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SURVEY OF MACHINE TOOL ERROR MEASURING METHODS

This paper presents the factors and needs which make it necessary to increase the accuracy of machine tools. Types of machine tool errors, their causes and ways of identifying, measuring, reducing and compensating them are described. The most effective methods of identifying machine tool errors are discussed and classified. The measuring methods and tools are compared with regard to their range of application, time consumption, cost, market availability and main limitations.

1. INTRODUCTION

The improvement of cutting machine tools, dictated by product market needs, leads to an increase in their broadly understood productivity, particularly their accuracy, cutting speed and flexibility, and to the minimization of the cost of machine tools and that of the machining processes carried out by them. The accuracy of machine tools is increased through the introduction of innovative designs, control and software and by reducing and compensating errors. The different types of errors need to be accurately identified through measurements, modelling and numerical simulations. The more complex (because of their high-speed and multiaxis operation, multitasking and intelligent functions) the machine tools are, the more difficult it is to measure the particular error components and the more advanced methods are required for this purpose. It is often necessary (periodically or in real time) to combine the measurement of errors with their compensation and with the active correction of machine tool accuracy. Some measurements, especially the ones relating to geometry (subject to considerable deterioration in the course of machine tool service), are critical for correcting it, improving the servicing process and increasing the lifetime of machine tools. Therefore it is necessary to continuously diagnose accuracy in machine tool operating conditions, i.e. to measure it under considerable interference from thermal and dynamic loads and the machining process. This paper presents an analysis of the useful properties of the state-of-the-art measuring methods and devices available to the

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manufacturers and users of machine tools, and their solutions being currently experimentally verified. The design and measuring capabilities, including maximum accuracies and limitations, of the measuring methods and devices are highlighted.

2. GENERAL DESCRIPTION OF MACHINE TOOL ERRORS

A machine tool error can be defined as the difference between the actual tool position and the programmed one. The difference is the result of errors in the machine tool itself, control and measuring system errors and errors arising from the manufacturing process or the environment.

All the machine tool errors can be generally divided into two categories depending on the way they affect machine tool precision, i.e. into systematic and random errors. Regardless of their type (geometric, kinematic, thermal and control), systematic errors can be compensated with an accuracy depending mainly on their identification precision and the rate of their change. It is difficult to correct quickly changing errors, such as position errors caused by high accelerations of the rotating and sliding components.

The sources of errors, which should be included in a machine tool error model, can be described using the two groups of models (Fig. 1):

- ✓ error models mainly based on the identification of post-assembly machine tool errors (geometric errors (GE) and kinematic errors (KE)); such errors are machine-specific, i.e. determined by machine workmanship, assembly and tuning;
- ✓ the other models of errors (E1-E3 arising from loads and E4-E6 arising from heat) determined using computer simulations and artificial intelligence tools while the actual features of the machine are taken into account when fine-tuning the models using sensors installed in the machine tool structure, or measuring-testing equipment.

A model of the volumetric machine tool error should take into account its variation in space and time and constitute a synthesis of the two groups of models, i.e. models based on machine tool test measurements and models based on simulation studies aided by experiments.

Geometric-kinematic errors can be minimized through the choice of a proper geometric-motion structure, the use of high-quality subassemblies and the precise assembly of the subassemblies and the whole machine tool [30]. In this way one of the chief sources of imprecision of current CNC machine tools can be limited [48]. However, this solution is very costly. Geometric errors include shape errors and errors in the mutual position of surfaces. Kinematic (motion) errors are deviations from the required relative motions of the main machine tool assemblies. They also adversely affect the precision of the motion resulting from the simultaneous operation of several controlled axes [23]. In the case of a well designed and made machine, kinematic errors are highly repeatable [46], which makes their compensation easier.

Variation in the temperature of the machine tool's subassemblies caused by their work or the environmental impact is the cause of its (usually significant) thermal errors. In many cases, errors of this kind determine the accuracy of the part being machined [23].

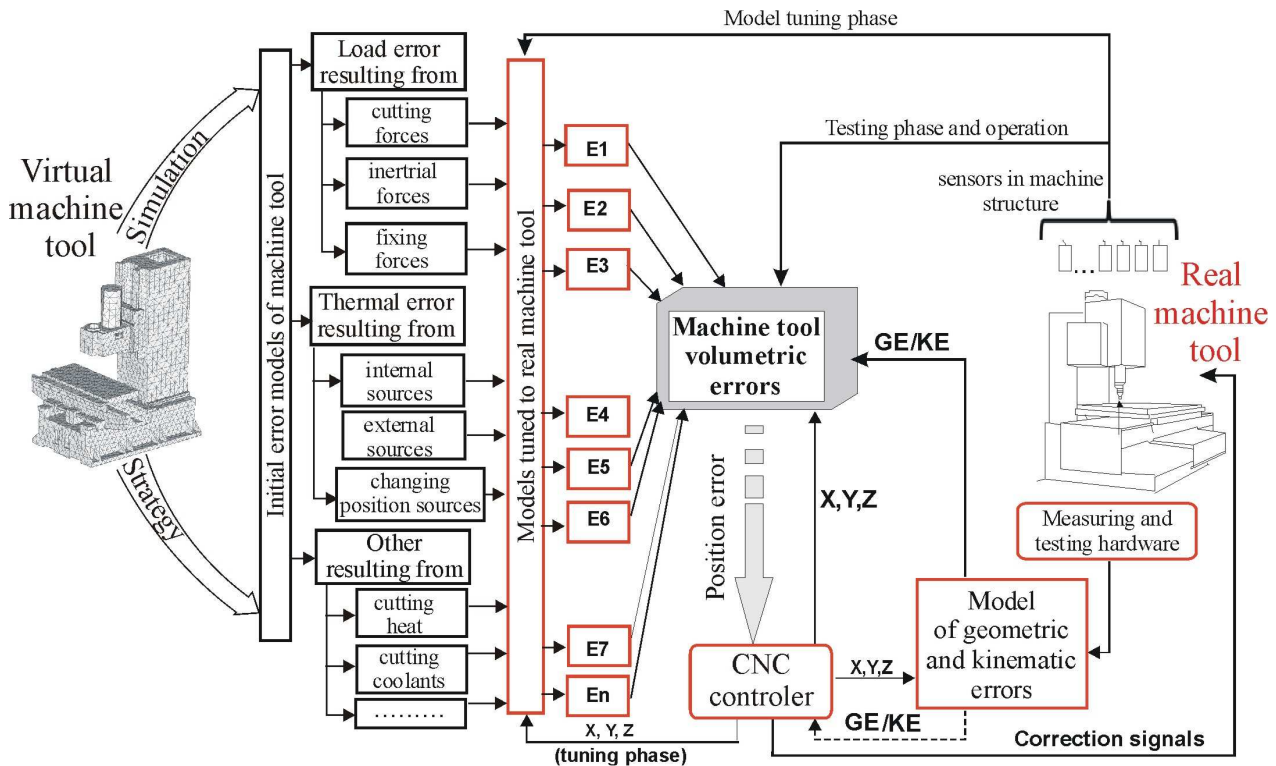


Fig. 1. Sources of errors affecting volumetric machine tool error

Temperature variations are generated by different heat sources, such as:

- motors, especially in controlled axis drives;
- bearings, especially spindle bearings;
- couplings and gears, especially rolling gears;
- pumps and hydraulic oil;
- the machining process;
- mechanical and mechatronical hardware of different type, including actuators and control systems.

The effect of the above heat sources on machine tool accuracy depends on their location relative to casings and tool and workpiece fixtures, and on their intensity [18]. Generally, the particular contributions to the machine tool error are directly proportional to the temperature rise and the thermal expansion coefficient of the material of the heated components. For steel this coefficient amounts to about 0,01 mm/m for each °C, which means that when the temperature of, e.g., the leading screw changes by 10°C, a dimensional change amounting to 0,1 mm per each meter of its length will result. For this reason, attempts have been made [13],[14] to use special composite materials with a much lower linear expansion coefficient than that of steel, such as composites of silicon carbide and its derivatives whose expansion coefficient is below 0,003 mm/m per each °C. This improves

the machine tool's accuracy, but increases the cost of its manufacture [22]. It is more advantageous to use correction and compensation through a proper function and the control system to reduce thermal errors. Good results can be achieved if mathematical models of error versus temperature (measured by an appropriate number of sensors located within the machine tool structure) and a regression function are employed [35],[43]. This method is called the sensor method. There is also another method (being studied by the authors) which is based on signals received from sensors installed by the manufacturer directly in the linear and rotary motors of the controlled axes, mainly for the needs of the NC system monitoring the operation of the drives.

Besides the above heat sources present in the machine tool, also the temperature on the floor shop and the accumulation of heat in the machine tool's closed spaces (including the ones closed with covers) affect its precision. Even in the stationary state (when none of the drives is switched on) a change in ambient temperature by a few degrees Celsius may result in spindle displacement by as many as tens of micrometers, depending on the thermal stability of the given machine tool. For this reason, efforts are made to make modern machine tools as thermally stable as possible. This is done through proper design ensuring the structure's thermal symmetry and reducing heating by forced cooling in the field of action of large heat sources. Error compensation in the case of such a machine tool is much easier. Through an analysis of the thermal behaviour of the machine tool, based on a thermal model and numerical simulations, one can determine which of the structural components are responsible for which thermal error components and where temperature sensors should be located to ensure effective compensation.

In the case of numerical simulations, it is quite difficult to take into account the changes in heat generation intensity and heat transfer, connected with the manufacturing process. During its operation the machine tool continually heats up or cools in a highly complicated way commensurate with the complexity of the processes of heat generation, transfer and accumulation within its structure. As a result, thermal errors in high-speed machine tools have a fast changing nature. Thermal changes in machine tool geometry, determined by computations, are illustrated in Fig. 2.

Errors which arise in the course of operation may be caused by the inaccuracy of the interpolators and the operation of the drives. Servodrives typically work in a feedback loop and never react instantly to a deviation. There is always a certain time lag corresponding to the refresh rate of the controller settings. The matching of this rate to the speed with which the machine tool assemblies can move has a bearing on the kinematic precision of the drives.

The machining process and its impact on the machine tool are mainly responsible for errors caused by vibrations. The magnitude of the errors depends on the process parameters, the dynamic properties of the machine tool and the operation of the kinematic pairs, e.g. bearings and rotary drives. It is very difficult to eliminate such disturbances. Therefore machine tool designers try to reduce dynamic errors already at the design stage and also through novel and more effective methods of active vibration reduction when the machine tool is in service.

As speed is changed in high-speed spindle units, dynamic axial spindle motion (shift) arises, reaching high values whereby it needs to be reduced and compensated. Shift

compensation is based on the computer modelling and simulation of the behaviour of the high-speed spindle assembly [9].

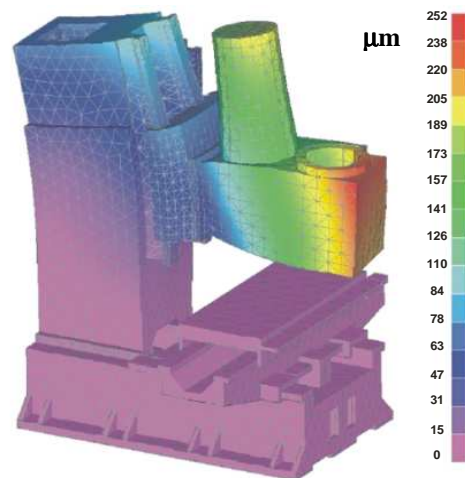


Fig. 2. Computationally determined effect of thermal deformation on machine tool geometry

3. VOLUMETRIC ERROR

Volumetric error is a parameter which best describes machine tool precision. If the Volumetric error is known for the whole workspace one can greatly increase the precision of the manufactured parts through its compensation by the CNC system. The kinds and number of volumetric error components depend on the machine tool design, mainly on the number of controlled linear and rotational axes. Errors which may occur in the controlled axes of machine tools are shown in Fig. 3. Besides these errors, there may also occur squareness errors due to the impact of errors in one axis on errors in another axis.

In the case of a three-axis machine tool with three linear axes there are 21 component errors, 3 of which are the squareness errors of the X, Y, Z axes. The other components are 3 linear (positioning, horizontal and vertical straightness) errors and 3 angular (pitch, yaw, roll) errors for each of the three axes. Many more volumetric error components occur in machine tools with a larger number of axes. For five-axis machines with two rotational axes the number of error components is as high as 43.

According to the conventional definition, a volumetric geometric error in a 3D space, determined by a 1D laser interferometer is an rms average of the three positioning errors in the X, Y, Z axes. Even if this volumetric error is minimized to zero, this does not guarantee the expected machine tool accuracy, since the above definition does not take into account all the error components. The identification of all the 21 error components through linear and angular measurements in points distributed in the whole workspace, by means of a 1D interferometer is unrealistic for time reasons and because of the long thermal action impact of the environment.

The advances made in measuring tools and methods have led to the redefinition of volumetric error. According to ASME B5.54 and ISO 230-6, since 2000 the volumetric

error, besides positioning errors, has also included horizontal and vertical straightness errors and angular (pitch, roll, yaw) errors.

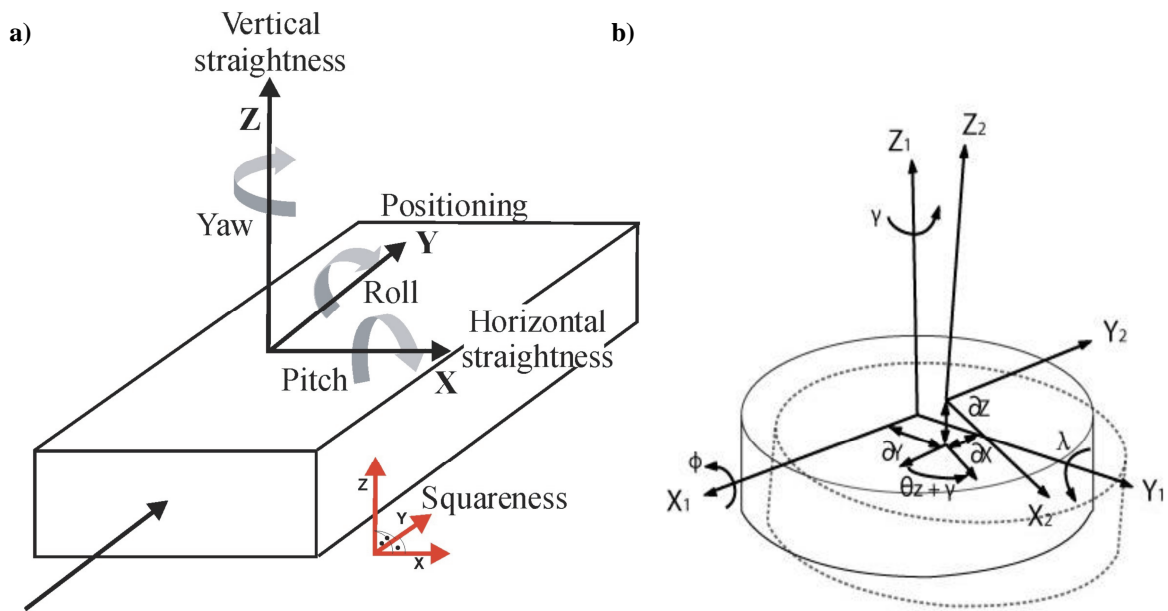


Fig. 3. Errors in controlled axes: a) linear axis, b) rotary axis [12]

As it is increasingly easier to measure and compensate positioning errors, axis squareness and straightness errors begin to predominate. Besides, the measuring devices and methods which are effective for linear axes are rather unsuitable for identifying rotational axis errors. When the number and diversity of error components are very high, it is extremely difficult to determine the volumetric error.

Only the latest technology and measuring methods, such as vector laser bars measuring angular position or tracking laser systems, can meet this challenge. Because of the increasing availability of innovative optoelectronic microcircuits, such as laser diodes, CCD cameras, PSD transducers and so on, relatively inexpensive measuring devices and methods aimed at not the total machine tool error, but at measuring the motion precision of the main assemblies, such as the spindle, the swivel spindle head, the tilting table, etc., are still offered. The errors of these assemblies can be independently compensated or added to the other volumetric error components.

4. INDIRECT METHODS OF DETERMINING VOLUMETRIC ERROR

4.1. GENERAL DESCRIPTION OF METHODS

The range of commercial specialist measuring instruments for measuring the workpiece or evaluating the precision of the machine tool is very wide. These are mainly contact and contactless measuring probes for evaluating the workmanship precision of the

machined product, widely used in the machine-tool industry. Kinematic double ball bars (DBB) and optical cross grids are usually used to quickly identify the machine tool's errors and evaluate its accuracy.

4.2. DOUBLE BALL BAR

One of the tools most commonly used today for testing the shape (roundness) accuracy of three-axis CNC machine tools, are Ballbar systems, such as. QC10, QC20 and DBB 110. In the roundness test the machine tool performs circular motion in a specified plane at set feed rates. As regards hardware and software, this method is developed mainly by Renishaw and Heidenhain. The accuracy of circular motion, also called circular interpolation accuracy, is checked using a kinematic double ball bar placed between the machine tool's table and its spindle. Ballbar QC20-W enables 3D error measurement, i.e. in three orthogonal planes, with no change of the central support (Fig. 4). In one plane (usually XY) full circular interpolation (0° - 360°) is performed while in the other planes (XZ and YZ in this case) measurements are made along a partial arc (maximally 220°). In this way, at one fixing of the instrument the test can be carried out in all the three planes, which greatly speeds up the machine tool accuracy check.

Using the diagnostic test one can identify many errors. Besides the already mentioned roundness deviation, the test can be used to determine backlash, reversal spikes, regular and irregular vibration, the follow-up error, the scale error, the axis squareness error and so on (Fig. 5). A roundness deviation diagram [30], consistent with ISO 230-4:2005 and ASME B5.54-2008, is displayed on the monitor screen. Apart from the roundness deviation value, also the values of the particular errors in min-max intervals and the percentages of the different types of errors in the circular interpolation are displayed. Another parameter describing the quality of a machine tool is positioning accuracy. This parameter contains most of the errors and indicates with what tolerance parts can be manufactured.

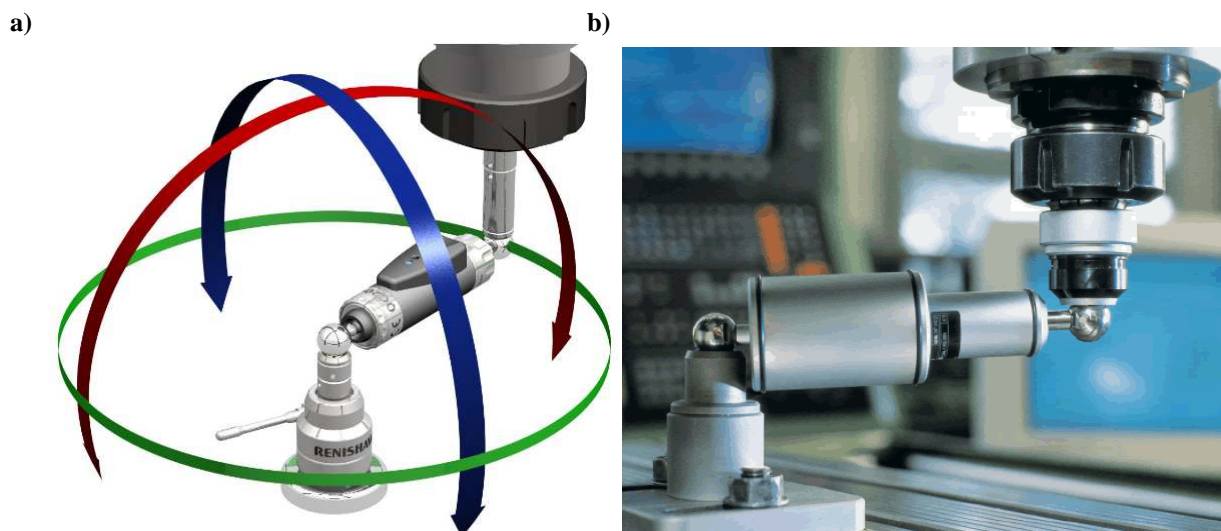


Fig. 4. Measurement of machine tool errors by means of Ballbar instruments: a) QC20-W[58] and b) DBB 110 [56]

Machine tool precision is evaluated on the basis of circular interpolation accuracy and positioning accuracy. The measurements can be analyzed using the Ballbar dedicated software. The subassemblies having the most adverse effect on the precision of a machine tool can be located in it on the basis of the test diagram and the percentages of the particular errors in the circular interpolation. For example, reversal spikes may result from an excessive ball screw/nut clearance, clearance in the toothed gear and especially a too slow servodrives response to the control system signal.

The Ballbar 20 software by Renishaw offers a function called a diagram simulator. It can be used to display test results on the screen and to simulate different modifications of machine tool geometry, clearances and dynamic parameters. Through such simulations the operator can select the optimum machine tool operating parameters, such as the position gain coefficient, which if incorrectly matched causes a follow-up error. Since these are merely simulations one can always be sure that the original data will not be altered. Only when the simulations have ended and the optimum coefficient values have been determined, the latter are entered into the machine tool control. However, this is not possible in every case since machine tool manufacturers do not always provide the possibility of correcting geometry, clearance or dynamic parameters via software. In order to enter altered data one often must switch the machine tool into the service mode, which requires a special service authorization. Other functions available in Ballbar QC 20 are the backup of the data from the particular tests and the creation of test templates [52]. In this way one can find out at what rate the machine tool wears out and on this basis its servicing (repair or replacement of the worn out parts) can be predicted and planned.

The specifications of Ballbar QC 20 are: accuracy $\pm 1,25 \mu\text{m}$, resolution $0,1 \mu\text{m}$ and maximum sampling rate 1000 per second. The error of the distance transducer alone does not exceed $\pm 0,5 \mu\text{m}$. The Bluetooth device enables data transmission for a distance of up to 10 meters. As a result, several problems which arose in the previous generation Ballbar QC 10 (where data were transmitted via a cable which could be damaged or broken) have been eliminated. Moreover, thanks to the wireless transmission of measurement data one can carry out tests while the machine tool workspace shields are closed.

The kinematic Ballbar is a popular tool for machine tool diagnosis, chiefly because it can be used in workshop conditions, is resistant to soiling and the cooling agent, and is quick to use. According to the manufacturer, a full diagnosis of the machine tool can be made within ten minutes. The Ballbar owes its soiling resistance mainly to the fact that it includes no optical systems, whereby it has an advantage over the laser interferometer which incorporates such systems.

Since it was designed for only simple three-axis milling centres and three-axis lathe centres with ball screws and feed drives, the expert system aiding inference about the causes of errors is a serious limitation of the above method. Consequently, only simple circular interpolation tests can be carried out for other machines, both conventional ones and with parallel kinematics.

Another drawback of the Ballbar device is that measurements are taken only in a selected part of the machine tool workspace. Even though the manufacturer offers Ballbars of different length (whereby tests for a circle with a radius of 50-1350 mm can be carried out), still no error map for the whole workspace can be obtained. Moreover, the measuring

path must always have the shape of a circle or its segment. Despite the above drawbacks, the Ballbar enables machine tool diagnostics and does not necessitate long breaks in the manufacturing process, mainly owing to measurement simplicity and speed.

Volumetric Ballbar diagnostics (μm)

Machine: Volumetric examples

Test Parameters

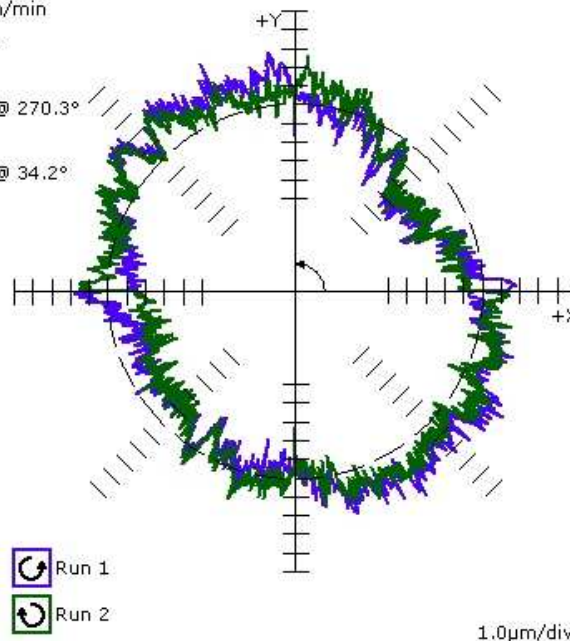
Radius 100.0000mm
Feedrate 1000.0mm/min

Volumetric Test Results

Maximum deviation $7.0\mu\text{m}$
ZX Plane @ 270.3°
Minimum deviation $-5.5\mu\text{m}$
ZX Plane @ 34.2°
Sphericity $12.5\mu\text{m}$

Circularity

XY $7.0\mu\text{m}$
YZ $7.9\mu\text{m}$
ZX $12.5\mu\text{m}$



RENISHAW

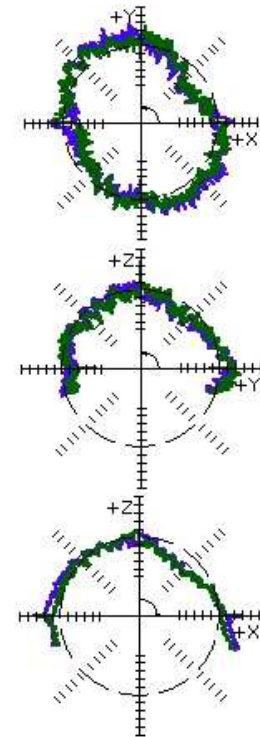


Fig. 5. Exemplary roundness test results [58]

In order for the Ballbar test results to be used for volumetric error compensation, supplementary measurements by other methods need to be taken and proper procedures interrelating the results with the volumetric error components need to be developed. Such procedures are developed as part of research projects [16] and by commercial equipment manufacturers.

4.3. CROSS GRID METHOD

The cross grid method and the KGM grid encoder currently developed by Heidenhain serve mainly the purpose of evaluating static and dynamic machine tool errors. The device consists of a laser scanning head fixed to the spindle and two glass plates with light reflecting and suppressing titanium grids superimposed on them. The plates are mounted on the machine tool table (Fig. 6). The two grids are set perpendicularly to each other, i.e. they cross.

The method makes it possible to distinguish between errors connected with the mechanical structure of a machine tool and the ones relating to the control of the motions of the two axes. When small circle radii are used, control errors predominate while the influence of geometric errors is negligible. At large circle radii one can determine geometric errors more accurately. In the course of measurements, any motions can be performed in the tested planes XY, XZ or YZ. Similarly as in the case of the Ballbar, this test is performed clockwise and anticlockwise to detect the hysteresis connected with the control of the machine tool axes.

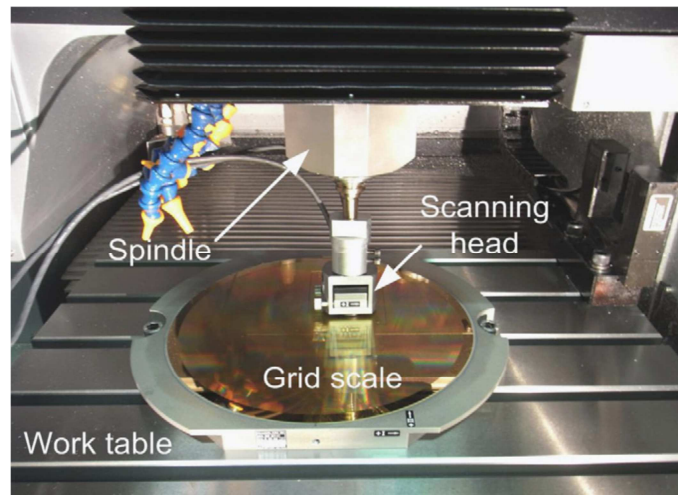


Fig. 6. KGM system setup during measurement of precision machine tool accuracy [46]

In order to transform the KGM grid encoder results into the volumetric error components one needs proper conversion algorithms. Using such algorithms, described in, e.g., [50], one can determine 21 components of the volumetric error for a three-axis machine tool. The algorithms are based on the kinematic error model and use the homogenous transformation matrix (HTM) method. The measuring system's accuracy is estimated at $\pm 2\mu\text{m}$.

5. DIRECT METHODS OF DETERMINING VOLUMETRIC ERROR

5.1. 1D LASER INTERFEROMETER

One of the most precise methods of evaluating machine tool accuracy consists in the construction of an error map for the whole machine tool workspace. For this purpose linear and angular measurements in all the controlled axes of the machine tool need to be performed. Because of its precision, a laser interferometer is used for such measurements [1].

Currently, the simplest laser interferometers can perform measurements in only one axis. They are used to measure linear and angular displacements, flatness, machine tool subassemblies positioning accuracy and so on. Such 1D interferometers are offered by, among others, Hewlet-Packard, Lasertex and Renishaw (Fig. 7). In comparison with the Ballbar, they are characterized by a greater linear measurement accuracy of $\pm 0,5 \mu\text{m/m}$.

In order to measure volumetric error by means of a 1D laser it is necessary to reset the laser head and the optics many times to take linear and angular measurements in each of the controlled axes. In addition, all the measurements should be repeated at least 3-5 times. After each resetting the measuring system must be recalibrated. This means that it takes a few days to determine twenty one components of the geometric error for a three-axis machine tool [38].

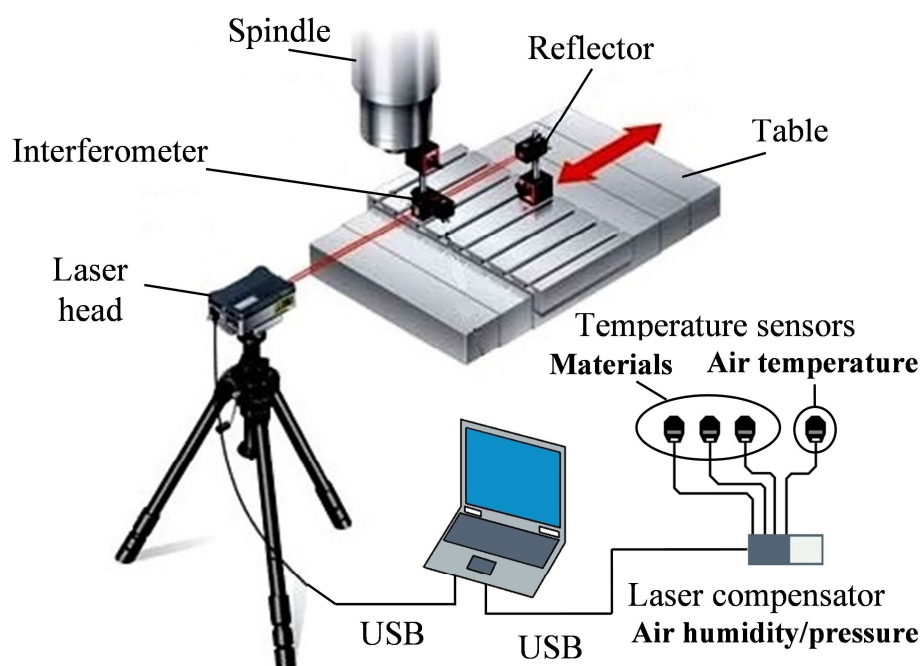


Fig. 7. 1D laser interferometer hardware configuration for linear measurements [61]

It is usually impossible to remove the machine tool from the manufacturing process for such a long time. For this reason, in practice only the most important components are determined whereby the idle time can be reduced, but at the expense of volumetric error evaluation accuracy. Thus it is an imperfect solution which does not allow one to exploit the full potential of the machine tool.

5.2. 3/6D LASER INTERFEROMETER

A 3D interferometer design is usually based on that of the 1D interferometer with added optoelectronic circuits (e.g. CCD cameras, PSDs, four-field detectors) enabling the simultaneous measurement of the lateral motions of the reflector.

During linear interferometric measurements by means of a 3D laser, taken in, e.g., the X axis, analog measurements of $\pm 1\text{mm}$ deviations in axes Y and Z are simultaneously performed using a liquid crystal cell and a four-field detector. Owing to this, the positioning error along the given axis and two errors of the latter's horizontal and vertical straightness are recorded in each point. The accuracy of measurement along the given axis is equal to that of the interferometer, while in the other two axes it is usually lower.

An example of such a design is the laser interferometer with a four-field detector, shown in Fig. 8 [1]. It is a bifrequency interferometer exploiting the heterodyne method and it is intended mainly for measuring the geometry of CNC machine tools and coordinate machines. In the case of bifrequency lasers, laser beam stabilization is of major importance. The stabilization consists in measuring the frequency resulting from the Doppler effect.

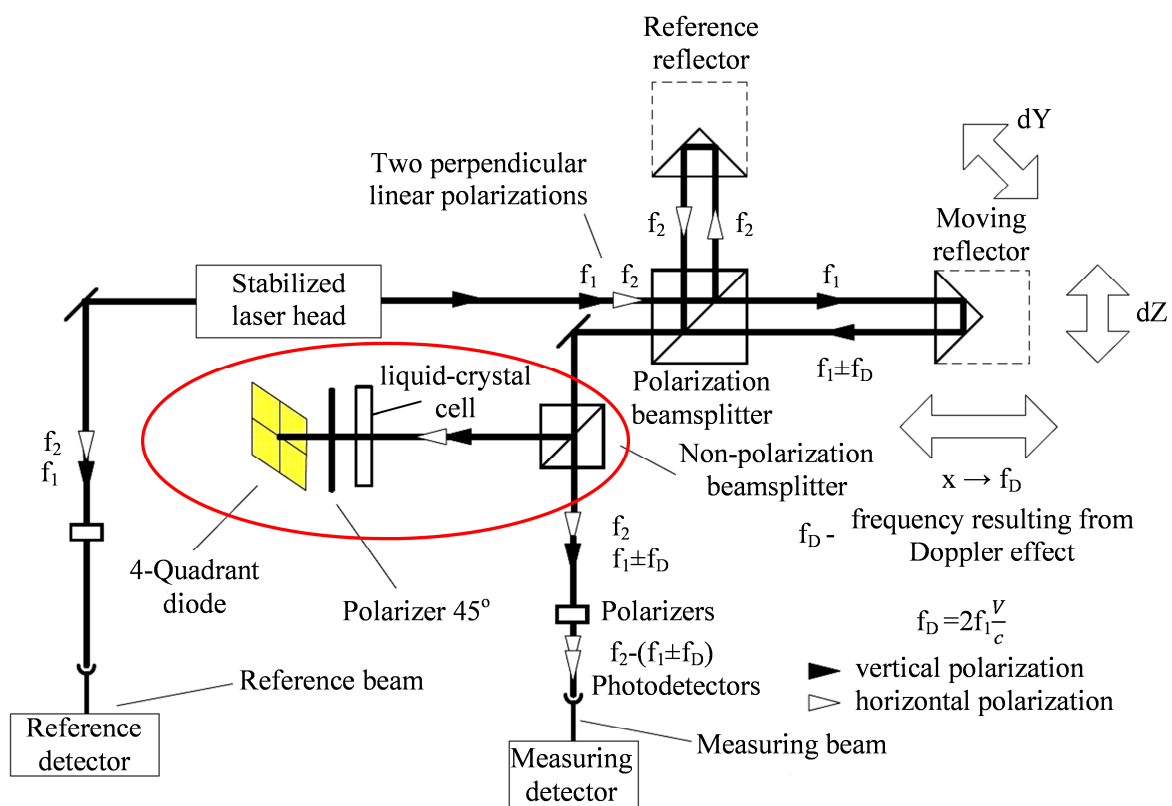


Fig. 8. Modification of 1D laser to 3D laser [1]

Since the difference in frequency between the measuring path and the reference path is measured, the whole system is resistant to the variation in return beam amplitude and to inference from the detectors. A major drawback of this solution is the limitation of the measuring arm travel speed in one direction to about 0,3 m/s [51]. If a proper splitter is used, it is possible to measure the other axis, but then the laser beam power drops by 50%. This may make it difficult or impossible to perform measurements on larger machine tools.

By adding more optoelectronic circuits, 6D lasers were built. Thanks to the latter the error measuring time can be reduced by as much as 89% [59]. Besides measuring the positioning error, horizontal and vertical straightness and angular errors (pitch and yaw),

a 6D laser system can be used to measure the roll error. This means that the components of a 6D laser measuring system need to be set and calibrated only once for each of the measured machine tool axes.

As a rule, laser interferometers are more precise than the optoelectronic systems which in 3D and 6D laser measure some volumetric error components. Moreover, some manufacturers offer enhanced precision laser systems incorporating more stable electronic circuits, or with limited measuring ranges. Table 1 shows measurement accuracies of the API XD laser system (made by Automated Precision Inc.) presented in Fig. 9.



Fig. 9. Components of laser system API XD [58]

Table 1. Measuring accuracy of API XD laser systems [58]

Laser configuration		Error	Accuracy	
			Regular	High Precision
6D	1D	Linear positioning ($\mu\text{m}/\text{m}$)	0,5	0,2
	3D	Vertical and horizontal straightness (μm)	$\pm (1,0+0,2/\text{m})$	$\pm (0,2+0,05/\text{m})$
		Pitch & Yaw (arc-sec)	$\pm (1,0+0,1/\text{m})$	$\pm (0,2+0,02/\text{m})$
	6D	Roll/Squareness (arc-sec)	$\pm 1,0$	$\pm 0,5$

5.3. LASER INTERFEROMETER – VECTOR METHOD

Measurements of all the volumetric error components by means of the 1D and 3D methods are technically difficult and laborious. In order to simplify them, most of the components are analytically determined on the basis of 1D laser measurements of the diagonals of a cuboid describing the machine tool workspace [17]. All the four diagonals need to be measured in order to uniquely determine the error components (Fig. 10).

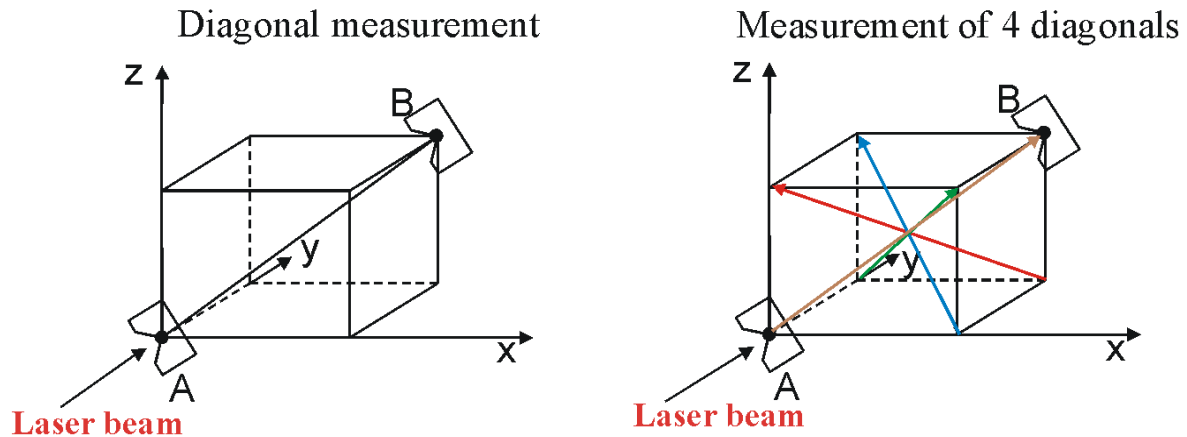


Fig. 10. Diagram showing measurement of diagonals [39]

A reflector in the form of a possibly large flat mirror, which can be tilted sideways relative to the laser head without misaligning the laser system optics, is needed for the measurement of diagonals by means of the 1D laser. The measurement of a diagonal involves the sequential shifting of the mirror (setting the measured diagonal) relative to the laser beam in directions x , y , z by a value of Δx , Δy , Δz (Fig. 11). The advantage is that linear positioning errors, straightness errors and squareness errors are measured simultaneously.

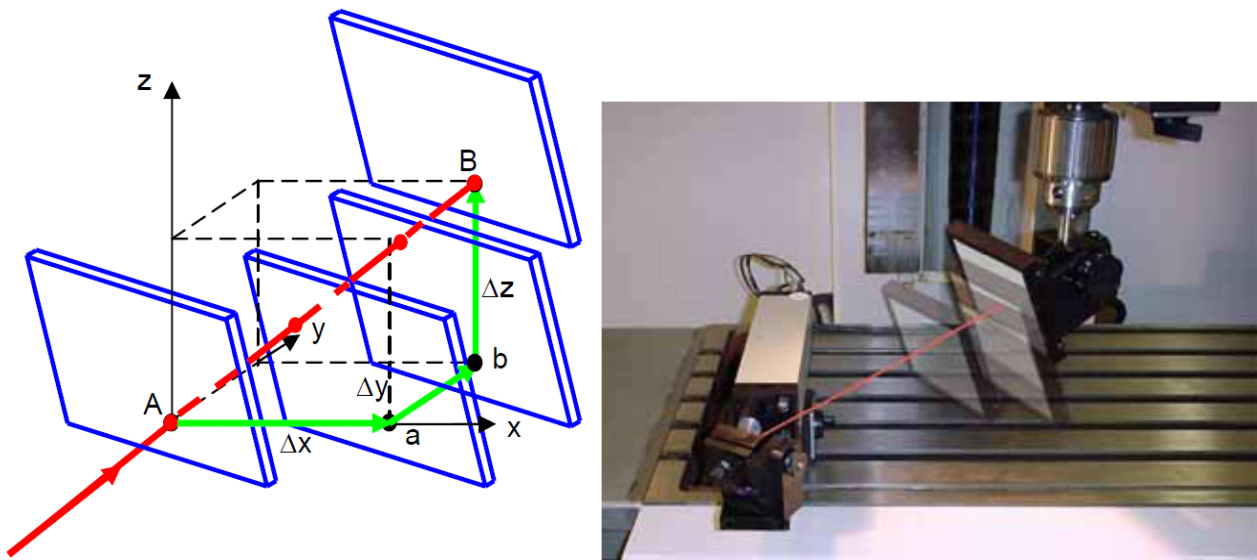


Fig. 11. Vector measurement method [36], [39]

In comparison with the direct measurement of diagonals, using the vector method one can obtain three times more data owing to its motion sequentially ensuring the acquisition of displacement measurement results for all the intermediate mirror positions. As a result of the measurement one gets twelve data sets for the four diagonals, from which one determine twelve errors: 3 positioning errors, 3 horizontal straightness errors, 3 vertical

straightness errors and 3 squareness errors. No angular errors can be determined by this method. The results can be presented in the form of tables or diagrams.

Using the vector method for a machine tool or a coordinate machine with a workspace of up to 1 m³ one can measure all the four diagonals in 2-4 hours. As a result, machine tool error determination time can be reduced in comparison with the method in which all the three types of errors are individually determined [1]. This method and the software tools for determining corrections for machine tool error compensation are being developed by, among others, Optodyne Inc. For some controllers (e.g. Fanuc, Siemens, Giddings and Lewis), compensation tables are automatically generated and their application results in a multiple improvement in accuracy. Moreover, this method is fully compliant with ASME B5.54 and PN-ISO 230-2. The whole measuring system is portable whereby it can be applied to many different machines, and machine tool accuracy can be checked in small plants where it would be uneconomical to purchase more expensive equipment for this purpose [38].

The vector method requires a special laser interferometer with the geometrical outgoing beam and the returning beam insulated from each other, capable of working with a flat mirror. The linear measurement accuracy of the laser systems made by Optodyne is 1 ppm.

The main limitations of the vector method are: the small range of motions (due to the size of the mirror) in axes x, y, z, the fact that only some of the volumetric error components are taken into account and its low accuracy for large positioning errors [32].

5.4. LASER BALL BARS

A laser ball bar (LBB) is a device for evaluating machine tool precision through direct measurements of tool position in the workspace relative to the surface of the table. The LBB consists of a two-stage telescoping tube with precision balls attached to its ends, and an optical system which enable the laser measurement of the distance between the two balls (Fig. 12). The laser head is connected by fibre-optic cables to the LBB.

It is not possible to precisely determine the coordinates of spindle position in the workspace from measurements of the distance between the machine tool worktable and the spindle tip point. On this basis one can only determine circular interpolation errors and squareness errors for the axes active in the tests. This means that the length of a diagonal does not explicitly define its orientations in space. Therefore a trilateration procedure, consisting in sequential LBB measurements from three bases located on the surface of the worktable (Fig. 13), has been developed [26].

The mutual distances between the three bases, i.e. 1-2, 1-3 and 2-3, are known thanks to the calibrated LBB positions whereby when the three edges (L4, L5 and L6) of the tetrahedron formed in this way have been measured, one can determine the coordinates of its vertex. The following geometrical relations:

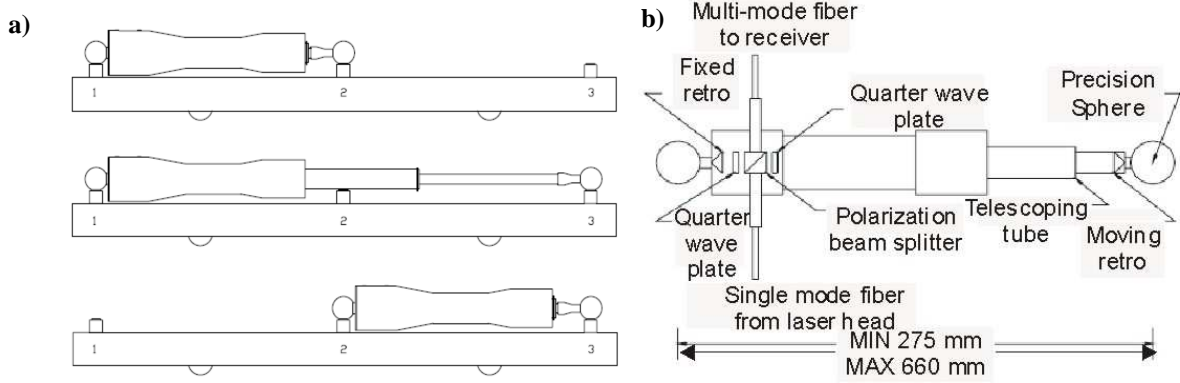


Fig. 12. Laser ball bar (LBB): a) calibrated positions [27], b) optical system [26]

linear regression models and the homogeneous transformation matrix (HTM) model are used to determine the actual volumetric coordinates x, y, z of the vertex and to evaluate measurement uncertainty [8],[26].

$$\begin{aligned}
 x &= \frac{L_4^2 - L_3^2 + L_1^2}{2L_1} \quad c_b = \sqrt{L_3^2 - x_b^2} \\
 y &= \frac{d_1^2 - L_6^2 + c_b^2}{2c_b} \quad \text{where:} \quad x_b = \frac{L_3^2 - L_2^2 + L_1^2}{2L_1} \\
 z &= \sqrt{c_1^2 - y^2} \quad d_1 = \sqrt{c_1^2 + (x_b - x)^2} \\
 c_1 &= \sqrt{L_4^2 - x^2}
 \end{aligned} \tag{1}$$

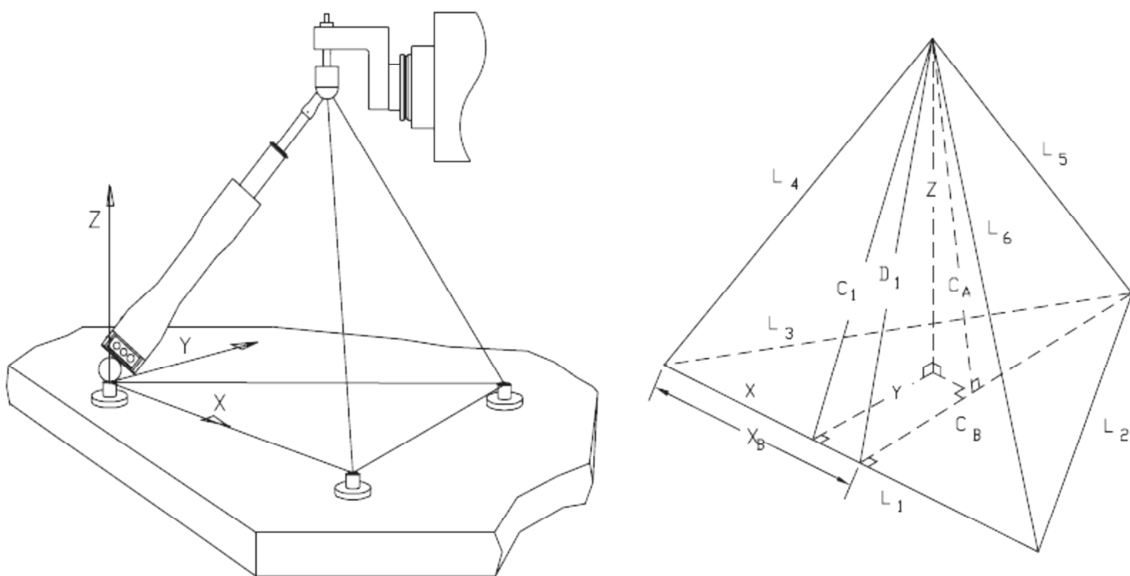


Fig. 13. Diagram of coordinate system and trilateration procedure setup [26]

Thanks to the trilateration procedure, one can determine 21 volumetric error components for each of the three controlled linear axes on the basis of spindle position measurements taken by the LBB. The determined error components cover all the geometric, elastic and thermal factors having a bearing on the machine tool error. Thermal factors may adversely affect evaluations by any method when ambient temperature stabilization is not ensured during volumetric error measurements lasting several hours.

5.5. 3D LBB

By adding the possibility of measuring two angles of rotation of the bar, an instrument called 3D LBB was obtained. This instrument enables the direct real-time measurement of spindle tip position. Two rotary laser encoders for measuring the angle of rotation relative to vertical axis Z and horizontal axis X and for linear measurements are used in the case shown in Fig. 14. The laser is a Doppler scale compact laser (made by Optodyne Co.) with a system accuracy of up to 1,0 ppm. The encoders have a maximum resolution of 1,0 arc-sec and an accuracy of 1,6 arc-sec [6].

The LaserTRACER-MT (MT: mechanical tracking) system made by ETALON (Fig. 14c) is an exemplary commercial implementation of the above idea. The system can be used to calibrate small and medium-sized machine tools with their assemblies shifted by up to 1,5 m.

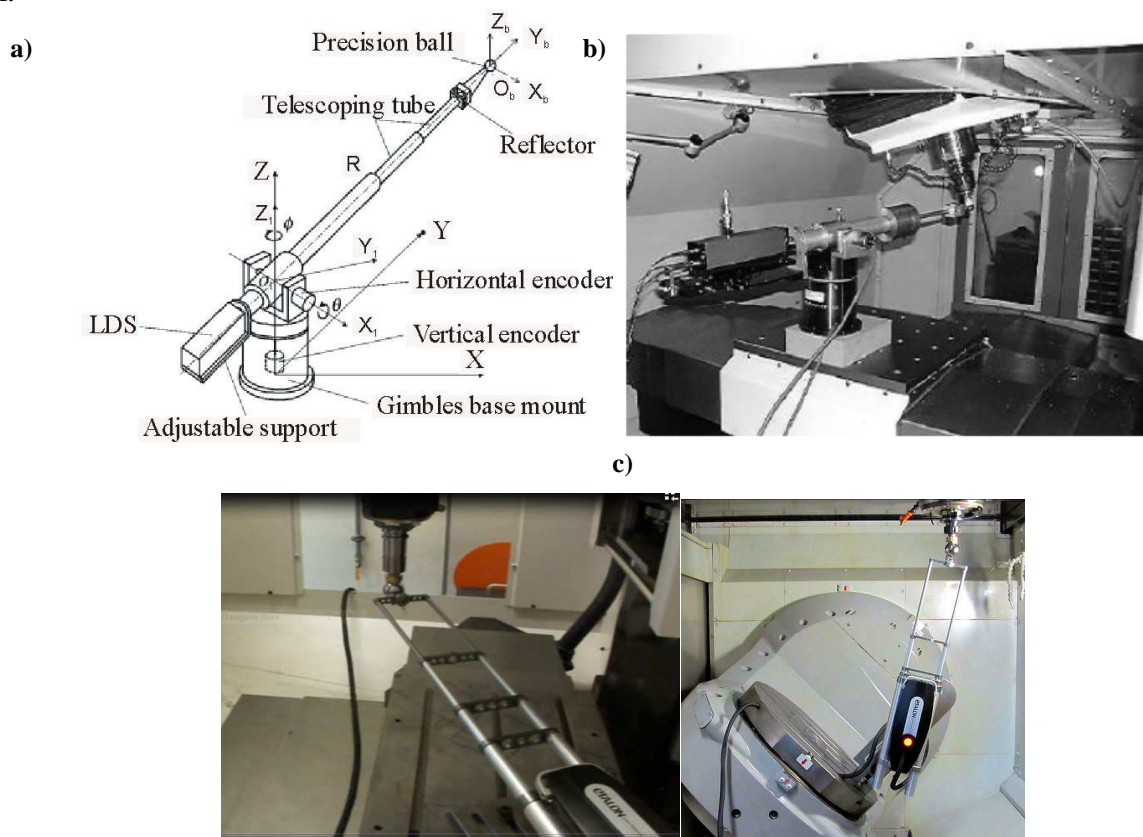


Fig. 14. 3D LBB: a) structure b) 3D LBB during measurement [6], c) measurement of linear and rotational axis errors by means of ETALON LaserTRACER-MT system [52]

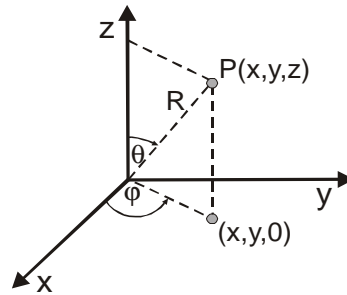


Fig. 15. Transformation of results to Cartesian coordinate system

Thanks to the three sensors, one for linear measurements and two for angular displacement measurements, recording the position of the bar in the spherical coordinate system, one can easily transform the measurement results to the Cartesian coordinate system (Fig. 15). In order to determine the position of a point in the spherical coordinates one needs to determine the length of radius R and two angles of rotation: θ and φ .

Also vector bars are based on the above principle, but differ in their method of measuring the length and the angle or the number of measured angles (Fig. 16) [33].

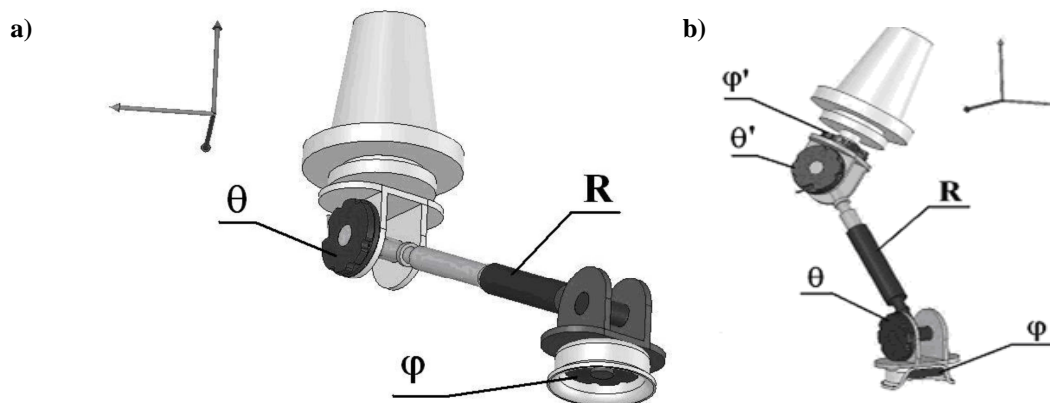


Fig. 16. Vector bar: a) with separate angle measuring sensors, b) for measuring five coordinates [33]

The main limitation of the LBB and 3D LBB devices is the minimum length of the telescoping tube, which determines the dead part of the workspace (in which no measurements can be made) and the maximum size of the workspace in which measurements can be made. The state-of-the-art tracking laser systems have no such limitations.

5.6. TRACKING LASER

The implementation of the tracking laser concept became possible thanks to a new approach to the representation of machine tool errors. The approach consists in the interferometric measurement of displacements between a reference point connected with the

machine tool base and a moving point (target) connected with the toolhead or the tool holder (Fig. 17) [29], whereby the limitations typical for LBB and 3D LBB devices have been eliminated.

For each of the three laser positions the machine tool performs spindle motions maximally filling its workspace. In each point of the space grid the axis motions are stopped and the displacement of the reflector relative to the stationary reference ball is recorded. Machine tool errors are defined as the differences between the programmed displacements and the measured ones.

One of the leaders in machine tool geometric error identification and compensation is the ETALON company. Its tracking laser (bearing the name LaserTRACER) together with its software was designed in collaboration with Physikalisch-Technische Bundesanstalt (Germany) and the National Physical Laboratory (UK) (Fig. 18). The system consists of a laser interferometer, two drives (for executing interferometer horizontal and vertical motion), an invar environmental impact compensator and a movable reflector.

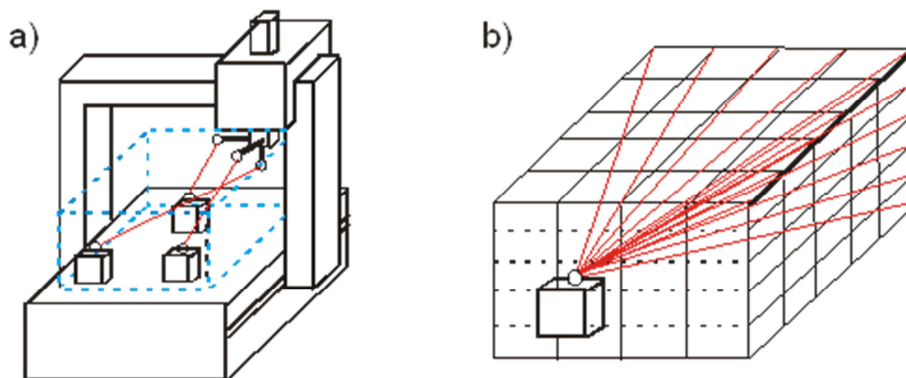


Fig. 17. Laser tracker in at least three positions on workpiece table: a) tracker positions, b) volumetric grid [29]

The interferometer appropriately controlled by the motors automatically tracks the position of the moving reflector whereby the distance can be measured at any instant. In this design the interferometer stem moves in the Cardan joint inside of which a precision ball (constituting a stationary reference point and simultaneously serving as the reference for the interferometer) is fixed. A cats-eye optical system (with a measurement area limited to $\pm 60^\circ$) performs the function of the reflector.

The precision of length measurements mainly depends on the precision with which the reference ball was made. The latter's roundness error should not exceed 50 nm [49] in order to ensure a constant accuracy in the whole operating range of the interferometer. Moreover, the reference ball is mounted on a support made of material characterized by a low thermal expansion coefficient and the laser beam is transmitted via a fibre-optic cable from a laser head located outside the interferometer housing. Owing to this, thermal effects and the weight of the instrument's movable parts have been reduced [34]. Also this interferometer has an environmental impact (temperature, pressure, humidity) compensator whereby the obtained measurements are ten times more precise than the ones taken by conventional tracking lasers used in other fields. The manufacturer (Etalon) estimates the precision at $0,2 \mu\text{m}$ for a distance of 0,2 m, and $3 \mu\text{m}$ for a distance of 5 m.

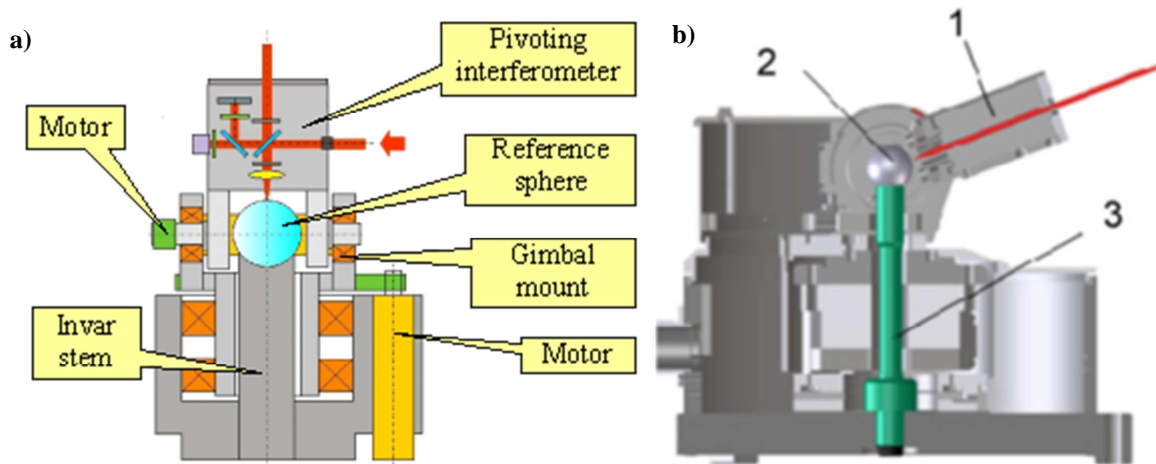


Fig. 18. LaserTRACER: a) structure [28], b) schematic view: (1) tracking interferometer, (2) stationary reference sphere, (3) thermally invariant stem supporting reference sphere [30]

Figure 19 shows a schematic of the optical system of the interferometer. The laser beam supplied via a fibre-optic cable is refracted by a two-way mirror, some of it passing directly to a measuring detector and some of it being directed towards the reference ball. Before it is superimposed on the reference beam, the light beam is redirected towards a four-quadrant diode [28]. The latter detects a difference in the position between the reference ball and the reflector. In this way the automatic reflector position tracking function is carried out. The four-field detector consists of four silicon photodiodes separated from each other by a gap a few tens μm wide. Each of the detector's areas generates a separate signal. The laser beam falling on the detector's surface generates four signals in the form of photocurrents whose intensity is commensurate with the given area's illumination intensity. When the light beam falls centrally, each of the detector fields is illuminated with the same intensity and each of the diodes generates the same photocurrent (Fig. 20). Otherwise, the particular areas are illuminated with different intensity. On this basis the displacements in the particular axes are calculated to make the laser beam follow the reflector movement [1].

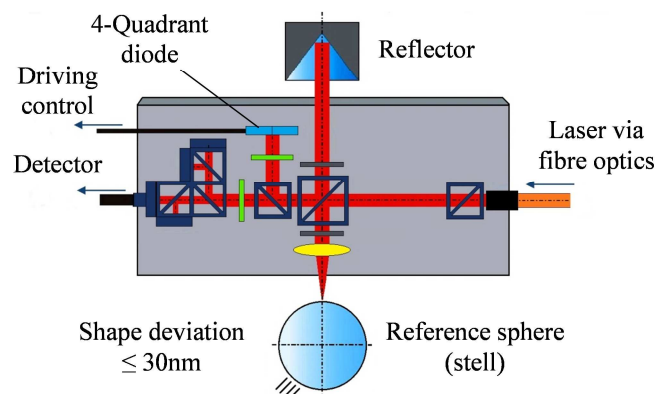


Fig. 19. Optical system design in LaserTRACER interferometer [28]

A major advantage of the LaserTracer are its small dimensions (200 mm × 220 mm × 220 mm) whereby it can be used to measure the accuracy of both medium-sized and large machine tools.

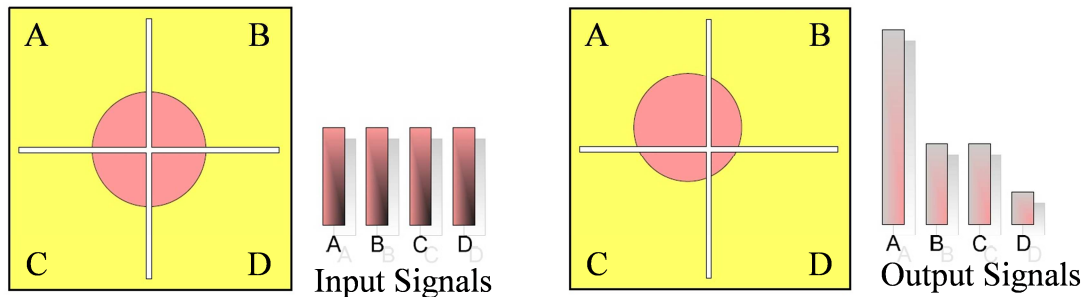


Fig. 20. Dependence between detector output signal and laser beam position [1]

Calculations during machine tool accuracy measurements are performed by an external PC using dedicated TRAC-CAL software [44]. The reflector fixed to the spindle moves along a programmed three-dimensional grid, with 1-2 second breaks for taking measurements. The measurement sequence lasts 10-20 minutes for one interferometer setting [35]. After such a sequence the tracking laser is fixed in a new position and the measurement sequence is repeated. Measurements can be performed for 3-5 different laser fixings. The multilateration procedure carried out by TRAC-CAL uses only distance measurements whereby less precise angular measurements are avoided. After measurements have been taken in all the planned positions, the TRAC-CAL program computes errors for all the parameters [35]. In addition, the errors are presented in the form of measurement reports whereby one can analyze machine errors in detail. The compensation tables have been adjusted to the controllers capable of full volumetric compensation (e.g. Siemens 840D sl, Heidenhain TNC 530, Fanuc). The processed measurement data in the form of a file are read into the controller which computes the compensation values.

In 2010 Etalon introduced and patented a newer version of TRACK-CAL. Thanks to the “on the fly” option the measurement time has been reduced and the number of measuring points has been increased to three per millimetre [49]. The LaserTracer can be connected to the control system of the machine to be measured whereby the measurements can be smoothly performed without stopping in the measuring points.

The algorithm used for measuring the linear axes can be applied to the rotational axes if the error model is suitably adjusted. The rotational axis error procedure requires that measurements should be performed for several configurations of laser positions (3 positions – I, II, III) and reflector positions (4 positions – 1, 2, 3, 4). This is shown in Fig. 21 for the tilting table of a five-axis machining centre [31].

Errors for the rotational axes are also calculated by means of multilateration algorithms, which are also used to evaluate the linear axes. The kinematic error model must be adjusted to the motions of the rotational axes. The model proposed in [31] covers all the geometric errors of the rotational axes, mentioned in ISO 230-7.

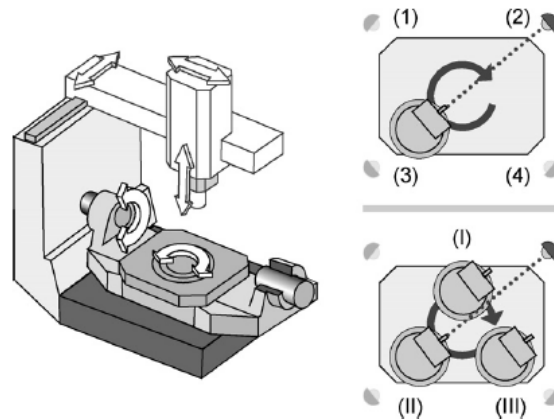


Fig. 21. Procedure for rotary axis calibration using tracking interferometer in three positions (I–III) and four reflector locations (1–4) [31]

Having in mind higher precision in determining the position of a point in space, research on the realization of the multilateration procedure in accordance with the GPS (Global Positioning System) principle, i.e. through the use of not one, but several electronically interconnected transmitters, is underway [25],[44],[58]. The MULTITRACE system made by ETALON (Fig. 22) has been designed for this purpose [58]. Such a solution may substantially reduce test time.

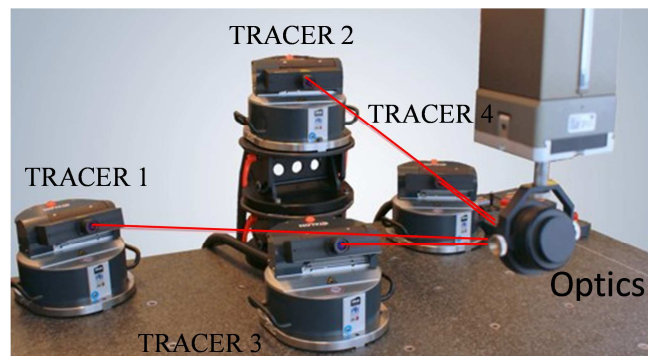


Fig. 22. Multilateration system MULTITRACE by Etalon [56]

Attempts are also made to replace Lasertracker systems with GPS transmitters. However, so far no higher measurement accuracy than 0,5-1,0 mm (thousand times lower than the accuracy obtained using lasers) has been attained [43].

5.7. TRACKING LASER WITH ACTIVE TARGET

As part of the project entitled “Volumetric Accuracy for Large Machine Tool” carried out jointly by Boeing, Siemens, Mag Cincinnati and Automated Precision Inc. (API), a methodology enabling the precise calibration of large multiaxis machine tools in a very short time (in a matter of hours) has been developed. A special tracking laser, called API

T3, working in tandem with the patented Active Target (Fig. 23) is used for the measurements [53].

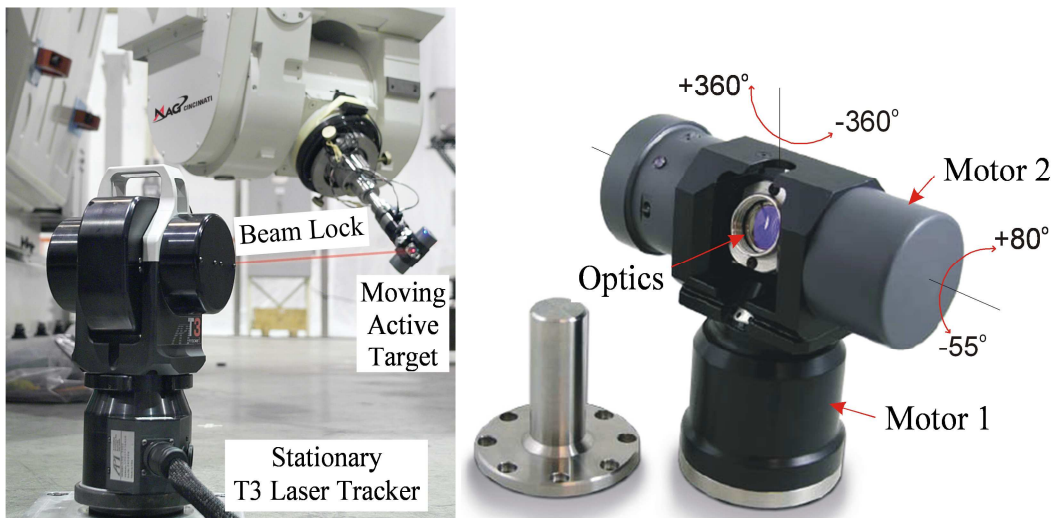


Fig. 23. Active Target API T3 laser tracker [48]

Active Target devices are new-generation retroreflectors equipped with two drives whereby they can automatically position themselves and track the laser beam, preventing it from being interrupted. The angle of laser beam incidence on the retroreflector can change at a rate of $50^\circ/\text{s}$. Since the retroreflector can rotate by $\pm 360^\circ$ in one axis and from $+80^\circ$ to -55° in the other axis, only one tracking laser position is required for measuring the volumetric error. The measurements end when the number of results (a cloud of points) needed to describe machine tool errors in the whole workspace has been recorded (Fig. 24) [17].

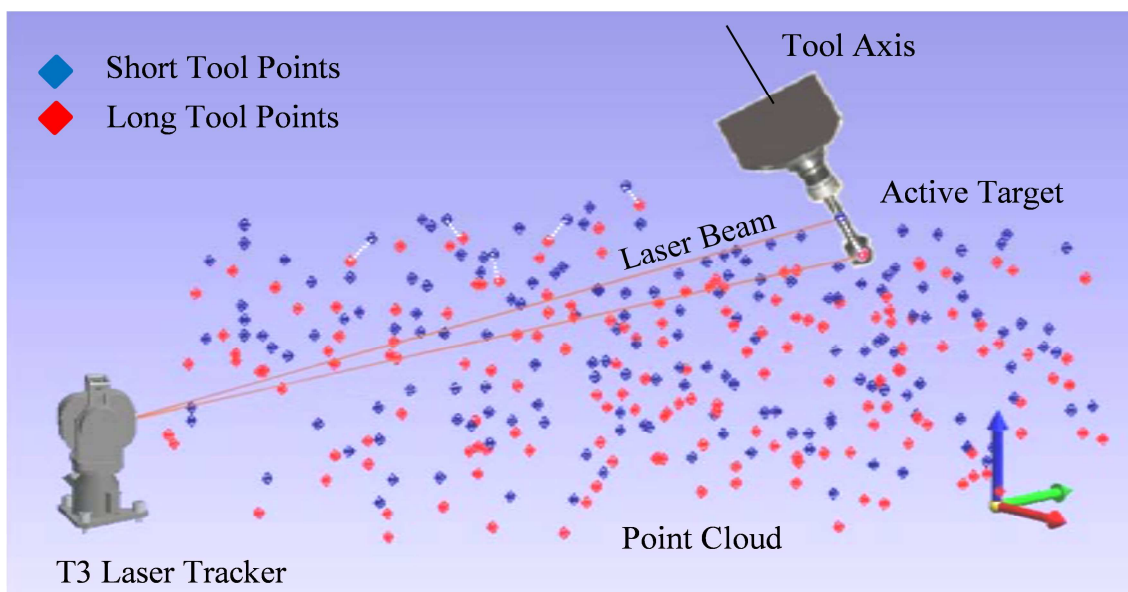


Fig. 24. Map of volumetric errors in whole machine tool workspace [17]

Using a CAD machine tool model a software called VEC (Volumetric Error Compensation) creates a kinematic error model covering all the linear and rotational axes. A plan of measurements, avoiding any collisions but maximally filling the machine tool workspace, is developed on this basis. Representative (200-400) points are determined in the whole workspace. A preliminary simulation is run to check whether there are no collisions and whether the laser beam will not be broken between the laser and the active target. As the measurement plan is being carried out, the measurement is repeated 30-100 times for each of the planned measuring points and the average error is calculated using statistical methods.

The advanced VEC software processes the measurement data in a few minutes. It can simulate the tool path and graphically display errors due to machine tool inaccuracy. In addition, it calculates compensation tables for two different tool lengths (short, long), verifies the compensated values and sends them directly to the machine tool controller.

It takes only a fraction of the time needed by the previous methods for the VEC software to process the measurement results.

6. OTHER INEXPENSIVE SOLUTIONS

6.1. 3-PSD OPTICAL SYSTEM FOR EVALUATING ACCURACY OF THREE-AXIS MACHINE TOOLS

The currently available measuring systems may be unsuitable for atypical (small, very small and miniature) machine tools not only for economic reasons, but also for purely technical reasons (their size). The inexpensive and small measuring laser system for three-axis machine tools, presented below, instead of interferometric measurement uses laser beam direction tracking by position sensitive detectors (PSDs).

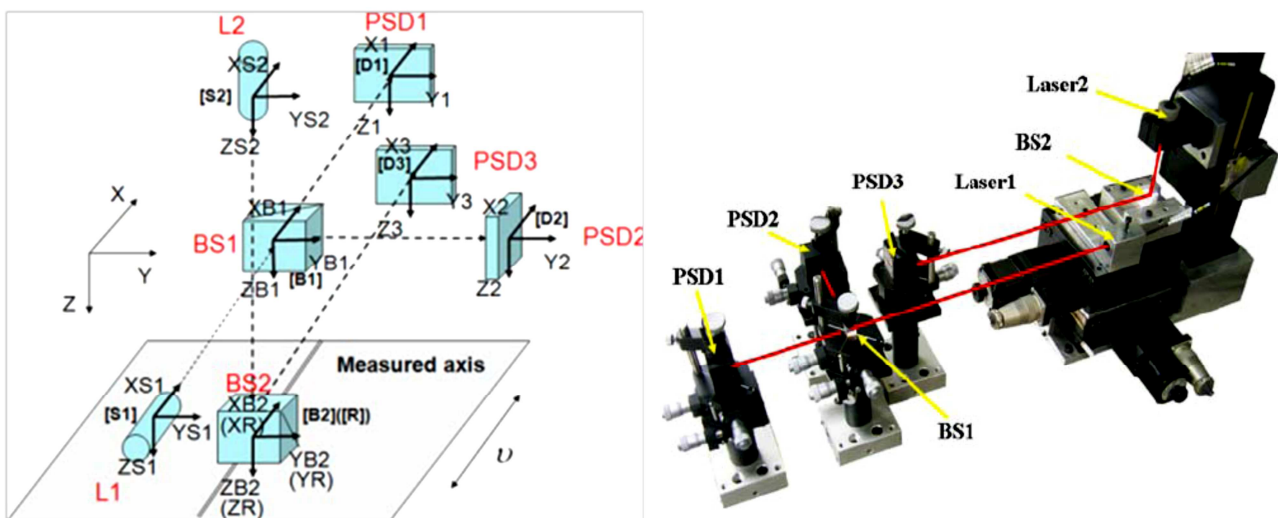


Fig. 25. Idea of 3-PSD system and experimental setup [41]

The system consists of two laser diodes L1 and L2, two laser beam splitters BS 1 and BS2 and three laser beam tracking PSDs: PSD1, PSD2 and PSD3 (Fig. 25). The key difference between this method and the previously described laser methods lies in the fact that in the latter methods the target is usually moving while the reference point remains stationary, whereas in this method all the targets (PSD1, PSD2 and PSD3) are stationary.

The dependencies between the readings from the PSDs and the particular volumetric error components are calculated by an algorithm using the HTM method, taking into account the configuration of the investigated machine tool. The method makes it possible to determine the total volumetric error, i.e. three linear errors and three angular errors for each of the axes and three errors of squareness between the axes.

The resolution for linear measurements is estimated at 0,5 μm and at 0,2 μrad for angular measurements. The resolution of the laser diode-PSD system relative to the machine tool error values has been found to be sufficient [42].

6.2. 4-DOF OPTICAL SYSTEM FOR EVALUATING ACCURACY OF PRECISION ROTARY TABLES

The conventional techniques used for the calibration of rotary tables are based on the reference method in which usually a reference table with the Hirth clutch, and a laser interferometer for angular measurements are used. The calibration accuracy then depends on the accuracy of the reference table. In the method presented below [11], the laser interferometer has been replaced by an inexpensive laser diode, a diffraction grating and two PSDs (Fig. 26). The position of the PSDs (Fig. 26) depends on the adopted unit angle by which the evaluated table is turned each time. When the set of the two tables is turned by a unit angle, the reference table turns by the unit angle in the opposite direction.

As a result of the rotation of the diffraction grating one can then observe the differences between the rotations of the two tables on the stationary PSDs. For this measurement concept it is not the positioning accuracy of the reference table, but the repeatability of its positions which is important. Thus it can be assumed that

$$\varepsilon_{zr1} + \varepsilon_{zr2} + \varepsilon_{zr3} + \dots + \varepsilon_{zrn-1} + \varepsilon_{zrn} = 360^\circ$$

and the target rotary table error is the difference between the readings

$$\varepsilon_{z1n} = \varepsilon_{ztn} - \varepsilon_{zrn},$$

where: ε_{z1n} – the first set of angular readings,
 n – the number of an interval in a range of 0-360°,
 t – the error of the target rotary table,
 r – the error for the reference rotary table.

After two full test revolutions, errors for the four degrees of freedom of the reference rotary table and the target rotary table are calculated. These are three angular positioning errors and one linear error. The angle measurement stability in this system after 4000

seconds was found to be below 2" while the stability of linear measurements was below 1,2 μm .

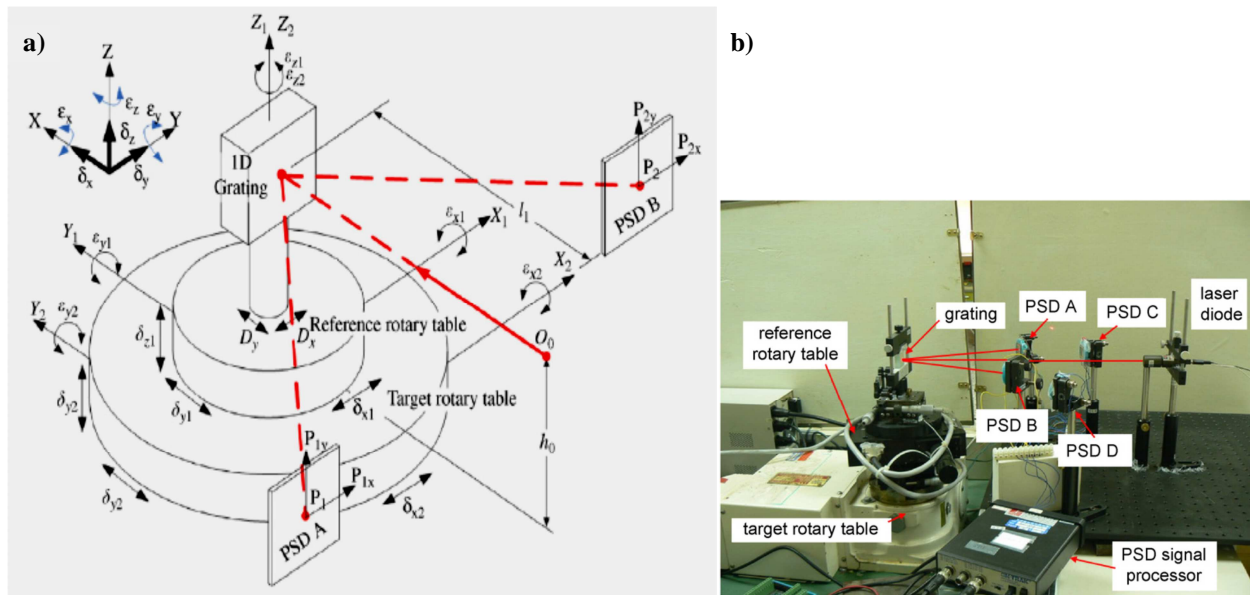


Fig. 26. 4-DOF measurement system: a) functional diagram, b) experimental setup [11]

By increasing the number of PSDs from 2 to 4 one can reduce the number of required measuring points from 720 to 72 for the whole test and so substantially reduce the time needed for the evaluation of the accuracy of a rotary table.

6.3. R-TEST FOR EVALUATING ACCURACY OF ROTARY AXES

One of the principal methods of checking the accuracy of coordinate measuring machines (CMMs) is a test consisting in measuring a precision master ball by means of a probe. The test is included in many international standards, such as VI/VDE (the V3 test), ASME (the point to point probing test) and ISO (the R-test). The aim of the test is to precisely determine the position of the centre of the master ball during the operation of CMM drives. The principle of this test has been exploited to build simple (in comparison with the laser systems) measuring devices in which three displacement sensors spaced at every 120° touch the surface of the ball whereby at any instant one can determine the actual position of the ball's centre relative to the other controlled axes of the machine tool, reading coordinates x , y , z . Such systems in different configurations are used to evaluate the accuracy and degree of preparation of data for the compensation of machine tools with rotational and linear axes. An exemplary device based on the R-test principle is shown in Fig. 27.

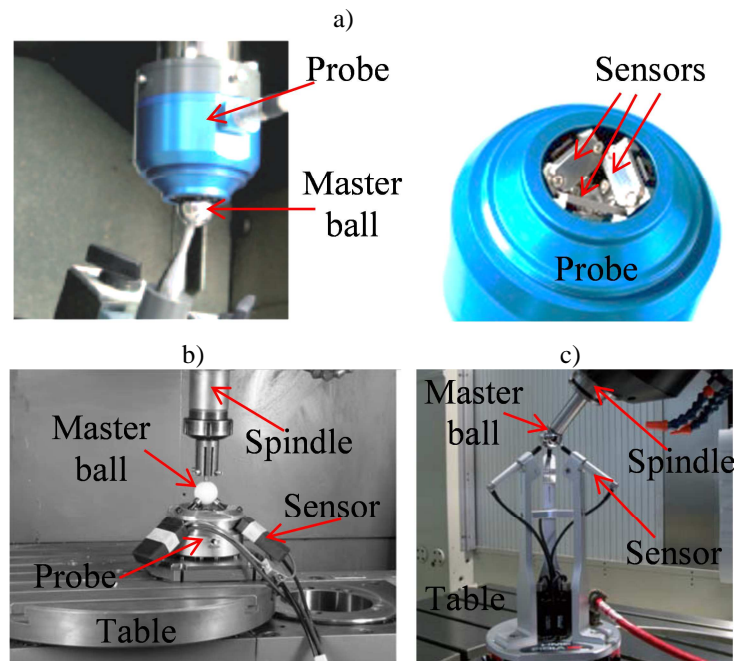


Fig. 27. Configurations of devices based on R-test principle: a) R-test device made by IBS Precision Engineering [55], b) functional prototype of R-test device [35], c) HMS device made by Fidia [51]

In the solution, called the R-test, offered by IBS Precision Engineering the probe and three displacement sensors are fixed to the spindle while the master ball is fixed to the machine tool table (Fig. 27). In the other proposed solutions it is the other way round, i.e. the ball is fixed to the spindle and the probe with the sensors is fixed to the table. The measurement principle in all the three cases remains the same. There are only differences in the software for the probes. The IBS Precision Engineering software enables both manual and automatic measurements and generates NC codes for Siemens, Fanuc and Heidenhain controllers.

The solution, called HMS (Head Measuring System), offered by FIDIA is supported by FIDIA control systems class C and has been designed for the automatic calibration and diagnosis of two-turn rotary heads and tilting tables in five-axis machine tools. This device is managed by a dedicated configuration, measurement and processing software. After coupling with a FIDIA class C control system the measuring cycle runs automatically for about 30 minutes. When it ends, calibration with a precision higher than the one achievable by the traditional methods is carried out. The software includes geometric error compensation functions for the different types of heads and tables. In this way the positioning errors for the two axes and the permanent centre of a tilting table are compensated.

The accuracy of measurement by means of the devices based on the R-test principle ranges from 1,4 μm for the prototype configuration [36] to 0.6 μm for the IBS Precision Engineering device within a measuring range of respectively 0,5 mm and 1,25 mm [57]. The devices make it possible to check machine tool geometry whenever a need arises and reduce downtimes connected with machine tool calibration.

7. CONCLUSION

The measuring tools and methods discussed in this paper are dedicated to the evaluation of the machine tool error through the determination of its distribution in the workspace (the volumetric error) and they enable respectively: the direct measurement of the error and its orientation in space, the calculation of the error and its orientation on the basis of the measurements of all or nearly all the error components, and the determination of the volumetric error (indirect methods). There are tools/methods considered to be peculiar and so put under the “other solutions” category. A general description of the devices/methods grouped according to the above division is presented in Table 2.

Table 2. Characteristics of measuring devices/methods used to determine volumetric error

Device/ method	Accuracy	Setup number of measurement system/axes type	Application	Time	Cost	Availa bility on market
INDIRECT METHODS						
DBB	$\pm 1,25 \mu\text{m}/\text{linear}$	1/linear	medium-sized machine tools	I	I	Yes
KGM grid	$\pm 2 \mu\text{m}/\text{linear}$	3/linear	medium-sized machine tools	I	II	Yes
DIRECT METHODS						
1D laser	$\pm 0,5 \text{ppm}/\text{linear}$	3/linear	3-axis machine tools	IIIIIIII	III	Yes
3D laser	$\pm(1+0,25/\text{m}) \mu\text{m}/\text{straightness}$ $\pm(1+0,1/\text{m}) \text{arc-sec}/\text{Yaw, Pitch}$	3/linear	3-axis machine tools	III	IIII	Yes
6D laser	$\pm 1 \text{arc-sec}/\text{Rol}$	3/linear	3-axis machine tools	II	IIII	Yes
Laser – vector method	$\pm 1 \text{ppm}/\text{linear}$	1/linear	medium-sized 3- axis machine tools	IIII	IIII	No
LBB	No data	3/linear	medium-sized 3- axis machine tools	IIII	IIII	No
3D LBB	$\pm 1 \text{ppm}/\text{linear}$ $1,6 \text{arc-sec}/\text{rotary}$	1/linear/rotary	medium-sized multiaxial machine tools	II	IIII	Yes
Tracking laser	$\pm(0,2+0,3/\text{m}) \mu\text{m}/\text{linear}$	3/linear	large- and medium-sized multiaxial machine tools	IIII	IIIIII	Yes
Tracking laser with active target	$\pm(0,2+0,3/\text{m}) \mu\text{m}/\text{linear}$	1/linear/rotary	large- and medium-sized multiaxial machine tools	II	IIIIIIII	Yes
OTHER						
3PSD system	$\pm 0,5 \text{ppm}/\text{linear}$ $0,2 \mu\text{rad}/\text{angular}$	2/linear	small-sized 3-axis machine tools	III	I	No
4DOF system	$\pm 1,2 /\text{linear}$ $\pm 2 \mu\text{rad}/\text{angular}$	1/rotary	rotary tables	IIII	I	No

R-test	$\pm 0,6\mu\text{m}/\text{range}-1,25\text{mm}$	1/linear/rotary	medium-sized multiaxial machine tools	II	II	Yes
LIMITATIONS						
DBB	Only circular motion, limited bar length					
KGM grid	Limited diameter of optical grid					
1D laser	Only linear axes					
3D laser	Lower accuracy in axes perpendicular to axis being measured					
Laser – vector method	Only linear axes, limited extent of motions x,y,z					
LBB rod	Only linear axes, limited telescope length, dead zone					
3D LBB rod	Limited telescope length, dead zone					
Tracking laser	Limited reflector angle of view, dead zone, accuracy of 0,2-3 μm in range of 0- 5m					
Tracking laser with active target	accuracy of 0,2-3 μm in range of 0- 5m					
3PSD system	Only linear axes, small measuring range					
4DOF system	Only rotational axes					
R-test device	For machine tools with rotary heads and roto-tilting tables					

The table also shows: the number of settings needed to determine the volumetric error for the (small, medium-sized and large) machine tools to which the particular measurement systems are dedicated, exemplary measuring accuracies and the main limitations. This table should facilitate making decisions on the choice of a measuring tool most suitable for the evaluation and compensation of machine tool errors.

It does not always make sense to determine the global error for the whole machine tool since this requires expensive measuring hardware. From the economic point of view, it may be better to use two less expensive accuracy measuring methods, one for the linear axes and the other for the rotational axes.

In many cases, it is enough to employ two indirect methods (DBB, KGM), which make it possible not only to determine a few volumetric error components, but also to determine and compensate other kinematic errors, controller errors and circular interpolation errors. For machine tools with rotary tables the methods based on the R-test are very promising.

Much is expected of the methods using the state-of-the-art. optoelectronic systems. But these are methods which are now at the conceptual stage or under laboratory testing.

The choice of a measuring method/tool will always be determined by the accuracy requirements which the machine tool must meet, the cost of the measuring device, the test time and the availability of the device on the market.

One should bear in mind that because of the duration of accuracy tests, the geometric error measurement results always carry a thermal error. The innovative measuring tools and methods induce many research centres and manufacturers to take the thermal error into account in their models.

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