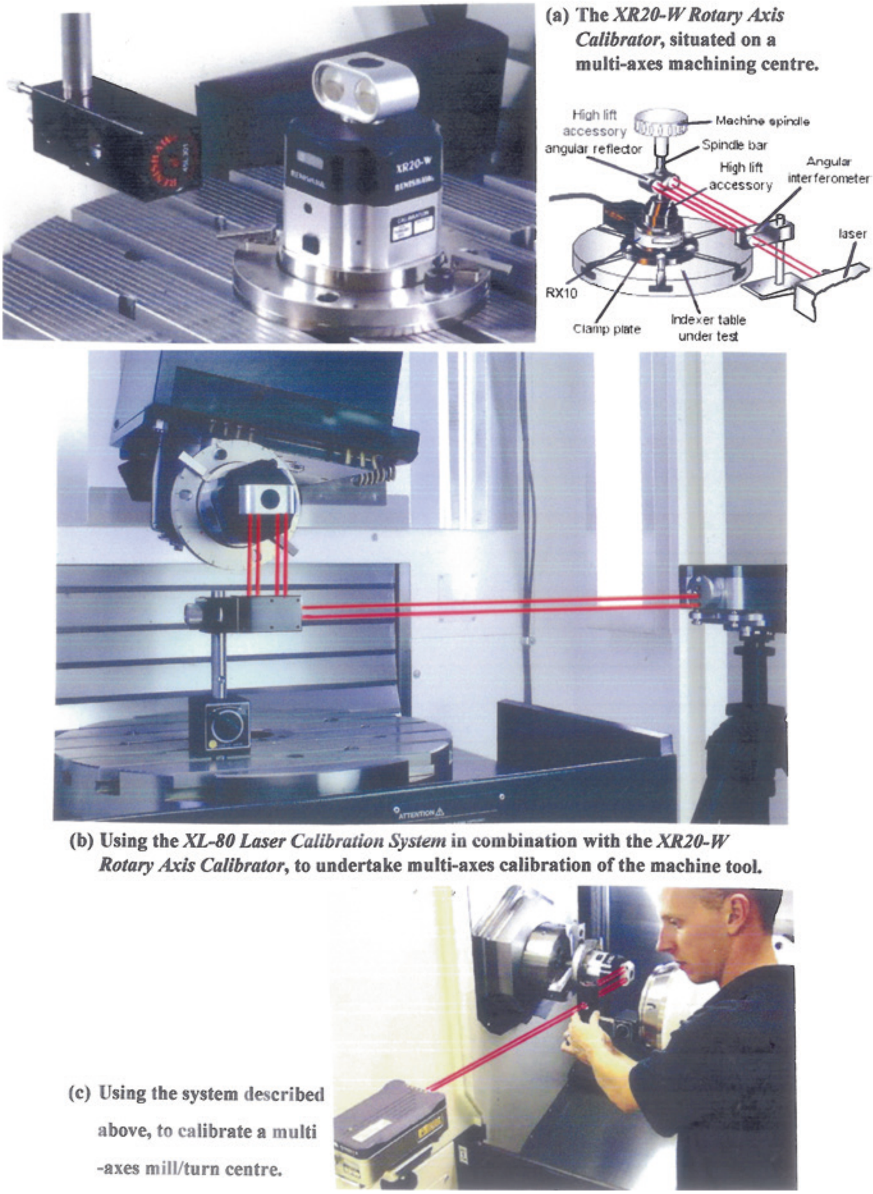
[20]**Gear-hobbing and Shaving machining processes**:

Gear hobbing—in basic terms: a Hobbing-machine is utilised, with two skew-spindles, one mounted with a blank workpiece and the other with the gashed-hob—having the desired gear-cutting tooth involute-geometry. The angle between that of the hob's spindle and the workpiece's spindle will vary, dependent upon the type of gear-tooth profile being produced. For example, if a Spur-gear (i.e. with straight-cut teeth) is being produced, then the hob is angled equal to the helix-angle of the hob; while if a Helical-gear is being produced (i.e. with helically-curved teeth), then this angle must be increased by an identical amount as to that of the helix-angle of the required helical-gear. Then these two shafts—one with hob and the other with the gear-blank—are then rotated at a previously-calculated and proportional-ratio, then the gear blank is cut (i.e. by feeding it across the hob at the desired depth), which determines the number of teeth on the blank.

Gear shaving—which is a technique for generating an improved tooth shape in gears of an involute-profile. By the action of a minute stock-removal process via Gear shaving, it may be used to improve the quality of meshing between two gears, or between a gear and its rack. So by this Gear shaving, it makes possible to vary the interaxial-distances within gear-transmission, providing a machining-solution for a number of important design problems.

[21]**Rotary table—angular indexing capability**: in Fig. 2.13, this typical full-axis rotary table can achieve an indexing: resolution of 0.001°; with an accuracy of ±15 arcseconds; plus a repeatability of 10 arcseconds.



(a) The ***XR20-W Rotary Axis Calibrator***, situated on a multi-axes machining centre.

(b) Using the ***XL-80 Laser Calibration System*** in combination with the ***XR20-W Rotary Axis Calibrator***, to undertake multi-axes calibration of the machine tool.

(c) Using the system described above, to calibrate a multi -axes mill/turn centre.

Fig. 2.14 Typical images of multi-axes laser calibration of machine tools (courtesy of Reinshaw plc)

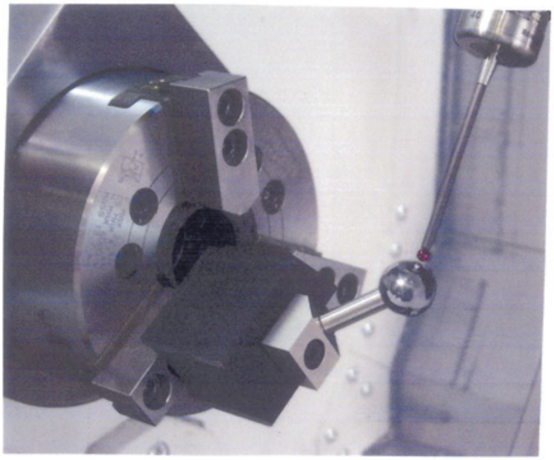
One of the key benefits of utilising an angular-interferometer to provide the coupling between the counterrotating rotary axis calibrator and a stationary part of the axis under-test is that it is somewhat insensitive to small translation (i.e. side-to-side) movements of the reflector. This particular arrangement ensures that system alignment is much easier to achieve, by virtually eliminating a major potential source of angular-measurement error. For example, eccentrically mounting of a rotary axis calibrator, when being placed 1 mm from the centre of rotation of the axis under-test, will add <±0.5 arcseconds of additional measurement error. By way of comparison, a Ø200 mm rotary-encoder disk, with external read-head, would have to be mounted to within 0.25 μm to achieve similar level of rotational-performance. Even a fully enclosed rotary encoder with its integral-bearings and sophisticated precision shaft-coupling, has to be mounted within ≈0.05 mm (i.e. a 40 times tighter-tolerance than that required by the rotary axis calibrator). On the other hand, keeping overall accuracy levels within ±1 arcseconds, requires careful design and attention to detail to ensure that all of the possible error-sources are similarly controlled.

2.4.1 AxisSet™ Checkup—Utilised for Machine Tool Alignments

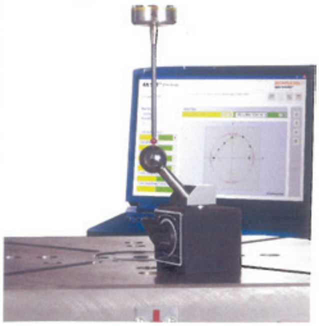
In order to achieve a cost-effective solution for checking the alignment and positioning performance of rotary axes, the AxisSet™ Checkup was developed—see Figs. 2.15b, c. Consequently, within just a few minutes of fitting this artefact to users of multi-axis, or multi-tasking (mill-turn) machines (i.e. here, typified by the CNC machine tool in Fig. 2.15a) it can efficiently identify and report on poor machine alignments and geometry that can cause extended process-setting times, as well as for checks on any non-conforming parts. The notable-features and accompanying-benefits of utilising this AxisSet™ Checkup device, are quite numerous and include the following:

- discrete reporting of the pivot-point on a CNC lathe/Turning Centre—line-error along linear axes (i.e. as commonly defined in CNCs);
- a reliable check and the ability to track any machine performance trends over time;
- enabling the measurement and reporting of critical-errors speedily and effectively;
- providing recommended correction-values for machine tool optimisation;
- increasing the confidence of the CNC-user, prior to critical features being machined;
- elimination of unplanned-downtime, which then reduces scrap levels and subsequently enables increased profits to be made;
- the ability to obtain both incremental and absolute reporting modes;

(a) The *machining* of a large *Hydro-impeller* situated on an integral *rotary table* on the Travelling Column CNC Milling Machine.
[Courtesy of Canyon Hydro (Deming, WA, USA)]



(b) Utilising the *AxisSet*™ *Checkup* on a Turning Centre with automatic probing routines to obtain performance data from a calibrated *Reference Artefact* – for the identification of poor *machine alignments*, prior to its *correction*.
[Courtesy of Renishaw plc]



(c) Employing an *AxisSet*™ *Checkup* on a CNC Milling Machine's rotary table.
[Courtesy of Renishaw plc]

Fig. 2.15 In order to ensure that the CNC machine tool's rotary/*C*-axis, has the correct alignments, a quick and efficient artefact/probing routine can be exploited

- the system allows for user-selectable calculation methods—to establish pivot-points;
- displays of both form-error and the machine's swing-radius—where appropriate;
- the system can achieve automatic-import and backup—of multiple data sets.

AxisSet™ Checkup—Circular Plot—Software Overview

A graphical representation of rotary axis movement (i.e. see Fig. 2.15c—screen display), provides the user with a magnified view of errors in the machine path. Moreover, the actual tracking error gives an indication of the total effect of all measured errors, including both its centring and form errors. In particular, the definitions here will include:

- **Form Error**—which can be considered as, "The deviation of the measured points from a perfect curve";
- **Test Radius**—is, "The distance of measured points from the centre of rotation" (i.e. where the sphere is within the machine under-test);
- **Centring Error**—is, "The total error between the nominal and actual measured pivot point and represents the total magnitude of the pivot point error";
- ***X*/*Y*/*Z* Axis Component**—is, "The error between the nominal and actual pivot point, expressed along each relevant linear axis".

These specific definitions provide a practical understanding of what and where the errors are present within the machine tool, moreover, this also allows qualified-operators to correct these errors by updating CNC machine tool's parameter settings.

AxisSet™ Checkup—Angular Plot

Using the bespoke-software to produce an Angular Plot, it is then possible to understand the alignment of a rotary axis, then comparing it to its linear axes. This angular plot displays the rotary axis position against the linear axis, which is perpendicular to the axis of rotation and should of necessity, be stationary during the test. This linear axis here is also known as the static axis. As a consequence, any apparent movement of the static axis can be considered as the error caused by misalignment between the rotary axis and that of the static axis. Therefore, the maximum deviation of these errors is displayed as its tracking error.

2.5 Machine Tool Linear Axes—Factors Affecting Their Accuracy and Precision

An overall inaccuracy of machine tools, when they are machining components, can arise from a series of interrelated factors. Some quite significant problems can have an undue-influence on the machine's linear axes and their anticipated calibration, which could include inaccuracies due to:

- **geometric and kinematic machine tool inaccuracies**—affecting the linear ways, etc.;
- **internal stresses**—in the major machine tool's structural elements;
- **elastic deformation**—within the inherent rigidity (i.e. resulting from its lack of loop-stiffness) of the machine/tool/workpiece coupling resulting from the influence of cutting forces and other resistances;
- **thermal deformation of machine tool**—both internal and external thermal-effects;
- **wear and cutting forces**—resulting from the worn-tooling—increasing cutting forces, and as such, affecting these axes;
- **specific types of vibrations and some oscillation within the machine tool**—this is particularly apparent when machining at specific vibrational frequencies.

From this listing, probably the most important factor within a machine tool is that of its inherent machining accuracy and precision. Although, this accuracy and its accompanying measurement may be precise, but is it truly accurate? One technique in establishing the levels of accuracy of linear ways, is by statistical-methods. Here, the usual-approach is to use some form of statistical measures[22]—that are based upon well-established principles.

So, by utilising the **ISO 230-2** Standard, it is possible to employ it for the calibration and verification of, for example, the CNC machine tool positioning of its table. From Fig. 2.16, just one of the parameters that can readily establish the difference between the forward and backward linear series of runs along a measured-axis length, here termed its backlash, or alternatively, the uncorrected hysteresis error. Moreover, the **ISO 230-2** testing regime is targeted for both testing and evaluation of the accuracy and repeatability of positioning axes in CNC machine tools, by employing direct measurement of these axes. In this situation, the **ISO 230-2**-technique is equally applicable for either the machine's linear or rotary axes. The objective of these measurements under the **ISO 230-methodology**, is

[22]**Statistical measures**: which are often utilised in both machine tool and CMM calibration-techniques, being normally-based upon the following well-established principles, for their:
- **standard deviation**—known also as 'σ', which is a statistical measure of the precision in a '$\overline{x}$' (i.e. which is pronounced as: x-**bar)** series of repetitive 'x_i' measurements—with 'n', the number of data, while 'x_i' is each individual measurement and, the **mean** of all measurements;
- value '$x_i—\overline{x}$' is called the **residual**—for each measurement.

Thus, it follows that:

$$\sigma = \sqrt{\sum_{i=1}^{n} (x_i - \overline{x})^2 \Big/ n-1};$$

where:

$$\overline{x} = 1/n \sum_{i=1}^{n} x$$

to construct a compensatory curve and to then utilise this measured data to compensate for positioning-errors within these CNC machine tool's axes. In order to obtain the data necessary for the production of a graphical plot—similar to that shown in Fig. 2.16—these measurements are performed on the axis at a steady-state temperature. In accordance with requirements of **ISO 230-2**, the range of calibration of linear axes is invariably restricted. As a consequence, Fig. 2.16 displays the graphical representations of the results of accuracy and repeatability analysis

A large-scale Twin Column (LK) CMM
– with Horizontal Scanning Arms,
equipped with Digital Cross-scanner/laser
for Reverse Engineering comparison/validation.

[Courtesy of: Nikon Metrology/LK MSI/Warwick University]

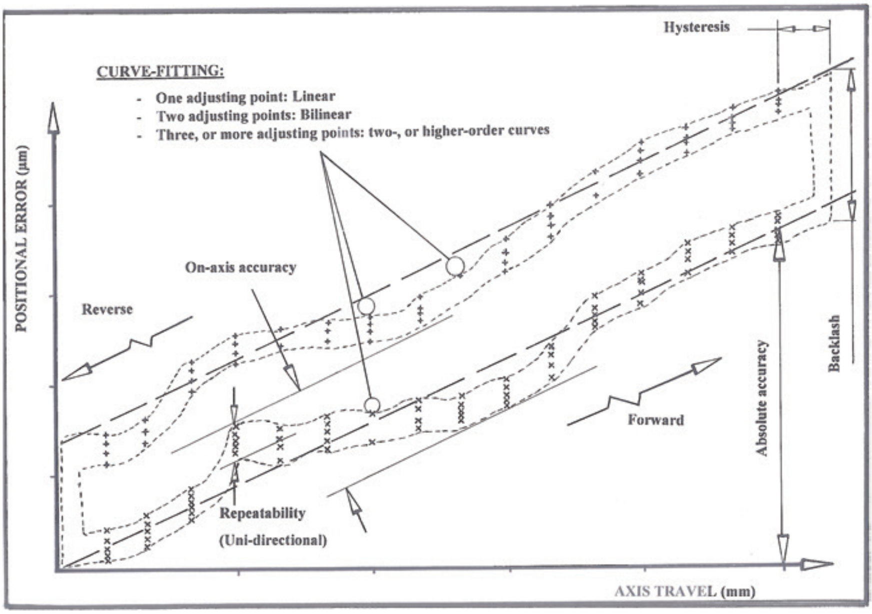


Fig. 2.16 A representative plot of a machine tool axis, illustrating: accuracy, repeatability and resolution (adapted from: ISO 10360/Hexagon Metrology)

of positioning on a typical axis, which highlights the additional parameters shown, that are also described in the **ISO 230-2**, these being evaluated by the envisioned calibration procedure—for the actual machine's table-positioning.

2.6 Laser Tracker—Instrumentation, Testing and Applications

The original Laser Tracker was patented in the USA in 1987—see the basic and schematic representation of it in Fig. 2.17. These now very-popular Trackers can be considered as Polar coordinate measuring systems, being capable of high-accuracy measurements over quite long linear distances. For example, in one of the systems now being utilised by The NPL, it can measure at distances of up to 40 m—to within discrete-accuracies of measurement of ±60 µm. Thus, in a Laser Tracker, it makes measurements of the positions via its Spherically mounted retro-reflectors (SMR's)—in terms of two angles—namely in the horizontal and vertical planes, which are measured using angular-scales mounted in the Tracker-mechanics, and distance (i.e. radius) to the SMR—by utilising a laser interferometer. By exploiting some relatively simple trigonometry, the Laser Tracker converts these obtained values into the usual cartesian coordinates (i.e. namely, into its *X*-; *Y*-; and *Z*-coordinates). Special-purpose tooling-fixtures allow the measurement of not just individual point locations, but also of surfaces such as for flatness and level, angles and squareness, surface form, as well as alignment between separate, or attached parts. By combining laser trackers with other measuring-systems, such as laser scanners, large objects with complex-surface features can be effectively and efficiently measured.

The metrological application of the laser tracker is especially useful for optical alignment—for three main reasons, these being:

1. **accuracy**—the current Laser Trackers can make measurements to ~10 µm accuracy without any special geometry, or data processing. By choosing advantageous geometry, calibrating repeating errors and by averaging random errors, the instrument's tracking allows it to measure to even tighter levels, of: <1 µm;
2. **flexibility**—the Laser Tracker can measure over a wide range of angles and distances. Moreover, a typical tracker can even measure through windows, thereby enabling the most difficult geometries to be measured with this type of instrument;
3. **ability to measure different optical spaces**—frequently optical systems incorporate fold mirrors to help with the system packaging. The laser tracker beam is also reflected by the mirrors, so the Tracker can determine optical-coordinates directly.

The relative merits of a laser tracker and its usage has been briefly mentioned above, but it needs re-stating once again, that they are utilised in wide-ranging metrological/calibration applications, some of which are simply depicted in

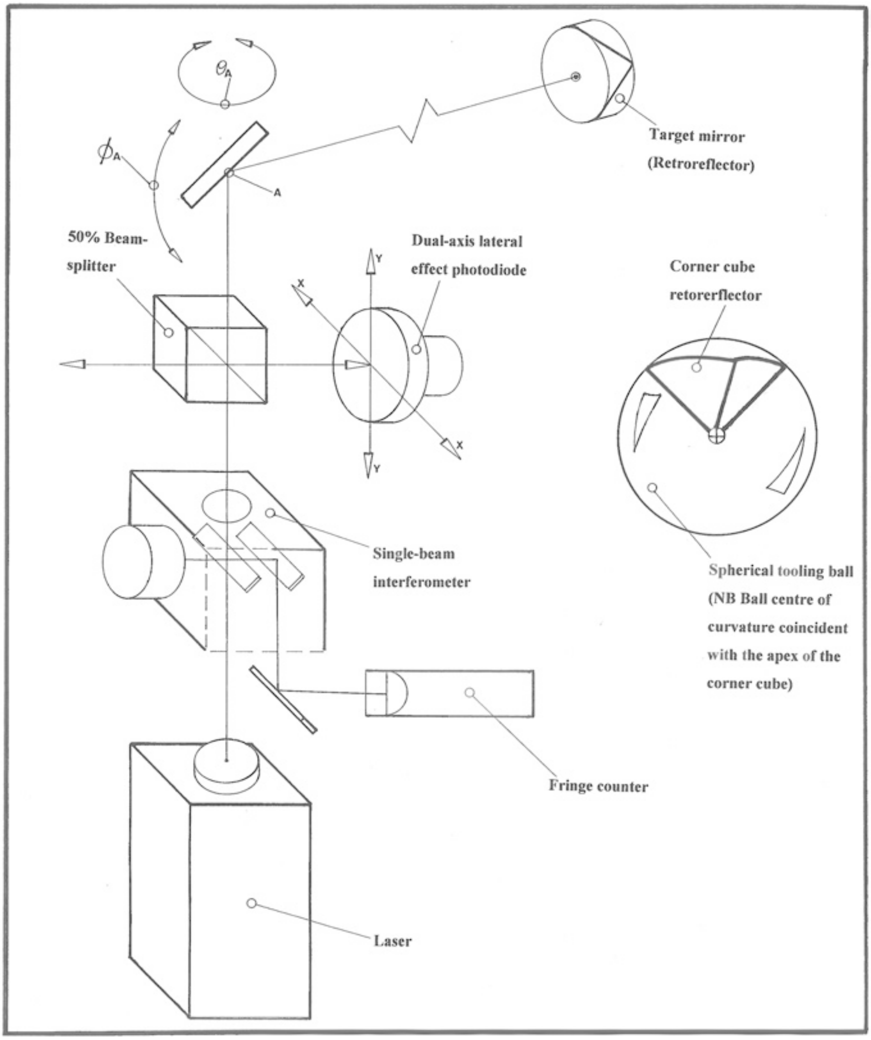


Fig. 2.17 An exploded view of the original *laser tracker* and its main components (*Source* US patent #4,714,339, in: proc. of SPIE vol. 6676 667760E-12)

Fig. 2.18—for various alignments and measurement of, say, large castings and for certain inspection procedures on alignments of machine tools. Typically, these trackers are often employed to ascertain and align the massive lengths of large aircraft wings—usually during final assembly. Accordingly, to take measurements with the tracker, the Inspector firstly sets-up a laser tracker on a tripod, with an unobstructed view of the object to be measured—see Fig. 2.18. Then the Inspector removes a target from the base of the tracker and carries it to the object, for certain regions of its features to be measured, moving smoothly to allow the laser

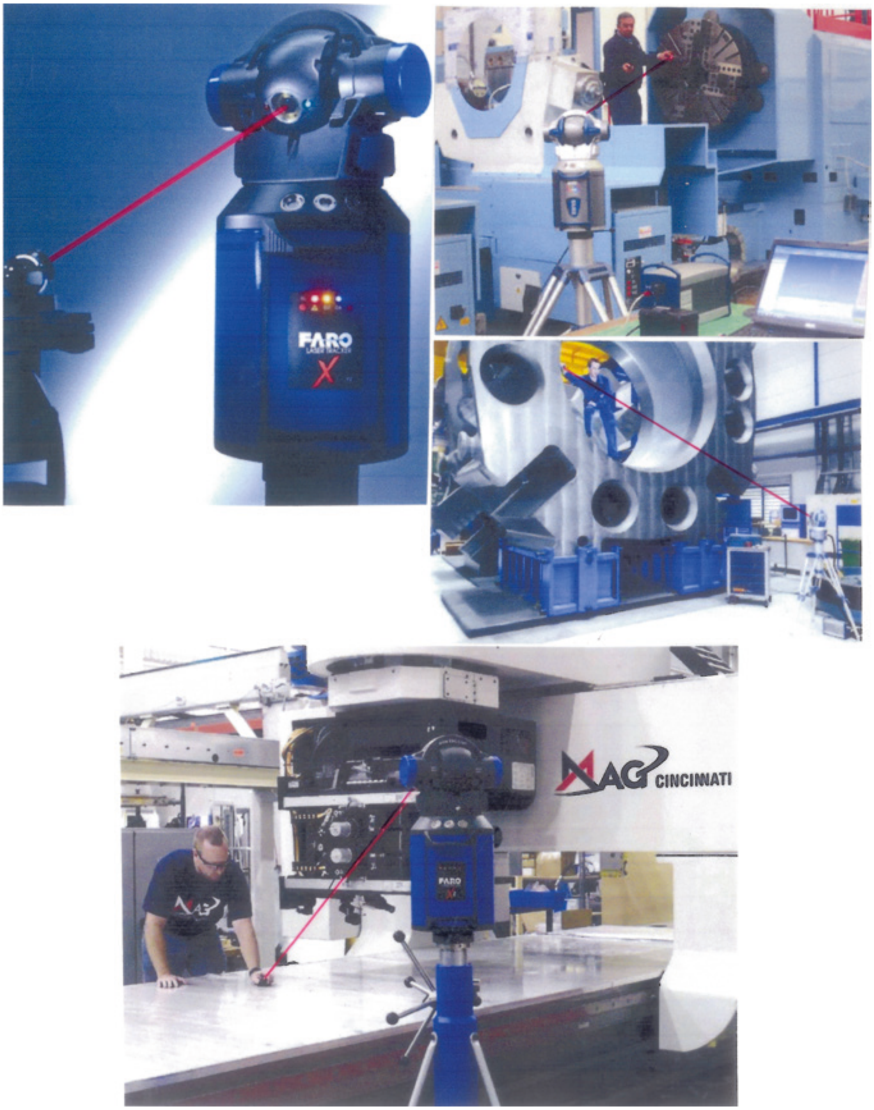


Fig. 2.18 Laser tracker applications can be wide-ranging in their inspection/calibration applications (courtesy of FARO Technologies Inc)

tracker to follow these movements of the target. During this procedure—as just mentioned—the Inspector individually places this target against the object, triggering-measurements to be taken at preselected points, sometimes utilising a remote control device. These direct-measurements can then be imported into different types of software to plot the relevant-points of interest, or to calculate deviation from the correct position. These targets are known as retroreflective, because they reflect the laser beam back in the same direction it came from—in this case, back to the Laser Tracker. One type of target that is in common usage is the Spherically mounted retroreflectors (SMR)—often termed a spherical tooling ball, which resembles a ball-bearing with mirrored surfaces cut into it—see Fig. 2.17 (middle-right).

These laser trackers will also require periodic calibration, often by a country's National Institutions like the one which is typically provided by The NPL, which in this case utilises the seven tests prescribed in the **ASME B89.4.19** Standard—see below, in Sect. 2.6.1. These laser tracker tests are designed to exercise the tracker's measurement systems over a wide range of angles and distances, similar to those encountered in real-world usage. As a consequence, the Laser Tracker is subject to a configurations-test, which assesses the horizontal and angle encoder scale errors and eccentricities, together with its distance and displacement measuring systems. While the accompanying range-tests will verify the accuracy of the absolute distance meter (ADM), as well as the fringe counting performance of the laser interferometer (IFM)—if fitted.

2.6.1 Laser Tracker—Calibration Procedures

As mentioned in the previous Sect. 2.6 there are basically seven Laser Tracker test-procedures that are contained within the **ASME B89.4.19** Standard, which prescribes a series of repeated length-measurement tests for the verification of its IFM; its ADM; plus two-face tests: also the ranging-tests, which are undertaken in the following manner:

1. **horizontal length measurement system test**—in 9 configurations;
2. **vertical length measurement system test**—in 8 configurations;
3. **right diagonal length measurement system test**—in 8 configurations;
4. **left diagonal length measurement system test**—in 8 configurations;
5. **two-face system test measurement**—in 12 configurations;
6. **ranging tests**—for **IFM** and/or **ADM** up to 30 m;
7. **user-selected volumetric tests** —in 2 configurations.

These calibrated results from the Laser Tracker testing-regimes, are then reported against the performance specification (MPE-value)—these values being supplied by the particular laser tracker manufacturer. Additional calibration options, can also include laser wavelength calibration—with a comparison against Reference interferometer; plus its accompanying Weather station—for assessment (i.e. concerning testing it for temperature, humidity, also pressure).

2.6.2 Laser Tracker—Frequently Asked Questions

Invariably, some representative questions that are often raised concerning the practical usage and typical application of these laser trackers, might include:

- **What does it do?**—the Tracker can measure the three-dimensional location of a mobile-target with an accuracy of a few micrometres, over a range of tens of metres;
- **Why use this technique?**—Laser Trackers provide fast measurement of a target which can be moved almost anywhere within line-of-sight of its base-unit. A key factor in favour of the Tracker is the high relative-accuracy that can be achieved. Of note, is that these Trackers have largely superseded some of the more traditional measurement-techniques, such as by Theodolites, or conventional metrology tools in some instances as in the case of certain Auto-collimators, but more will be said concerning this optical-instrumentation—in Chap. 3;
- **What are Laser Trackers used for?**—these Trackers are often utilised for robot tracking, inspection and alignment; calibration tests, maintenance and testing procedures; aircraft manufacturing alignments; automotive jig-build and setup; verification of the design of manufactured structures; together with certain reverse Engineering applications;
- **Type of information gathered?**—data can vary from Raw 3-D coordinates; CAD models and surfaces; deformation and movement; Reverse Engineering-data; plus the tracking of moving objects;
- **How do these Laser Trackers work?**—Trackers operate by being based on the combination of two techniques: (i) a laser interferometer to measure relative distance; (ii) optical encoders to measure azimuth and elevation of a beam-steering mirror. Linear interferometers are a standard industrial measurement tool, working on the principle of light interference. In a standard Michelson interferometer setup, a coherent light source (i.e. from the laser) is split into two beams. One beam is used as a reference while the other beam is reflected-back from a mirror, or retro-reflector at some distance. This beam is then merged with the reference-beam, thereby producing interference. These interference-fringes are then counted as the external path-length changes. Since the wavelength of the laser is known and is highly stable, the distance can be calculated from the number of fringes. These devices are restricted to linear measurement. A Laser Tracker overcomes this limitation, by using a beam-steering mirror to direct the laser beam in a wide range of directions. The critical-task is for the beam to follow the movement of a retro-reflective target. This is achieved by a feedback loop. When the laser beam hits the retro-reflective target off-centre, it is reflected back, parallel to the incident beam, but will be displaced. A two-dimensional sensor will then measure this displacement, allowing the Tracker to adjust the beam-steering mirror to return the beam to its desired coaxial-state. Tracking mechanism—as described previously—is by using a corner-cube reflector. So, when the beam hits the centre of the target it returns without displacement, indicating the beam has hit the correct location. This mechanism

allows the laser beam to follow the movement of the target—by up to 5 m s^{-1}. Hence, the tracker follows a retro-reflective target, recording the distance; azimuth; plus its elevation. These polar co-ordinates are transformed into Cartesian coordinates, which can be centred anywhere in the measurement-space;

- **Laser trackers how do they operate?**—the operator simply walks around the object being measured, placing the retro-reflective target in positions to be recorded. Care must be taken not to break the beam from the laser tracker to the target, since the distance-count kept by the interferometer will be lost. If this happens, the target must be returned to a reference-position to reset the co-ordinate system. An additional feature is that some Trackers also have a secondary method of distance measurement that can be utilised to measure-arrays of mounted-targets. The tracker points the beam towards a given retro-reflector, and then a spiral-search pattern is used to establish a lock onto the hunted-target. The distance can then be measured without the interferometer and the process repeated. In this manner, a machine's structure, or assembly can be monitored for deformation, or movement without the Inspector being near the instrument. Alternatively, the Inspector can re-establish the interferometer-tracking once again, without going-back to the instrument. The accuracy of what is sometimes known as the absolute distance metre (ADM) is of the order of 50 μm. A camera can be utilised with at least one laser tracker, where the user can use a video-camera to view the object being measured and for the respective measurement-points to be selected. A hidden point device allows the user to measure using a small probe, instead of the relatively large spheres that typically range from 12.7 to 37.5 mm;
- **What are the benefits of this system?**—these benefits can include intuitive—here, an operator places the target anywhere a co-ordinate is required; fast—each data-point can be recorded in a few seconds; single-user—one device with an Inspector can record points working alone; range—typically over tens of metres, creating a large working volume; together with a reasonably large installed user-base in high-value operations;
- **What are the limitations of this system?**—the limitations include occlusion—this can only operate in line-of-sight, so by breaking the beam, it requires resetting the co-ordinate system; contact—the target must physically touch the measured-point; offset—must be recorded, with the co-ordinates being offset from the actual surface; target size—therefore the size of the retro-reflector limits the minimum radius of curvature measurable; static scene—the scene must remain static as the points are measured; environment—any changes in air temperature, pressure and humidity can affect measurements; cost—a Tracker is an expensive piece of equipment; portability—the Tracker is relatively large and heavy, making it unsuitable for some applications; ruggedness—the Tracker is a high precision piece of equipment and is unsuitable for use in many hazardous, dirty or unstable environments.

(Source (adapted): The questions and answers provided herein, plus for any further additional information, concerning these laser trackers, contact: **Optical Metrology Centre**, Bishop's Stortford, Herts, UK).

2.6.3 Laser Tracker—Machine-Based Research Applications

Machine Tool

In Fig. 2.19, is depicted a relatively new technique for the volumetric-verification of machine tools—in this case for a vertical machining centre. Beyond the consideration for a specific machine, a general verification methodology can be utilised to verify the number and movement of axes and by employing different techniques with a Laser Tracker. Therefore, a schematic and kinematic model—with the inclusion of the measurement system depending on the kinematics of the machine—can be achieved.

In this situation when utilising a laser tracker, the model describes the geometry and kinematics of an industrial machining centre, based upon a parametric synthetic data generator, which generates a test with known geometric errors and noise—enabling it to study different optimisation techniques and models. Likewise, dissimilar errors and identification techniques, plus volumetric verification models, can be obtained and analysed. This laser tracking research highlights the improvement that can occur in verification by considering optimisation-phases, the appropriateness of using new techniques of feedback and, the influence of optimisation-parameters. In this noted tracking research work, the use of Chebyshev polynomials[23] and its characteristics were employed, as well as a regression-function for the new verification model for the machine tool. Therefore, this newly developed Laser Tracking volumetric verification technique enables

[23]**Chebyshev polynomials**: are named after Pafnuty Lvovich Chebyshev, who was a brilliant Russian Mathematician (Born: 16 May 1821, Borovsk, died: 8 December 1894, Saint Petersburg, Russia). Chebyshev was educated at the Moscow State University. He introduced a sequence of orthogonal-polynomials which are related to: de Moivre's formula, which can be defined-recursively. One usually distinguishes between **Chebyshev polynomials—**of the first kind which are denoted 'T_n' and, **Chebyshev polynomials—**of the second kind, which are denoted 'U_n'. The letter 'T' is normally utilised, because of the alternative transliterations of the name Chebyshev—as Tchebycheff. These Chebyshev polynomials 'T_n', or 'U_n' are polynomials of degree 'n' and, the sequence of Chebyshev polynomials of either kind, composes a polynomial-sequence. As a consequence, these Chebyshev polynomials are polynomials with the largest possible leading-coefficient, but subject to the condition that their absolute value is bounded by the interval of: '1'. Hence, these Chebyshev polynomials are important in Approximation-theory, because the roots of these Chebyshev polynomials—of the first kind, which are also known as: Chebyshev-nodes, that are utilised as nodes in polynomial-interpolation. The resulting interpolation-polynomial, minimises the problem of what is termed Runge's-phenomenon (These various types of phenomenon and their associated equations, are somewhat outside the remit of the present metrological/calibration text, but are well-documented in the relevant and associated texts) and provides an approximation that is close to the polynomial of best approximation to a continuous-function under the maximum-norm. This approximation, then leads one directly to the method known as the: Clenshaw–Curtis quadrature (These various types of phenomenon and their associated equations, are somewhat outside the remit of the present metrological/calibration text, but are well-documented in the relevant and associated texts). So, in the study and usage of differential equations, they arise as the solution to these Chebyshev differential equations:

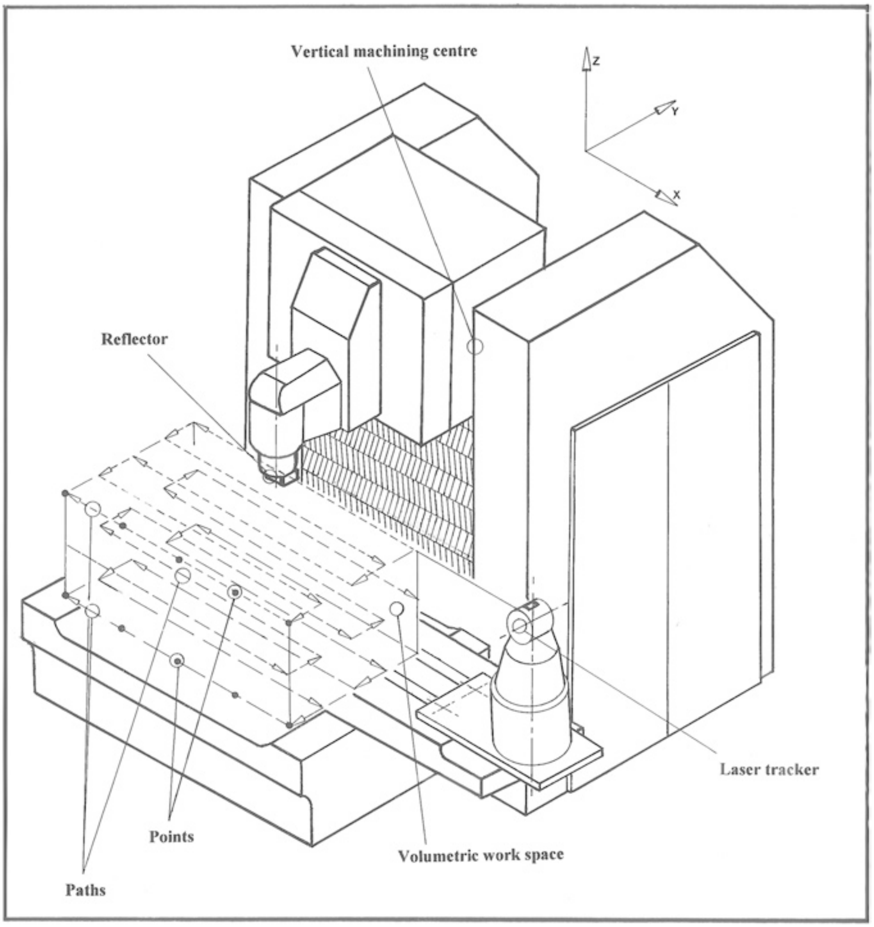


Fig. 2.19 The schematic arrangement for the volumetric verification of a machining centre *utilising laser tracking for the 'parametric generator test'* (Adapted from: Aguado, Samper, Santolaria and Aguilar, in: Int. J. Mach. Tools Manuf., Feb. 2012)

the characterisation of the different errors in the whole volumetric-workspace of the machine and in somewhat less time than by the more usually- employed direct laser and conventional optical verification methods.

Footnote 23 (continued)

$$\text{thus:}\quad \left(1 - x^2\right)y'' - xy' + n^2y = 0$$

$$\text{and:}\quad \left(1 - x^2\right)y'' - 3xy' + n(n+2)y = 0$$

for the polynomials—of the first and second kind, respectively.
NB The above equations are special cases of the: Sturm–Liouville differential equation (These various types of phenomenon and their associated equations, are somewhat outside the remit of the present metrological/calibration text, but are well-documented in the relevant and associated texts).

Coordinate Measuring Machine

In Fig. 2.20 is schematically depicted a Laser Tracker, being employed for the technique of error-mapping a cantilevered CMM, based upon the concept that two-, or three-dimensional positions can be determined-exclusively from high-precision interferometric distance measurements, which is termed Multi-lateration. Here, all the relevant CMM distances are measured utilising a single conventional Tracker, with it being placed in four positions—see Fig. 2.20a. The CMM's errors are determined by creating a virtual-plate, which is comparable with a Ballplate—see Chap. 5 for more details of a typical Ballplate's geometry. The so-called virtual-plate is a set of reference positions, which are calculated from a large number of interferometric measured changes in length. As a consequence, a special-purpose optical retro-reflector unit (i.e. a turntable triple mirror) is mounted to the ram of the CMM, instead of the usual probing-head. In position, the laser tracker will then control the orientation of the triple-mirror, so that its open-side always points toward the direction of the laser beam. To achieve this relative mirror-motion, the mirror is rotated by a stepper motor, so that it prevents interruption of the interferometric signal, even when, for example the Tracker is located inside the bottom boundaries of this virtual-plate.

When mapping the CMM for its geometric errors, the machine moves the mirror into predefined positions in the horizontal and vertical planes—see Fig. 2.20a. When measuring in the horizontal plane for example, the Tracker at A is placed approximate to that plane for reasons of accuracy, and then it follows the movements of the CMM automatically. So, at position P_i for example, the CMM stops for between 5 and 10 s, until vibrations of the CMM have decayed—when the CMM's scales are read. The control programme of the Tracker automatically detects that the CMM has stopped, then it statically records the distance to the mirror. Thereafter, the Tracker once again changes into the dynamic measuring mode before the CMM starts to move the mirror to the next position to be measured. This motion-and-measurement activity continues until $\approx$50 points have been measured—forward and backward—taking <25 min—see Fig. 2.20c, d. After the first series of runs, it is necessary to reposition the Tracker to at least two other CMM-locations (i.e. B and C—see Fig. 2.20a)—it is normally beneficial to take a reading at the fourth position D, providing more accurate readings. The complete measurement process for the whole virtual-plane (i.e. over a relatively large surface area of 2×5 m)—see Fig. 2.20c—takes approximately 2 h, which will include the tracker-repositioning.

The evaluation procedure is based upon the measurement changes of lengths to a set of points from different positions, assuming that each set of changes of distances was sampled to the same set of pre-defined nominal positions—the mathematics and results of these tests are somewhat detailed and they appear in the appropriate reference at the end of this chapter. For this large CMM, its verification and full error-analysis is based upon the previously mentioned concept of Multi-lateration, which has proven to be quite a successful measurement

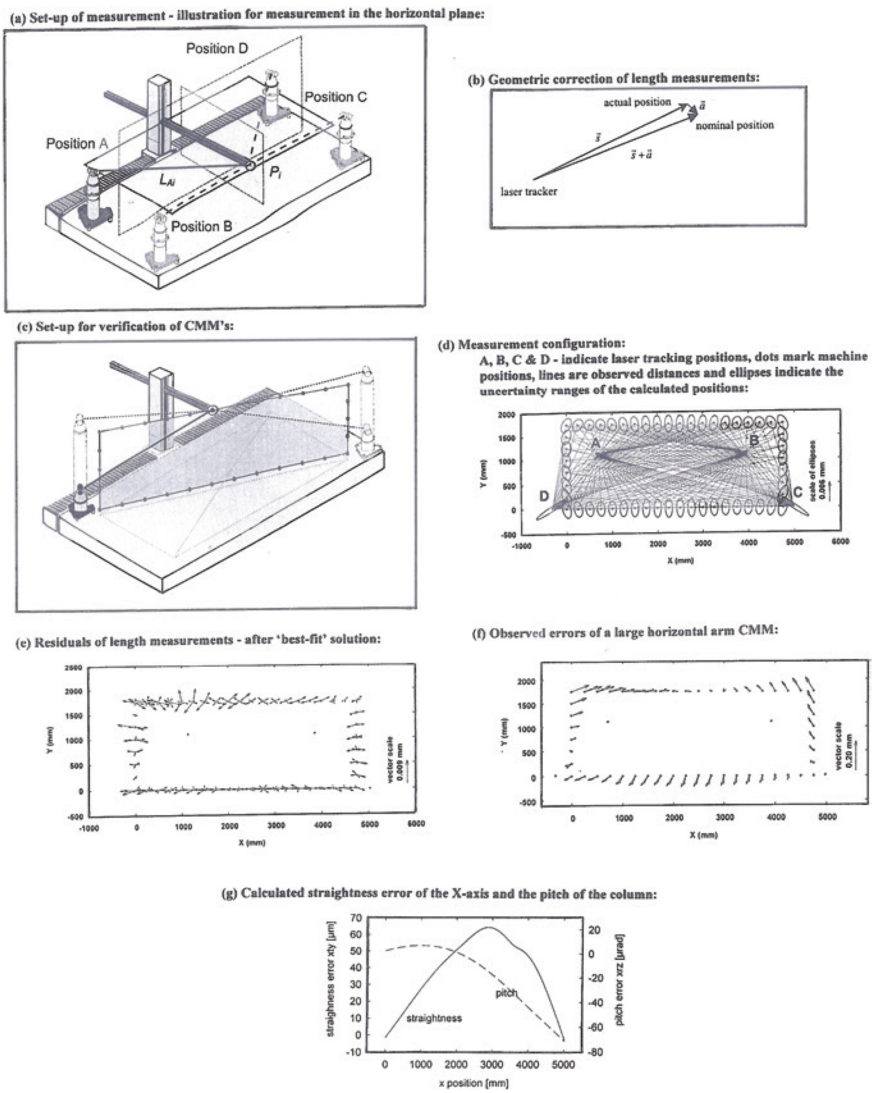


Fig. 2.20 The inspection of large-scale co-ordinate measuring machines (CMM's) by single multi-lateration, utilising a single laser tracker (After: Wendt, Schwenke, Bösemann and Dauke, 2003)

process—by employing the so-called Ballplate method, utilising a single Laser Tracker in this process—see Fig. 2.20. This measurement-technique allows one to systematically map all of the geometric errors for the CMM.

References

Journal and Conference Papers

Aguado, S., Samper, D., Santolaria, J. & Aguilar, J.J., *Identification strategy of error parameter in volumetric error compensation of machine tool based on laser tracker measurements*, Int. J. of Mach, Tools and Manufacture, Vol. 53 (1), 160-169, 2012.

Aguado, S., Samper, D., Santolaria, J. & Aguilar, J.J., *Machine Tool Rotary Axis Compensation Trough Volumetric Verification Using Laser Tracker*, Procedia Engineering, Vol. 63, 582-590, 2013.

Aguado, S., Santolaria, J., Samper, D. & Aguilar, J.J., *Influence of measurement noise and laser arrangement on measurement uncertainty of laser tracker multilateration in machine tool volumetric verification*, Precision Engineering, Vol. 37 (4), 929-943, Oct. 2013.

Bartscher, M., et al, *Artefact based traceability concept for large co-ordinate measuring machines*, Proc. of 9th Metrology Congress, Bordeaux (France), 158-161, 1999.

Birch. K.P. & Downs, M.J., *An updated Edlén equation for the refractive index of air*, Metrologia, Vol. 30, 155-162, 1993.

Birch, K.P. & Downs, M.J., *Correction to the updated Edlén equation for the refractive index of air*, Metrologia Vol. 31, 315-316, 1994.

Bridges, B., *How Laser Trackers Work*, Quality Digest, June 25, 2009.

Burge, J.H., Su, P., Zhao, C. & Zobrist, T., *Use of a commercial laser tracker for optical alignment*, Proc. of SPIE Vol. 6676 (66760E), 2007.

Burdekin, M., *Performance assessment of machine tools and co-ordinate measuring machines – some recent developments at UMIST*, Proc. of LAMDAMAP V Int. Conf., WIT Press, 91-104, 2001.

Callaghan, R., *Method for establishing machine tool performance specifications from part tolerance requirements*, Proc. of LAMDAMAP VI Int. Conf., WIT Press, 507-516, 2003.

Cedelnik, M., Sokovic, M. & Jurkovic, J., *Calibration and Checking the Geometrical Accuracy of a CNC Machine-Tool*, J. of Mech. Eng'g, Vol. 52 (11), 752-762, 2006.

Chapman, M.A.V., *Limitations of laser diagonal measurements*, Precision Engineering Vol. 27, 401–406, 2003.

Ciddor, P.E., *Refractive index of air: new equations for the visible and near infrared*, Appl. Optics, Vol. 35, 1566-1573, 1996.

Edlén, B., *The refractive index of air*, Metrologia, Vol. 2, 71-80, 1966.

Ekinovic, S., Prcanovic, H. & Begovic, E., *Calibration of machine tools by means of laser measuring systems*, Asian Transactions on Engineering, Vol. 2 (6), 17-21, Jan. 2013.

Gull, M., *Developments in BSI and ISO machine tool accuracy standards*, Proc. of LAMDAMAP III Int. Conf., 79-89, Computational Mechanics Pub., 1997.

Hale, L.C., *Principles and Techniques for Designing Precision Machines*, Doctor of Philosophy (Mechanical Engineering), Massachusetts Institute of Technology, 1999.

Hargreaves, B., *Measuring up*, Professional Eng'g., 71-73, April 2015.

Hof, A., *Theorie und Realisierung eines Abbé-Fehler-freien, selbst-kalibrierenden räumlichen Wegmeßsystems,* Fortschr. Ber. VDI Reihe 8, Nr. 134, VDI-Verlag, Düsseldorf, 1987.

Hong, C., Ibaraki, S. & Oyama, C., *Graphical presentation of error motions of rotary axes on a five-axis machine tool by static R-test with separating the influence of squareness errors of linear axes*, Int. J. of Mach. Tools and Manufact., Vol. 59, 24-33, Aug. 2012.

Ibaraki, S. & Hata, T., *A new formulation of laser step diagonal measurement – Three-dimensional measurement*, Precision Eng'g., Vol. 34, 515-525, 2010.

Iwasawa, K., Iwamaa, A. & Mitsui, K., *Development of a measuring method for several types of programmed tool paths for NC machine tools using a laser displacement interferometer and rotary encoder*, Prec. Eng,g, Vol.28, 399-408, 2004.

Knapp, W., *Test of the three-dimensional uncertainty of machine tools and measuring machines and its relation to the machine errors*, ETH Zurich, 459-464, 1993.

Knapp, W., *Interim checks for machine tools*, Proc. of LAMDAMAP III Int. Conf., Computational Mechanics Pub., 161-168, 1997.

Koelsch, J.R., *Should Laser Trackers be in your Arsenal of Metrological Tools?*, Quality Magazine, March 2012.

Kunzmann, H., Pteifer, T. & Flügge, J., *Scales vs. Laser Interferometers – Performances & Comparison of Two Measuring Systems*, Vol. 42 2), 753-767, 1993.

Kuric, I., Košinár, M. & Cisár, M., *Measurement and analysis of CNC machine tool*[s] *accuracy in different location*[s] *on work table*, Proceedings in Manufacturing Systems, Vol. 7 (4), 2012.

Lau K.C & Hocken, R.J., *Three and Five Axis Laser Tracking Systems*, United States Patent 4,714,339, 1987.

Longstaff, A.P., Fletcher, S. & Ford, D.G., *Practical experience of thermal testing with reference to ISO 230 Part 3*, Proc. of LAMDAMAP VI Int. Conf., WIT Press, 473-484, 2003.

Okafor, A.C & Ertekin, Y.M., *Vertical machining center accuracy characterization using laser interferometer, Part 1. Linear positional errors*, J. of Matls. Process. Technol., Vol. 105, 394-406, 2000.

Peták, T. & Kureková E., *Calibration of Biaxial NC positioning table*, Trans. of the VŠB – Tech. Univ. of Ostrava (Slovak Republic), Mechanical Series, Vol. LVIII (2), article No. 1922, 55-74, 2012.

Portable laser tracker measures large volumes accurately, Machine Design, Vol. 83 (14), 19, Aug. 25, 2011.

Santolaria, J., Majarena, A.C., Samper, D., Brau, A. & Velázquez, J., *Articulated Arm Coordinate Measuring Machine Calibration by Laser Tracker Multilateration*, The Scientific World Journal, Vol. 2014, Article ID 681853, 2014.

Schwenke H, et al., *Geometric error measurement and compensation of machines–An update*, Annals of the CIRP, Manufact. Technol., 57 (2), 660-675, 2008.

Smith, G.T., *Condition Monitoring of Machine Tools*, Chapter 9, in: Handbook of Condition Monitoring (1st Ed.), Elsevier Advanced Technology Pub., 170-207, 1996.

Soons, J.A., *Measuring the geometric errors of a hexapod machine tool*, Proc. of LAMDAMAP IV Int. Conf., WIT Press, 169-192, 1999.

Soons, J.A., *Analysis of the step-diagonal test*, Proc. of LAMDAMAP VII Int. Conf.,126-137, 2005.

Svoboda, O., *Volumetric positioning accuracy of a vertical machining center equipped with linear drives (evaluated by laser vector method)*, Proc. of LAMDAMAP VI Int. Conf., WIT Press, 141-150, 2003.

Svoboda, O., *Testing the diagonal measurement technique*, Precision Engineering, Vol. 30, 133-144, 2006.

Tomkinson, G., *Fitting laser interferometers to large machine tools as the primary positioning feedback system*, Proc. of LAMDAMAP III Int. Conf., Computational Mechanics Pub., 205-213, 1997.

Trapet, E. & Wäldele, F., *A reference object-based method to determine the parametric error components of co-ordinate measuring machines*, Measurement, Vol. 9, 17-21, 1991.

Ueno, S. & Matsumaru, S., *Evaluation of numerically controlled machine tool positioning accuracy*, Proc. of LAMDAMAP VI Int. Conf., WIT Press, 485-494, 2003.

Wendt, K., Schwenke, H., Bösemann, W. & Dauke, M., *Inspection of large CMMs by sequential multi-lateration using a single laser tracker*, Proc. of LAMDAMAP VI Int. Conf., WIT Press, 121-139, 2003.

Wang, C., *Laser vector measurement technique for the determination and compensation of volumetric positioning errors, Part 1: Basic theory*, Review of Scientific Instruments, Vol. 71 (10), October, 2000.

Wang, C. & Liotto, G., *A laser non-contact measurement of static positioning and dynamic contouring accuracy of a CNC machine tool*, Proceedings of the Measurement Science Conference, Los Angeles, 24-25, Jan. 2002.

Wang, C. Liotto, G., *A theoretical analysis of 4 body diagonal displacement measurement and step diagonal measurement*, Proc. of LAMDAMAP VI Int. Conf., WIT Press, 463-472, 2003.

Wang, C., *Machine tool calibration: standards and methods*, American Machinist, Jan. 2009.

Yin, J., Pan, F. & Li, M., *Accuracy Calibration of a Five Axis Gantry Machine Tool Using Laser Tracker*, International Conference on Convergence Information Technology, Vol.19, 2012.

Books, Booklets and Guides

AIA/NAS, NAS 979 Uniform Cutting Tests, *NAS Series Metal Cutting Equipment Specifications*, 1969.

ANSI/ASME B5.57, *Methods for Performance Evaluation of Computer Numerically Controlled (CNC) Lathes and Turning Centers*, 1998.

ANSI/ASME B5.54, *Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers*, 2005.

ASTM E105: *Standard Practice for Probability Sampling of Materials*.

ASTM E122: *Standard Practice for Calculating Sample Size to Estimate, With a Specified Tolerable Error, the Average for Characteristic of a Lot, or Process*.

ASTM E141: *Standard Practice for Acceptance of Evidence Based on the Results of Probability Sampling*.

ASTM E1402: *Standard Terminology Relating to Sampling*.

ASTM E1994: *Standard Practice for Use of Process Oriented AOQL and LTPD Sampling Plans*.

ASTM E2234: *Standard Practice for Sampling a Stream of Product by Attributes Indexed by AQL*.

Bobroff, N. & Estler, W.T., *Interferometric Metrology*, Pub. by American Society for Precision Engineering, 1992.

Bucher, J.L., *The Metrology Handbook, Second Edition*, ASQ Quality Press, 2012.

Chapman, M.A.V., *Environmental compensation of linear laser interferometer readings*, Technical White Paper: TE329, Renishaw plc, 2013.

Chapman, M.A.V., Fergusson-Kelly, R. & Lee, W., *Interferometric straightness measurement and application to moving table machines*, Technical White Paper: TE325, Rensihaw plc, 2013.

Chapman, M.A.V., Fergusson-Kelly, R., Holloway, A. & Lee, W., *Interferometric angle measurement and the hardware options available from Renishaw*, Technical White Paper: TE326, Renishaw plc, 2013.

Crouch, S. & Skoog, D. A., *Principles of Instrumental Analysis*, Pub. by Pacific Grove: Brooks Cole, 2007.

Dotson, C., *Fundamentals of Dimensional Metrology*, Pub. by Thomson Delamar Learning 5th Ed. (2006), 6th Ed. (Feb. 2015).

Flack, D., CMM Verification, Good Practice Guide No. 42, NPL Publication.

Flack, D. & Hanniford, J., *Fundamental Good Practice in Dimensional Metrology*, Good Practice Guide No. 80, NPL Publication.

Galyer J.F.W. & Shotbolt, C.R., *Metrology for Engineers* (5th Ed.), Cassell Publishers Ltd., London, 1990.

Golz, H.U., *Analyse Modellbildung und Optimierung des Betriebsverhaltens von Kugelgewindetrieben*, Dissertation for the University of Karlsruhe, 1990.

Harihanan, P., *Basics of Interferometry*, Academic Press Inc. (Australia), 1991.

Hemming, B., *Measurement Traceability and Uncertainty in Machine Vision Applications*, MIKES Metrology, Espoo (Finland), 2007.

ISO 2859-1:1999: *Sampling procedures for inspection by attributes*.

JCGM 200:2008, *International vocabulary of metrology - Basic and general concepts and associated terms*, (VIM).

Kakino, Y., Ihara, Y. & Shinohara, A., *Accuracy inspection of NC machine tools by double ball bar method*, Ed. by Johannes Heidenhain (GmbH), Hanser Gardner Publications, Munich, 1993 .

Montgomery, D. C., *Statistical Quality Control: A Modern Introduction*, Wiley Pub., 2009.

Metrology Handbook - The Science of Measurement, Pub. by Mitutoyo, 2013.

Pennella, C.R., *Managing the Metrology System*, ASQC Quality Press - 2nd Ed. (USA).

Schmitt, T., *Modell der Wärmeübertragungsvorgänge in der mechanischen Struker von CNC-gesteuerten Vorschubsystemen*, Shaker publishing house, 1996.

Smith, G.T., *Industrial Metrology – Surfaces & Roundness*, Springer Verlag Pub., 2002.

Wilkening, G. & Koenders, L., *Nanoscale Calibration Standards and Methods: Dimensional and Related Measurements in the Micro and Nanometer Range*, Pub. by Wiley-VCH Verlag (GmbH), 2005.

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