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Performance Characterization of Precision Machines

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Contents

Abstract

Geometric error measurements are performed to evaluate a variety of machining factors and conditions as well as the work done on the machine tools. With the increasing complexity of machining processes and ever-growing requirements for accuracy and precision, the demand for advanced methods and instruments for process optimization has also increased. To meet this demand, error measurements and compensations for machine tool components, and on-machine measurement for process, require an expansion of manufacturing metrology to

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include comprehensive closed-loop control of the machining process. In this chapter, we firstly review the measurement methodologies of volumetric error generated in the machine tools from the perspective of measurement instruments and strategies. Then we review technical trends in on-machine measurements for process and product quality control, discussing the probing techniques for geometric parameters of workpieces and measurement tools for tool setting in detail, respectively. To eliminate the effects of disturbances on machining process and adjust the control quantities to optimal values for robustness, integration of online machining and process monitoring is essential. Spreading measurement targets and applications are comprehensively reviewed.

Keywords

Error · Machine tool · Characterization · On-machine measurement · Process monitoring

Introduction

Machine tools and measuring machines have been applied in enormous numbers and various fields of modern production. With the development of hi-tech and new tech, the requirements for machining accuracy have risen from micron to submicron and even nanometer level. The trend toward individualized products and smaller lot sizes with high precision increases the demands of higher machining reliability and flexibility in production. However, many factors still result in deviations compared to the design model, involving kinematics errors, thermal errors, cutting force-induced errors, servo errors, machine structural errors, vibration and tool wear, etc. Among them, the geometric error of machine tool components and structures is one of the uppermost sources of inaccuracy. In the past decades, considerable research has been conducted to compensate these geometric errors which can be preprocessed due to repeatability, aiming to improve the machining accuracy. The compensation techniques (Hsu and Wang 2007) are summarized into three steps: (i) to develop an error model for machine tools; (ii) to measure errors; and (iii) to conduct error compensation using the error model. The preprocess of error compensation is indispensable and a foremost technique to guarantee the machining accuracy.

However, the final machining error is a comprehensive interaction of various error sources including random errors such as vibration, tool wear, and environmental factors. It can be considered that the machining error is indirectly reflected in the relative position between the tool and workpiece. Hence the timely inspection of the workpiece and tool is essential in the process of machining (Roth et al. 2007). During conventional process, workpiece inspection is implemented with stand-alone equipment such as coordinate measuring machine, which is usually located at a separate room apart from the machine tool. This increases the overall machining cost and time to obtain the final products, and the production bottleneck may be caused by the product stagnation due to the time lag between the machining and inspection process in case of the flexible machining system. To increase the availability of metrology for applications in advanced manufacturing, a shift in the approach of metrology from offline, lab-based solutions toward the use of monitoring probes integrated into manufacturing platforms is urgently needed. On-machine metrology can avoid the errors caused by repositioning workpieces and use the machine axes to extend the measuring range and improve the measuring efficiency. For the critical requirement of machining quality, the errors induced by removal and remounting process would deteriorate the quality if re-machining processes are necessary. Therefore, development of on-machine measurement will enable the reduction of measurement cycle time, in addition to a potential improvement of machining quality.

Geometric Error Analysis and Characterization of Machine Tools

Error Parameters Description and Its Modeling

The main factors affecting the machining accuracy of CNC machine tools are the original errors of machine tools and the errors produced in the machining process. The main errors and their causes are shown in Fig. 1. From the perspective of the different mechanisms of error generation, the error sources can be divided into four categories: geometric and kinematic error, thermal error, servo control error, and cutting force error. Among the various error sources of the machine tool, the thermal error and the geometric error are the main errors, which account for 65% of the total error.

The geometric error of machine tools refers to the difference between the actual position and ideal position of the platform or tool in the process of motion. The term "volumetric error" is firstly introduced to define the ability of a machine tool to produce accurate 3D shapes. To analyze the geometric errors, the International

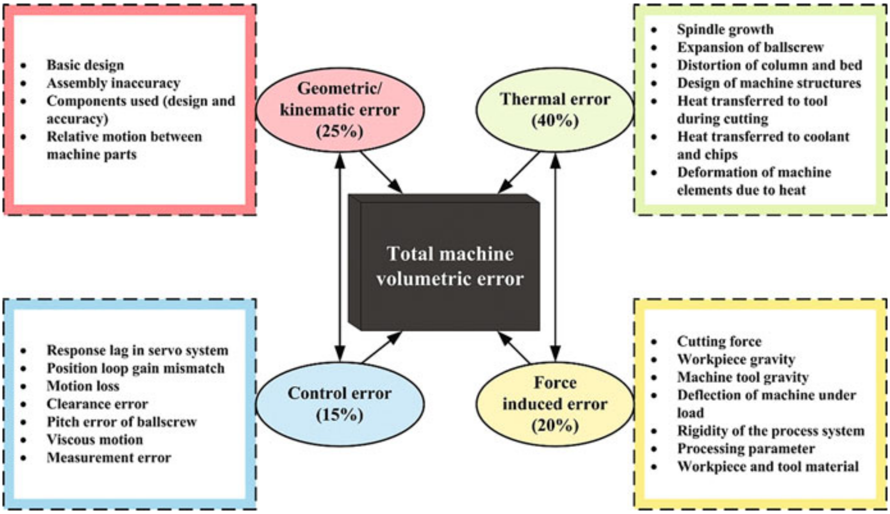


Fig. 1 The main error sources of CNC machine tools

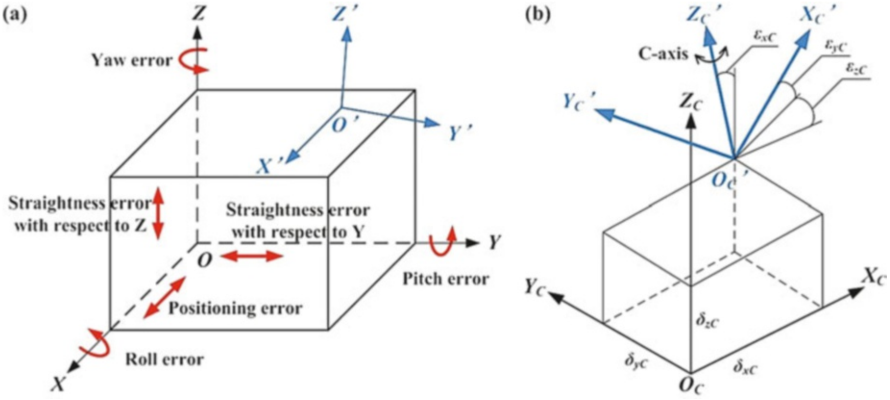


Fig. 2 Geometric errors of (**a**) X-slideway and (**b**) C-rotary table

Table 1 Notations of uniaxial kinematic errors

	Linear errors in respect to			Angular errors in respect to		
Error sources	X	Y	Z	X	Y	Z
X-slideway	δ_{xx}	δ_{yx}	δ_{zx}	ε_{xx}	ε_{yx}	ε_{zx}
C-rotary axis	δ_{xC}	δ_{yC}	δ_{zC}	ε_{xC}	ε_{yC}	ε_{zC}

Standards such as ISO 230 series have been developed to measure three main components of the machine tool, movable guide rails or linear axes, swiveling tables or rotary axes, and spindles, among which the spindles and the rotary axes can be bracketed together. Hence the main measurement objects, including five-axis machine tools, can be simplified as a linear axis and a rotary axis.

It is universally known that when an object moves in the three-dimensional space, it has six degrees of freedom (DOF); therefore, its position description has six errors. In a machine tool, similarly, there are six positional errors when a component moves along an axis. Taking X-slideway as an example, the six geometric error parameters are shown in Fig. 2a. The notation of error parameters is shown in Table 1.

For a 3-axis machine tool, there are 21 geometric error parameters, including positioning error (δ_{xx}), straightness error (δ_{yx}, δ_{zx}), pitch error (ε_{yx}), yaw error (ε_{zx}), roll error (ε_{xx}) of each axis, and squareness errors between every 2 axes. For multi-axis machine tools in precision and ultraprecision manufacturing, each rotation axis brings six geometric errors. Figure 2b shows the six geometric errors (δ_{xC}, δ_{yC}, δ_{zC}, ε_{xC}, ε_{yC}, ε_{zC}) of C-rotary table of a five-axis machine tool with a rotation-tilting table.

Error Characterization of Machine Tool

Measurement methodologies of geometric errors are divided into direct and indirect measurements. Direct measurements are used to measure linear positioning error, straightness error, angular error, etc. of individual axes, whereas indirect measurements are adopted to analyze volumetric error.

Single Error

Direct measurement methods (Uriarte et al. 2013) allow to measure component of errors separately regardless of the kinematic model of the machine and the motion of the other axes. Single error measurements can be classified in three separate subgroups according to their metrological reference: (i) Gauge-based methods, which are primarily subject to their dimensions and materials, use artifacts such as line scales, straightedges, and step gauges; multidimensional artifacts, such as ball plates, have gained widespread use in recent years, as they helped to overcome the drawback of elementary material standards which typically represent only one special use in terms of dimension or measuring task. (ii) Gravity-based methods, typically use devices such as inclinometers or spirit levels, allow angular error measurement around horizontal axes, while not measurable are angular motions around vertical axes; in inclinometers, a differential capacitive displacement transducer enables detection of even very small deviations. (iii) Laser-based methods use the laser light linear propagation and its wavelength as a reference. Laser interferometry is the most widely applied method for machine tool calibration because of high measurement accuracy.

The first demonstration of using light interference principles as a measurement tool was achieved by Michelson who developed the first interferometer in the 1880s. Laser interferometers have been applied to machine tool calibration tasks as the laser beam is particularly suitable for displacement/length measurement (Wuerz and Quenelle 1983). Due to their long-coherence length, the use of interferometric techniques for high-precision measurements is possible even for long axes. The most accurate and time-saving approach for either short or long machine axis is the use of laser interferometers. However, some error sources should be considered for a correct length measurement: errors in laser wavelength; beam deflection that occurred due to temperature changes and gradients; Abbe errors caused by misalignment between interferometer and axis of motion; and any movement of the equipment during the measurement process. These methods that based on laser interferometer principally measure the individual errors of machines (e.g., positioning, straightness, angular and squareness errors). Some measurement systems that combine multiple sensors are available for the measurement of rotary axes.

Positioning Error

Figure 3a presents the equipment setup to measure the Y-axis positioning errors on a cantilever-type lathe. The linear interferometer is placed on the machine table. The retroreflector is mounted on the end of the spindle. During linear measurement the laser system measures the change in relative distance between a reference and measurement optical path. Either optic can be moving, providing the other optic remains stationary. This setup measures linear displacement accuracy of an axis by comparing the movement displayed on the machine's controller with that measured

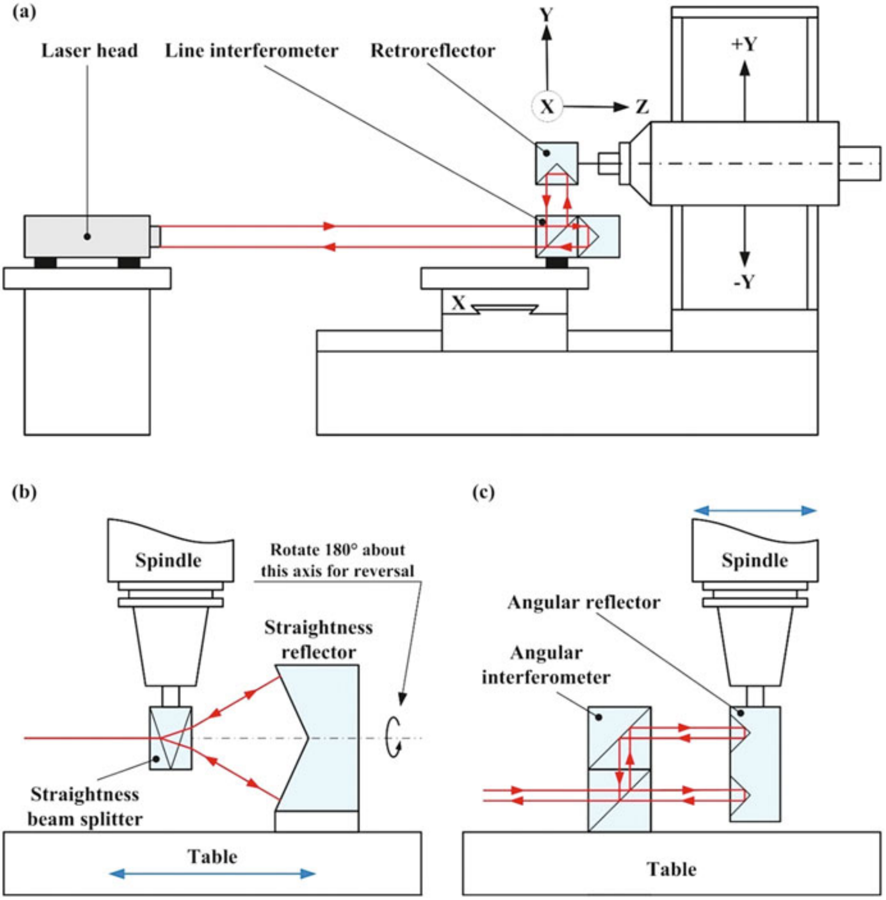


Fig. 3 Laser interferometers for (**a**) positioning error, (**b**) straightness error, and (**c**) angular error measurement

by the laser. Existing commercial laser interferometer can provide an accuracy of ±0.5 ppm with a resolution of 1 nm (Barman and Sen 2010).

Straightness Error

Straightness measurements record errors in the horizontal and vertical planes perpendicular to an axis movement. As is shown in Fig. 3b, a straightness interferometer is used comprising a Wollaston prism and a straightness reflector (Chen et al. 2005). The straightness reflector is mounted to a fixed position on the table even if it moves. The Wollaston prism should then be mounted in the spindle. Straightness measurements are made by monitoring the change in optical path generated by the lateral displacement of the straightness reflector or straightness beam splitter. The Wollaston prism performs as a beam splitter generating two separate beams that exit the prism at an angle. Both are reflected and recombined to generate an interference signal that allows the lateral displacement of the reflector to be determined. A combination of two straightness measurements makes it possible to assess the parallelism of independent axes.

Angular Error

Pitch and yaw angular errors are among the largest contributors to machine tool positioning errors. Even a small error at the spindle can cause a significant effect at the tool tip. The use of an angular interferometer (Bryan et al. 1994) to measure the angular errors is shown in Fig. 3c. Two parallel beams are generated with a beam splitter mounted in a fixed position on the machine table and are reflected by an angular reflector mounted on the end of the spindle. Angular measurements are made by monitoring the change in optical path generated by the movement of the angular reflector. Current instruments can measure maximum angular deflections of up to ±10° with a resolution of 0.01 arcseconds. Laser interferometers have been designed to operate with three parallel measurement beams, so the positioning, pitch, and yaw errors can be measured simultaneously.

Rotary Axis Error

Figure 4 illustrates the use of a laser and angular interferometer to measure small angles of rotation of a rotary axis. As the axis rotates, the laser system detects the relative change between the optical path lengths in the two arms of the interferometer. As the axis rotates by angle θ, the laser beam in Arm 1 will get shorter by $S\cdot\sin(\theta)$, and the laser beam in Arm 2 will get longer by $S\cdot\sin(\theta)$ where S is the separation between the two retroreflectors. The total relative change in the path lengths, between arm 1 and arm 2, is therefore $2S\cdot\sin(\theta)$. This change in path

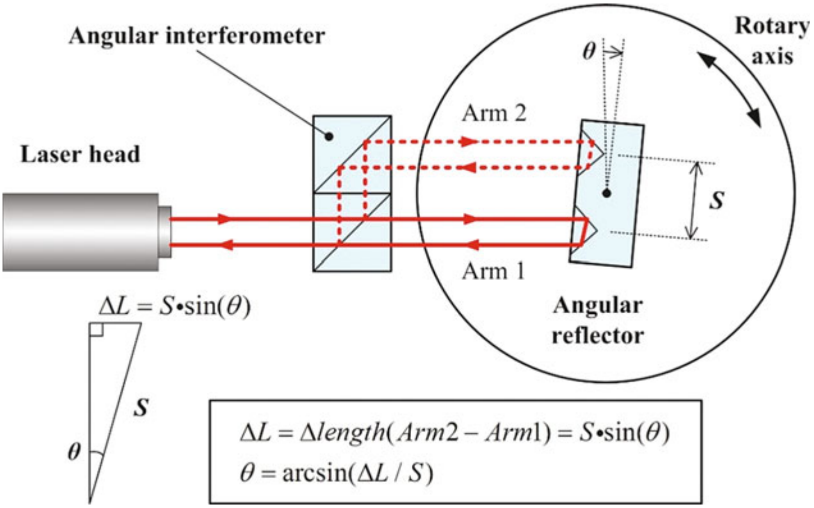


Fig. 4 Angle measurement principle of rotation of a rotary axis

lengths is detected by an interference fringe counter inside the detector unit of laser. The resulting fringe count is converted into a linear distance, ΔL, by multiplying by the $\lambda/2$. In angular mode the laser system software then converts ΔL into an angular measurement by calculating $\arcsin(\Delta L/S)$.

This arrangement is only suitable for checking angular movements over a range of about $\pm 10^\circ$, because, at larger angles, the rotation of the angular reflector will cause misalignment of the returned laser beams and a corresponding loss of signal strength. However, this limitation can be readily overcome by combining measurements from the laser interferometer with those from a high-accuracy rotary axis, such as Renishaw XR20, which allows calibration of the axis over 360°, even over multiple revolutions.

Squareness Error

The squareness measurement is to measure the straightness of two nominal orthogonal axes according the same reference, which is the extension of the straightness measurement in the two-dimensional direction. The squareness of the two axes can be obtained by comparing the straightness. The reference usually refers to the optical alignment axis of the mirror. The mirror is neither moved nor adjusted during measurements to maintain the reference line unchanged. The optical square is used for at least one measurement, allowing the laser beam to be aligned with the former straight line without moving the mirror straightness.

Multi-degrees of Freedom Measurement

Multidimensional laser interferometers have been adopted to measure more than one degree of freedom (DOF) simultaneously, so that several error components of a machine axis are calibrated with a unique measurement system setup through single error measurement methods. These multidimensional measuring solutions provide two main possibilities: (i) measuring time that is greatly reduced because different setups and measuring systems are not needed anymore and (ii) the possibility to be embedded into a machine tool, where the position of tool center point could be detected in real time by monitoring six DOFs of each machine movement at the same time, with multiple measurement systems performing all at once. Two main multidimensional solutions are available based on the straightness measurement principle: One is a multi-interferometer-based method, where the source of the interferometer is divided into three beams to perform a five-DOF measurement; another method uses the laser beam as a straight and a position-sensitive device as a pointing sensor unit to measure straightness error, which is suitable for small- and medium-size machine tools (Schwenke 2012).

Volumetric Error

Comprehensive volumetric error measurement is to separate the error parameters through mathematical identification model and to use the measuring instruments to measure the multiple volumetric errors of machine tools at the same time. Since the 1980s, error measurement mainly focused on the application of new types of precision measuring instruments of machine tools, such as the test bar and unidimensional probe, the disk gauge and bidimensional probe, double ball bar (DBB), capacitance ball probe (CBP), plane two-link mechanism, plane four-link mechanism, laser ball bar (LBB), etc. With the guidance of research works in the early 1980s (Bryan 1982; Knapp 1982), the tendency to take the abduction method of regular circular motion error measurement as the mainstream is basically formed. The ISO has added the motion test method for circular interpolation of CNC machine tools in the ISO 231. As a typical representative of the circular testing methods, DBB is widely applied and has been developed up to now. The CBP and LBB methods can all be regarded as the modifications of DBB.

Another established volumetric error indirect measurement method is the adoption of calibrated 1D, 2D, and 3D (Bringmann et al. 2005) artifacts. Figure 5 shows the 1D ball artifacts that were used to calculate the errors of the X-axis (Acosta et al. 2018). The artifacts have reference elements that are calibrated in two or three coordinates. By comparing measured coordinates to their calibrated values, error vectors resulting from the superimposed kinematic errors of the machine can be detected. By combining the data from several measurements at different orientations, an analytical or a best fit solution can be derived for the single kinematical errors. In general, this method has a higher requirement for the precision of the standard artifacts and can only measure a limited number of errors, so it is not widely used in practice. Recently, the research works have been focused on the improvement and application of mainstream methods such as laser interferometer and DBB, as well as the development and application of new detection methods and instruments, such as R-test and cross-grid encoder.

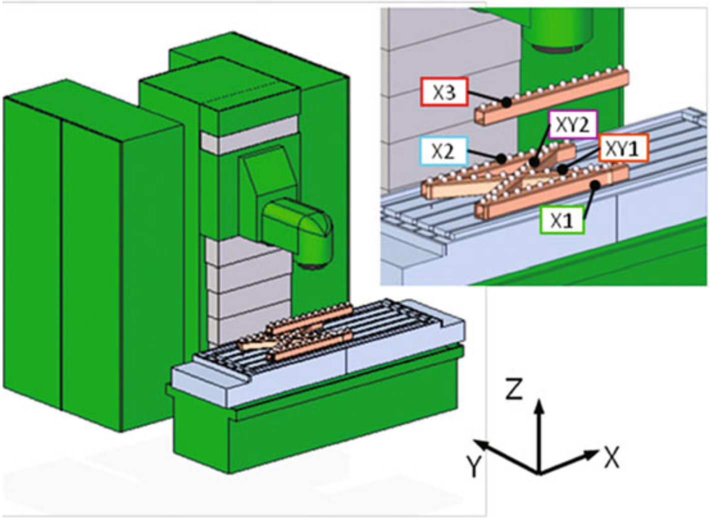


Fig. 5 Positions of the 1D artifact used to calculate the errors of the X-axis. (From Acosta et al. 2018)

Laser Interferometry

With the development of laser interferometry, the traditional interferometer-based single error measurements and comprehensive error measurements such as 12- and 14-line and 15- and 22-line methods have been widely applied in machine tool error measurement and identification. However, in actual measurement, most of these methods are extremely difficult to adjust, time-consuming, and long in measurement cycle, and additional expensive optical components are needed. ISO 230-6 defines the diagonal test method that the machine moves along each body diagonal of the machine's workspace, and the diagonal displacement is measured by using a laser interferometer (Ibaraki and Hata 2010). Diagonal test can calibrate the squareness errors of line axes, while the sensitivity to measurement error or noise is high in case of high aspect ratio of the measured volume. As an extension of diagonal measurement, the step-diagonal measurement has been put forward by Charles Wang (2000). The step-diagonal measurement modifies the diagonal measurement by performing a diagonal as a sequence of single-axis motions.

Conventional laser interferometers have long working range, but the variation of the measurement direction requires manual interaction. DBB can simply generate several measurement directions but is limited in the usable stroke. A combination can be seen in the use of the tracking laser interferometer or laser tracker. It is a laser interferometer with a steering mechanism to change the direction of the laser beam to track a target reflector which is usually mounted on the tool holder of the machine tool. Figure 6 (Gąska et al. 2014) shows a schematic grid of reference points within the distribution of probability and the laser tracker used to determine the distribution of errors, as reproduced by the machine. Since the angular measurement uncertainty of a tracking interferometer directly brings about the measurement uncertainty of the target's position, it is difficult to ensure the measurement uncertainty small enough to calibrate machine tools. Meanwhile, the tracking interferometers based on

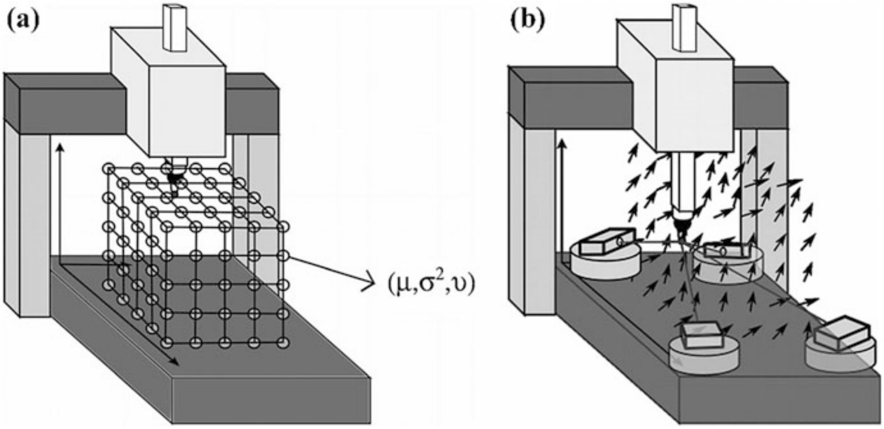


Fig. 6 (**a**) Grid of reference points. (**b**) Residual errors in nodes of reference grid and method of their identification. (From Gąska et al. 2014)

multilateration principle has been developed for machine tool measurement, in which the target of 3D position is calibrated by the distance from four or more tracking interferometers to the target (Ibaraki et al. 2014). Unlike traditional tracking interferometers which calibrate the target position from the distance and the laser beam direction, the multilateration measurement does not use the laser beam direction in its calculation and thus does not need higher angular positioning accuracy to ensure higher measurement accuracy of target position.

DBB

A ball bar usually consists of a kinematic artifact linking two precision balls, where precision linear variable differential transformers (LVDTs) are located between the two balls. A typical setup of a commercially available ball bar, where the measuring ball is fixed on the table of a machine tool and the center ball is attached to the spindle of the machine tool, can measure one-dimensional length variation and is ideal for quick checking of three-axis machine tools by means of the XY, YZ, and XZ planar circular tests (Kwon and Burdekin 1998). Figure 7 illustrates a DBB measurement in the X-Y plane (Lee et al. 2014); the two tested axes are driven simultaneously, causing the measuring ball to move on a circular path relative to the center ball. The change of distance between the two balls results from motion or dynamic errors of the two driven axes and is measured by a displacement sensor in the ball bar. Error origins can be rapidly diagnosed by comparing the resulting error trace with a set of reference trace patterns.

DBB is used extensively to calibrate the geometric and dynamic performance of linear machine tools. The main advantage of the DBB test methods is that it can find a servo mismatch of the simultaneously driven axes, while the laser interferometer and other optical displacement measuring devices only find positioning errors of a single axis. However, researches using DBB methods to test the rotary axes of

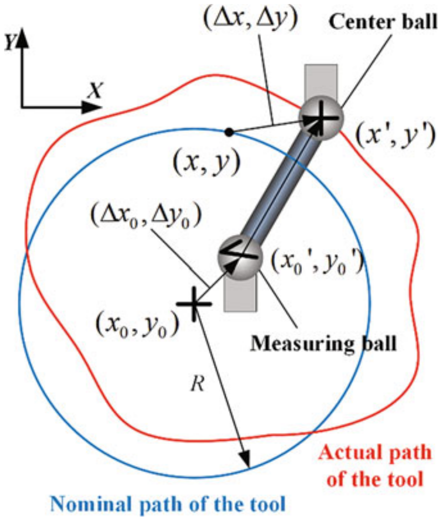


Fig. 7 DBB measurement in the X-Y plane

multi-axis machine tools simply, quickly, and effectively are deficient. Since ball bar measurement is one-dimensional, it often requires at least a couple of different setups to identify all location errors. A method for a tilting rotary-type five-axis machine tool has two steps to identify the imprecision of the rotary axes caused by the position-independent geometric errors (Jiang and Cripps 2017). The first step is designed to evaluate two rotary axes with one setup which performs fast diagnosis efficiency. A further accurate but slower check is carried out in the second step which aims to test the two rotary axes separately, each in two sub-steps. By means of varying the position of the pivot, the A- and C-axes can be tested individually. Both steps are performed with only one axis moving, thus simplifying the error analysis.

R-Test

As is described in ISO/CD 10791-6, many of the DBB tests presented above can be equivalently implemented by using a precision sphere and a linear displacement sensor (Utsumi et al. 2006). The 3D displacement of the sphere can be measured by using a nest of three (or more) linear displacement sensors. The R-test method was proposed based on this supposition (Weikert 2004; Bringmann and Knapp 2006). As depicted in Fig. 8a, the typical R-test device consists of a magnetic socket and three analogous distance sensors being arranged orthogonally to each other in a way that they are uniformly inclined to the horizontal plane. A ceramic sphere is adopted in contact with the three sensors at the same time. Using nominally flat contact geometries between the sensors and the sphere to be touched, the displacement of the center of the sphere is directly transferred by the three sensors (Hong et al. 2012). The three orthogonally aligned distance sensors presented in ISO 230-7 can be seen the same in principle. Furthermore, to identify all the geometric errors of the swiveling head in five-axis machine tools and to simplify the identification process, a new measuring approach (Fig. 8b) by indirectly using the R-test probing system is designed with the assistance of an auxiliary fixture (Li et al. 2017).

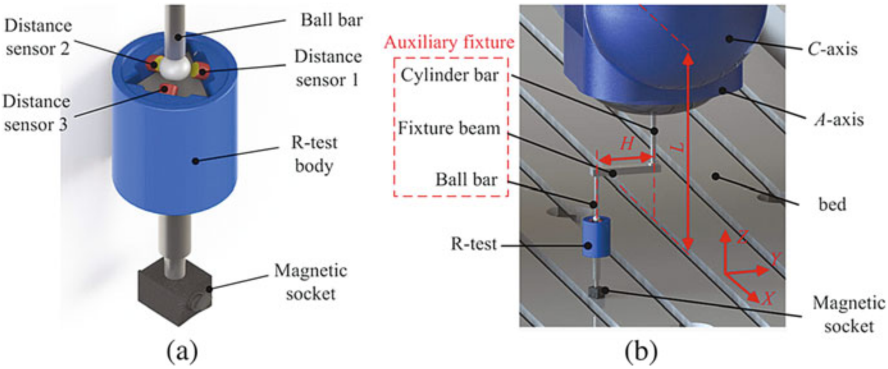


Fig. 8 R-test probing system. (**a**) Structure and (**b**) installation of the auxiliary fixture. (From Li et al. 2017)

Cross-Grid Encoder

The above methods have the problem that the installation, adjustment, and operation are very difficult and time-consuming. Aiming which, a cross-grid encoder (KGM) measurement system was developed by Heidenhain. It is a diffraction grating-type encoder to measure 2D position of an optical head by using a grid plate where grids are aligned orthogonally to each other. The KGM grid encoders consist of a grid plate with a waffle-type graduation, which is embedded in a mounting base, and a scanning head. During measurement, the scanning head moves over the grid plate without making mechanical contact. The KGM encoders capture any motions in a plane and separately transmit the values measured for the two axes. The cross-grid encoder test has many advantages such as high resolution, great agility of contact-free scanning measurement that permits free-form tests over any contours in two axes, and less restriction of relative motion speed. The resolution can reach 5 nm after subdivision, and the actual measurement speed can be up to 15 m/min, which means it is suitable for on-machine measurement (Du et al. 2010). The common KGM is 220 mm in diameter, making it unusable for error detection in the whole volume of a workspace.

On-Machine Measurement for Process and Product Quality Control

Various error measurement and compensation techniques and instruments have been developed and applied to greatly improve the performance of the machine tools. However, due to the mechanical and thermal deformations of the machine structure, motion errors of movable parts, and assembly error accumulated in a machine tool, the final machining accuracy disagrees with the output obtained from the embedded scales. In addition, clamping error of workpiece and tool wear also affect the final product quality. Progress in machine tools and measuring instruments requires the consideration of machine tool elements as well as setting and machining conditions, and it is essential to ensure the machining accuracy by providing the correct relative position between the cutting tool and workpiece. Therefore, on-machine and in-process measurements for the geometric parameters of workpiece and the tool setting are of equal importance.

Conception of OMM

A typical OMM system as illustrated in Fig. 9 is implemented using a workpiece measuring probe, which is usually stored in the tool library like a machining tool, and it is transferred to perform a certain measurement before or after a machining process. Integrating a workpiece measuring probe to the machine tool can deliver significant reductions in production time and cost and can be widely used for process improvement, automating, and speeding part processing, even eliminating part errors of the process. The machine tool should also be equipped with a tool setting probe

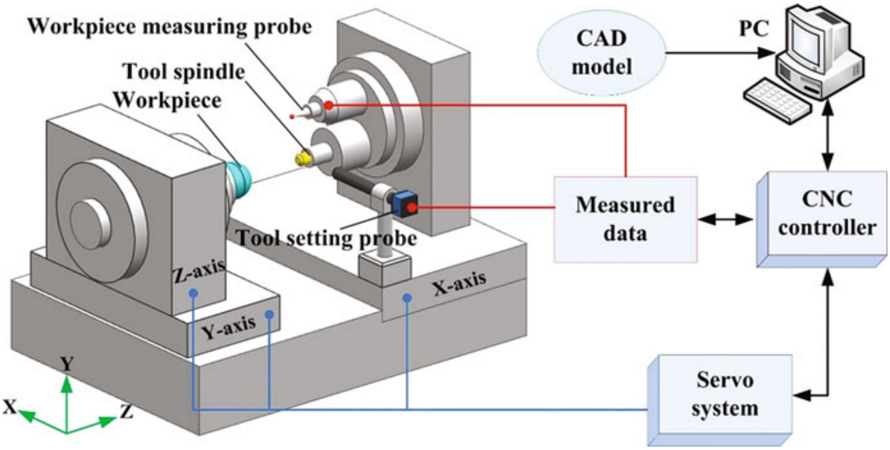


Fig. 9 Schematic diagram of on-machine measurement system structure

which is normally attached to the machine table or frame. Determining geometric information and the current condition of a cutting tool can help to improve the manufacturing process, including checking that the correct tool for the scheduled machining program has been loaded, correcting for tool wear, and automation of tool offset updating.

NC data generated using the part model is fed to the CNC controller for use in the first-step machining. After the machining process is finished, the workpiece measuring probe replaced with a cutting tool starts the measurement in the normal direction to the machined surface. Since a probe measures parts moving along the erroneous machine tool axes, the measured data inevitably include the probing errors originated from the structural characteristics of a touch probe and the positioning errors originated from the inaccurate axis motion of a machine tool. These errors should be eliminated from the measured data to obtain the true machining error. If the true machining error is larger than the given tolerance, the new toolpath is generated using the error compensation algorithm for the next-step machining. Machining and OMM processes are repeated until the required part tolerance is obtained, resulting in the closed-loop machining system.

ISO 230-10 has specified the test procedures for evaluating the measurement performance of contacting probe systems integrated with CNC machine tools. However, ultraprecision manufacturing that requires nanoscale measurement accuracy has accelerated their industrial application. On the other hand, the machine tools have largely spread to simultaneously multi-axis control machining to meet the ever-growing demands for precision parts with complex geometric properties, such as free forms and fine surface figures (Fang et al. 2013). To compensate for time-variable machining errors for the manufacture of complex structures in real time, on-machine measurement techniques with high accuracy are urgently needed.

Probing Techniques for Geometric Parameters of Workpieces

Contact Touch Probes

Contact touch probes can be classified into discrete and scanning groups based on the type of data being acquired, as shown in Fig. 10. Discrete probes, or touch-trigger probes (TTP), have the superiority of being cheaper than other options and are suitable for few data point acquisitions such as the position or size measurement. Scanning probes continuously touch the object as the probe is moved along the expected contour, which perform well in high-speed data acquisition on an object's form characteristics.

Machine-mounted probes are often referred to as TTPs, kinematic resistive probes, and strain gauge probes (Ali 2010), because they use switches that are triggered upon contact between the probe stylus and the workpiece being measured. As for kinematic resistive probes, most TTPs make use of a kinematic seating arrangement for the stylus. Three equally spaced rods rest on six tungsten carbide balls providing six points of contact in a kinematic location. An electrical circuit is formed through these contacts. The mechanism is spring loaded which allows deflection when the probe stylus contacts the part and also allows the probe to reseat in the same position within 1 μm when in free space. Under load of the spring, contact patches are created through which the current can flow. Reactive forces in the probe mechanism cause some contact patches to reduce which increases resistance of those elements. The variable force on the contact patch is measured as a change in electrical resistance. When a defined threshold is reached, a probe output is triggered. However, if the pivot distance varies depending on the direction in which the contact force acts in relation to the probe mechanism, pre-travel variation occurs to affect measurement performance. The use of strain gauge probes has improved the performance limitations mentioned above in kinematic resistive probes, because modern compact electronics and solid-state sensors have been embedded. The strain gauges are arranged to sense all stylus forces, which are summed together to acquire the measuring point. As a result, a lower trigger force is needed, and uniform pre-travel variation is achieved in all directions.

Analog scanning probe ensures a permanent and continuous contact between the probe and the component under measurement, so it is particularly suitable for

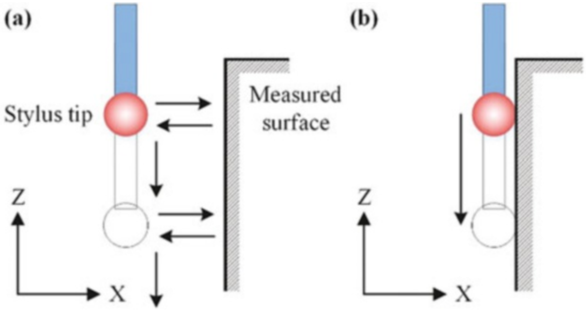


Fig. 10 Types of probes. (**a**) Touch-trigger probe, (**b**) scanning probe

free-form and contoured shaped components as well as for the measurement of large sheet metal assemblies, such as automobile components. Continuous analog scanning is a relatively new technology. Its main advantage is the high acquisition speed, which reduces dramatically the measuring time while offering a high density of data acquisition for a full definition of the size, position, and shape, enabling completely new opportunities for on-machine metrology (Weckenmann et al. 2004). To enable touch probing system to measure the shapes of both the workpiece and the tool during an electrical discharge machining process, a multiple-degrees-of-freedom arm for holding the probe with passive joints was reported (Furutani et al. 1999), which has the potential to be applied to OMM of a machined workpiece with a complex shape using multi-axis machine tools.

Optical Probes

Optical probes such as triangulation, interferometry, and confocal sensors have the advantages that they are non-contacting and nondestructive and, by using visual sensors, they also have a higher speed than contact methods, which can be used for rapid sampling. Interferometric probes among these methods have been widely applied because of high sensitivity and nano-level vertical resolution. In addition, the confocal laser probes can produce a very small spot with a resolution of up to 10 nm, which are suitable for the measurement of microstructure parts.

Optical Triangulation

Laser triangulation probes are increasingly considered as a viable alternative to touch probes for rapid dimensional measurements in a variety of applications. The main components of a triangulation probe are a collimated light source (generally a laser diode) and a detector unit consisting of an imaging lens and a detector (CCD line or position-sensitive diode). The optical axes of the light source and the imaging lens form a fixed angle, the so-called triangulation angle. The object surface is brought close to the point in which both axes intersect and the diffuse reflection of the light spot on the workpiece surface is imaged onto the detector. The position of the image on the detector is a function of the distance between sensor and specimen, as shown in Fig. 11a (Muralikrishnan et al. 2012). If a structured pattern generator is used to generate a laser line onto the target workpieces, the reflected laser line that follows the profile of the object is imaged back on the image sensor (Huang and Kovacevic 2011). The height of each point on the surface of the target stripe can be precisely determined based on the mathematical relationship derived from geometrical optics as illustrated in Fig. 11b. Another improvement is the realization of 3D scanning by adopting a galvanometer in a laser triangulation measurement system (Yang et al. 2018).

Interferometry

OMMs are very important for ultraprecision machining because it requires tolerance on the order of several tens of nanometers. The practical purpose is to make the repeated correction processes efficient and enable compensation for accidental and systematic machining errors by direct process control. To meet these demands,

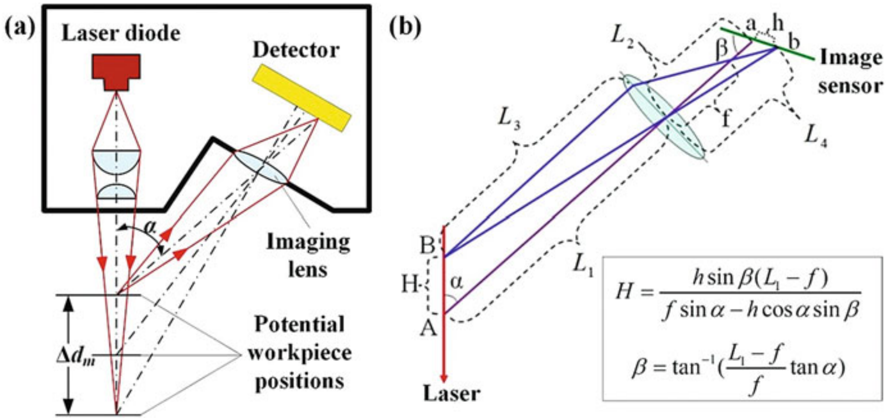


Fig. 11 Laser triangulation probe. (**a**) Structure, (**b**) measurement principle

high-precision optical interference measurement methods were initially developed. Many commercial compact laser interferometers (Muralikrishnan et al. 2016) are stable and reliable enough for dimensional measurement such as position, size, and profile scanning, while the shape and surface measurements using wavefront interferometry seem to be easily affected by disturbances such as vibration and air turbulence in the optical paths. Improved measuring instruments such as Fizeau interferometer, zone-plate interferometer, and lateral-shearing interferometer were mounted on a modified lathe to examine the measurement performance while the machine was running. Nomura (Nomura et al. 1998) invented a common-path lateral-shearing interferometer for machine running combined with fringe-scanning method, which was little affected by mechanical vibrations and air turbulence.

Phase-shifting laser interferometer (Tian and Liu 2016) is a common full-field shape measurement equipment for spherical or aspherical optical mirrors that are machined by ultraprecision diamond turning. When it comes to in-process or on-machine measurements, however, multiple frames of data are required over many milliseconds, which means vibration and turbulence have enough time to degrade the measurement results. A better approach for reducing these effects is to capture all the phase-shifting frames fall on a single CCD camera at once (Millerd et al. 2017). As shown in Fig. 12, a holographic optical element (HOE) is used to split interferograms into four separate beams. The four beams pass through a phase-shifting mask and a polarizer with its transmission axis at π/4 to the direction of the polarization of the test and reference beams placed in front of the CCD array. In this way a single detector array captures all four phase-shifted interferograms in a single shot.

To achieve trans-scale and close-to-machine measurement with low uncertainty, a complementary integrated system that combines the large-aperture DHI and the sub-aperture stitching WLI was proposed (Yang and Zhang 2018). As shown in Fig. 13, the DHI subsystem is used to complete a rough measurement of the overall profile of the object, and thus establish a reasonable way of path planning, and then guide the WLI probe to measure the local detail features with nanometer accuracy.

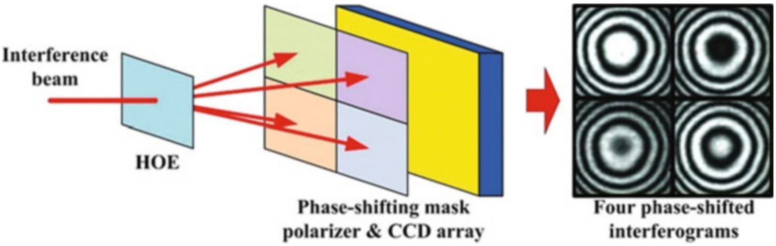


Fig. 12 A single-shot detector to capture four separate, phase-shifted interferograms

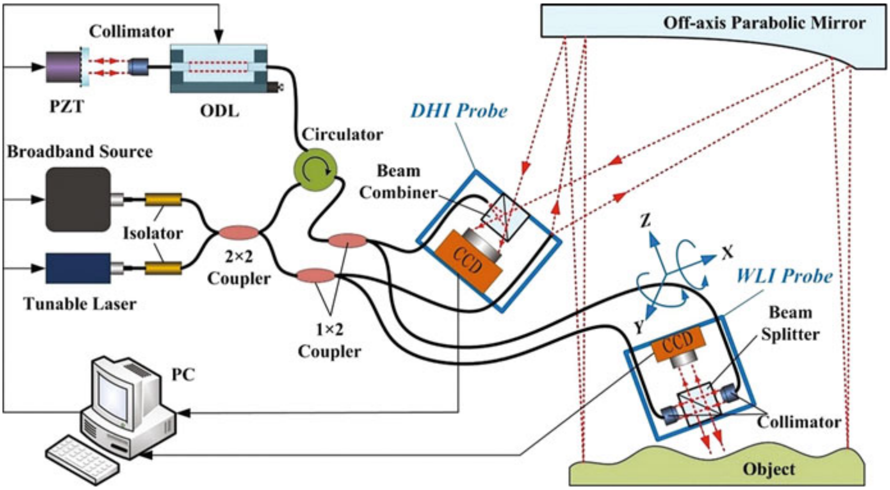


Fig. 13 A complementary integration of the large-aperture DHI and the sub-aperture stitching WLI. *ODL* optical delay line

Confocal Probing

Chromatic confocal sensing is a well-known measurement technique that is able to evaluate the position of a point on an object surface along the optical axis of the system with high accuracy. The optical principles of an improved chromatic confocal probe are illustrated in Fig. 14a (Zou et al. 2017). The white light point source passes through an objective lens, which diffracts the emerging light according to its wavelength. Only light of a wavelength λ_M is focused at a point M on the surface being measured. The backscattered light passes back through the objective lens and is then directed toward the detector by a beam splitter. The pinhole located at the image of *M* plays an essential role in this system because it filters out all wavelengths except λ_M that derive from points located on the optical axis above or below *M*. A confocal probe-based OMM system is shown in Fig. 14b. The system is composed of an aerostatic spindle and vacuum chuck, two horizontal hydrostatic slideways (x- and z-axes), an orthogonal y-axis precision stage, a chromatic confocal probe mounted on the y-axis translation stage, a standard radius sphere affixed in the vacuum chuck (the master sphere), and a second standard radius sphere

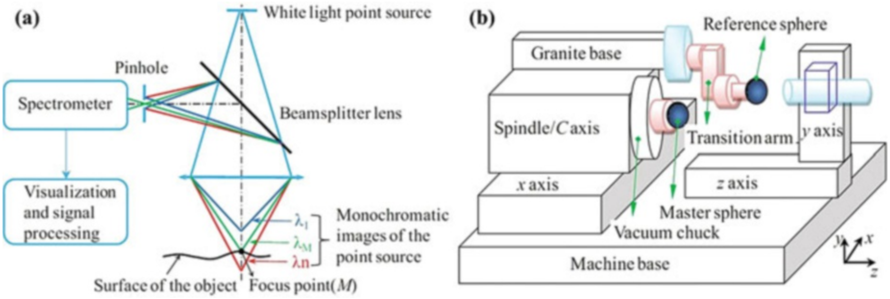


Fig. 14 A chromatic confocal probe. (**a**) The optical principle, (**b**) schematic diagram of the OMM system. (From Zou et al. 2017)

(the reference sphere) mounted to a granite base located on top of the spindle via a dedicated transition arm attached to a standard System 3R holder.

The chromatic confocal probe and y-axis translation stage form an integrated component of the OMM system, and the reference sphere and transition arm form another integrated component. The y-axis precision stage is bolted onto the z-directional slideway. The optical axis of the measurement probe is adjusted to be collinear to z-direction. The spindle and vacuum chuck are positioned on the x-directional slideway. The standard spheres must be of sufficiently high geometric accuracy and are employed to calibrate the relative distance between the rotary axis of the spindle and the center of the reference sphere.

Shack-Hartmann Wavefront Sensing

Shack-Hartmann wavefront sensing (Platt and Shack 2001) is one of the well-known optical measuring methods for lens aberration or concave mirror surface figure. The basic structure of the Shack-Hartmann wavefront sensor is composed of a microlens array and a CCD camera. Each lens takes a small part of the aperture (sub-aperture) and forms an image of the light source. According to the relationship of simple geometrical optics, the average slope of the wavefront can be calculated by measuring the difference between the centroid coordinate position of the actual imaging spot and the centroid coordinate position of the actual imaging spot and the centroid coordinate position of the reference imaging spot. The actual wavefront can be reconstructed between the slope data and the Zernike coefficients. The Shack-Hartmann wavefront sensor has a large dynamic range and high measurement accuracy, low environmental requirements, short detection time, and easy operation which is used for the on-machine measurement of the position and displacement and aspheric and free-form surfaces.

Measurement Tools for Process Control and Tool Setting

Machining accuracy is largely affected by tool conditions including the geometric features of the tool, tool setting, and tool behavior during machine running. Generally, systematic machining error is caused by the geometric features of a tool and the tool setting, while accidental machining error is introduced due to the tool behavior during machine running. The specific geometrical tool conditions related to systematic machining error are the tool length, tool diameter, cutting-edge sharpness, and tool setting with respect to the position of the tool tip and the dynamic balance. However, unexpected behavior and fluctuation of the tool such as deflection and dynamic and thermal conditions and tool wear during machining make the machining conditions unstable. With the help of OMMs, an essential control of machining process capability can be achieved by improving the machining repeatability.

Touch-trigger probe or laser-based technologies are usually applied for tool setting. The touch-trigger tool setter uses the same kinematic technology as workpiece inspection probe which has been introduced in section "Contact Touch Probes." Noncontact laser tool setting system uses a beam of laser light, passing between a transmitter and a receiver, positioned within the machine tool so the cutting tools can be passed through the beam. The passage of a tool into the beam causes a reduction in laser light seen at the receiver, from which a trigger signal is generated. This latches the machine position at that instant, providing the information to determine a tool's dimension. With approaches from several directions, tool geometry can also be accurately determined. These systems can also be used to detect broken tools, by rapidly moving the tool into a position where it should intersect the laser beam; if light reaches the receiver, the tool tip must be missing.

Tool cutting-edge profile is an essential factor that significantly affects the machining process capability index, and it is expected to remain changed during machining, ideally for stable and high machining accuracy. During ultraprecision cutting, the depth must be controlled within nanometers. Therefore, it is important for assurance of the machined surface quality to make periodic checks on the tool cutting edge without moving the tool from the machine. A measuring instrument consisting of an atomic force microscope (AFM) and an optical alignment probe was developed for fast measurement of 3D cutting-edge profiles of single-point diamond cutting tool (Gao et al. 2009).

The reduction of accidental machining error by monitoring the dynamic conditions of the tool, such as the tool wear which is the result of a combination of load factors (mechanical, thermal, and chemical) affecting the cutting edge of the tool, is an important technical issue. Various sensors have been developed while the machine vision sensors performed online monitoring with high-speed (real time) and noncontact capability. In addition, as machine vision and artificial intelligence are natural partners, integration of the two technologies is to provide a better understanding of the tool wear problem (Malekian et al. 2009). The edge radius of the tool is used for the monitoring of the tool conditions, and it could be measured by counting pixels from the vision system and comparing the number with the scale on the reticle. On the other hand, cutting forces (static and dynamic), AE, and vibration (acceleration) are considered the most widely applicable parameters. Advances and increased sophistication in instrumentation technology employed for measuring these parameters make them viable, practical, cost-effective, robust, and easy to mount and have the quick response needed to indicate changes for online monitoring of machining process (Teti et al. 2010).

Measurement of Distance Between Tool and Workpiece

Control of the relative distance between a tool and a workpiece is quite important in ultraprecision machining because the relative distance determines their interaction and the quality of a machining result. In general, the position of a tool or a workpiece is controlled with embedded scales of positioning systems. However, due to the mechanical and thermal deformations of the machine structure, motion errors of movable parts, and assembly error accumulated in a machine tool, the final relative distance between a tool edge and a workpiece surface disagrees with the output obtained from the embedded scales. In addition, clamping error of workpiece and tool wear are also added to the relative distance. Thus, a direct measurement of the distance between the tool edge and the workpiece surface is especially required.

Figure 15 shows a measurement model of laser diffraction for tool setting clearance between the tool tip and workpiece surface (Shi et al. 2015). The clearance between the tool and the workpiece is set for x, the wavelength of the laser beam is set for λ, and the diffraction light angle is set for θ. When the laser passes through the tool workpiece clearance, diffraction fringes will be generated. Then the diffraction fringes go through the Fourier lens with the focal length f and finally irradiate on the CCD screen. The computer will process intensity information of the diffraction fringes obtained from the CCD camera. According to the integral formula of Fraunhofer diffraction, the distance between the tool tip and the workpiece surface can be calculated.

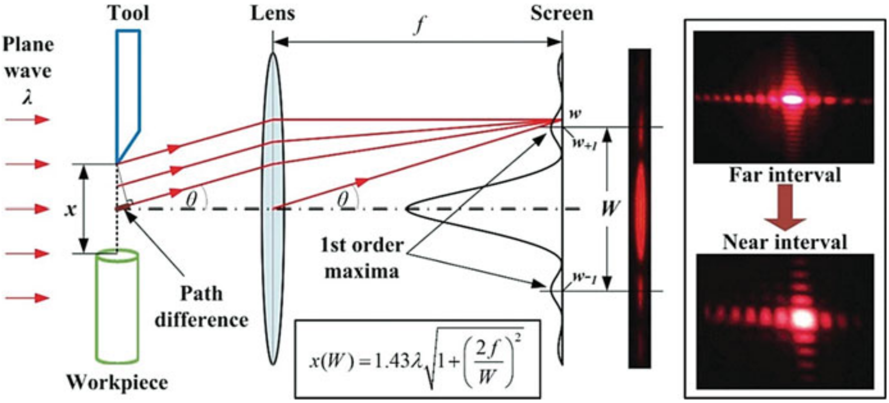
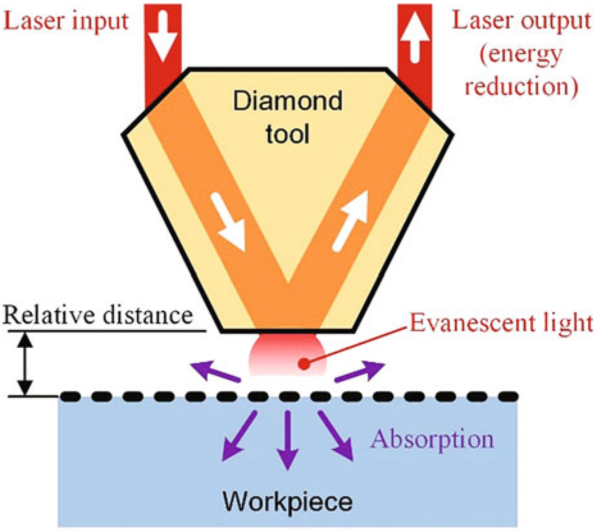


Fig. 15 Laser diffraction application on distance measurement

Fig. 16 Evanescent light application on distance measurement



Single crystal diamond tools are widely used as a tool in ultraprecision cutting, and the diamond crystal has a large index of refraction. As shown in Fig. 16, when a laser beam is irradiated to the tool edge over the critical angle, the total reflection of laser beam generates evanescent light in the sub-micrometer area from the tool edge. Evanescent light has the intensity distribution depending on a distance from the tool edge (Yoshioka et al. 2014). Approach of the tool to a workpiece results in absorption and dispersion of evanescent light, and it decreases the intensity of reflected light. Thus, the distance can be estimated by monitoring of the intensity of reflected light.

Integration of Online Machining and Process Monitoring

Various developments in machine tool metrology and OMM technology lead to increasing the automation, flexibility, and productivity of machine tools. The process capability is evaluated as being worse than the actual capability because of the measurement uncertainty (Mutilba et al. 2017). Therefore, when the improvement of process capability is attempted, the measurement uncertainty should be suppressed to determine the control target based on process capability indices estimated as accurately as possible. Meanwhile, it is important to enable further fine-tuning of the control qualities during the machining process for high repeatability and robustness. To achieve this progress in machine tools, a fusion of machining and measurement technologies is required to optimize the assessment and control of the machining process during machining.

In most developments of OMM, the measuring instruments were implemented or mounted externally to the machine tools. However, to develop more advanced methods for direct control of the machining process, machine tools with internal sensors were required. The sensing techniques for monitoring and controlling the machine force can be considered as in-process measurements that are independent of external and internal factors. And much research effort has gone into the autonomous determination of machining parameters for conducting feedback control while minimizing human intervention. This was developed to enable even a non-expert machine operator to perform highly productive and accurate machining processes. This is because in conventional NC machining, the process control of an expert machine operator can be provided as feedback control that includes the decisions of the human operator. Furthermore, it is suggested that the application of process monitoring and control to specific machining problems has practical values, which include micromachining and machining of new and difficult-to-cut material areas in which even expert human operators find effective process planning difficult. This productive insight was supported by the development of an adaptive spindle with three built-in force sensors, which enables active compensation of static and dynamic tool deflections and stabilization of milling processes (Möhring et al. 2010). For the simultaneous measurement of the grinding force and workpiece form error during cylindrical-plunge grinding, capacitive probes are embedded in the work spindle to produce normal and tangential grinding forces, and an additional capacitive probe is applied to measure the size of the workpiece.

Integration of online machining and inspection is an effective way for machining process control to improve machining quality. The conventional approach for the integration of the machining and inspection operations is that, first, inspect the workpiece after certain machining processes or just the final state of the machined workpiece using a CMM or using online inspection devices on machine tools and then compensate or adjust the tool path according to the inspection results. Construction of uniform information model and definition of standardized interfaces are the primary methods for the integration of machining and inspection. It is also important and beneficial to alert an abnormal state of a machining process and address the issue in a timely manner through the integration of machining and monitoring functions. Monitoring signal data analysis is the approach for machining condition recognition based on the sensor signals. Typical signal data analyzing methods include artificial intelligence algorithms, multi-signal fusion methods, and wavelet analysis methods. The ultimate goal of monitoring is used for adjusting the machining strategy timely to improve the machining stability and machining quality, i.e., modifying tool path and changing machining parameters and operation sequence and conditions. The current research efforts mainly include cutting parameter adjustment to stabilize the cutting force, decrease vibration, suppress machining chatter, and avoid surface defect of workpiece. Figure 17 describes an integrated manufacturing process planning and online control based on intelligent software agents and multidimensional manufacturing features (Liu et al. 2014).

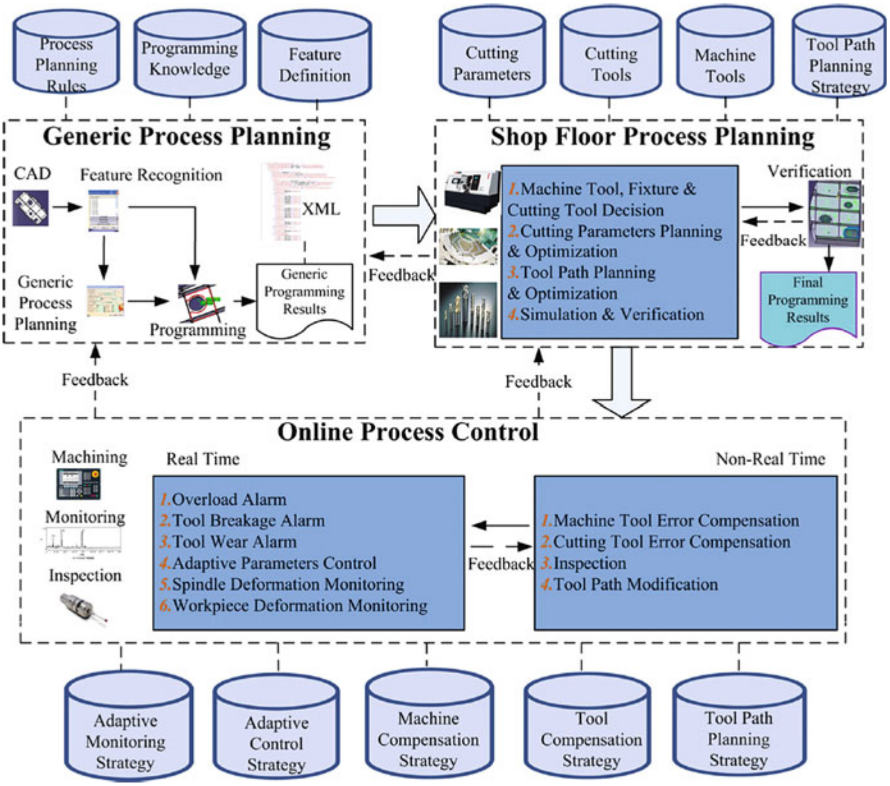


Fig. 17 Architecture of process planning and control system. (From Liu et al. 2014)

Conclusion

With the rapid development of hi-tech and new tech, the requirements for machining accuracy of parts have risen from micron- to submicron and even nanometer level. The trend toward individualized products and smaller lot sizes with high precision increases the demands of higher machining reliability and flexibility in production. However, many factors still result in machining errors which can be considered as the original errors of machine tools and the errors produced in the machining process, involving kinematics errors, thermal errors, cutting force-induced errors, servo errors, machine structural errors, vibration and tool wear, etc.

For the original errors of machine tools, various error measurement and compensation techniques and instruments have been developed and applied to greatly improve the performance of the machine tools. Measurement methodologies are divided into direct measurements and indirect measurements. Direct measurements are used to measure single errors such as the linear positioning error, straightness error, and angular error of individual axes, whereas indirect measurements are adopted to analyze volumetric error. Laser interferometers are undoubtedly the best choice for single error calibration because of its high measurement accuracy and long working range, and a series of mature commercial instruments have been launched to such applications. Some systems combine multiple interferometers for simultaneous measurement of positioning, straightness, and angular errors. However, the environmental factors have a non-negligible impact on the laser wavelength and optical path difference, which are directly transferred into errors in the measurement results. Comprehensive volumetric error measurement is to separate the error parameters through mathematical identification model and to use the measuring instruments to measure the multiple volumetric errors of machine tools at the same time. Recent research works focus on the improvement and application of mainstream methods such as the tracking laser interferometer and DBB, as well as the development and application of new detection methods and instruments, such as R-test and cross-grid encoder. These methods still have many limitations as follows:

1. Measurable dimension: DBB tests measure only one-dimensional displacement of the tool center position. Interferometer-based diagonal and step-diagonal tests also perform one-dimensional measurements.
2. Measurable positions: Artifact-based measurement can measure only at pre-calibrated positions. Motion trajectories for DBB tests are limited by the position of the fixed ball. Tracking laser interferometers can measure arbitrary positions in large workspace, although their measurement uncertainty may change considerably according to the target position.
3. Axis separation: DBB tests for rotary axes and R-tests are typically performed with two or three linear axes driven synchronously with a rotary axis of interest. The measurement result will be influenced by all axes involved. Most volumetric error measurement methods have the problem about the separation of error motions of linear axes and rotary axes in kinematic model construction.
4. Angular errors: Quasi-static measurement of artifact can evaluate angular errors directly. DBB tests and R-tests only measure the position of the reference sphere center, because the sphere does not define any direction. Angular errors can be assessed only when the kinematic model is best fitted by measuring data at multiple points.

The final machining errors are generated due to the interaction of geometric errors, thermal errors, force errors, and servo errors of machine tools. The mechanism of these error interactions is not clear, which brings difficulties to error measurement and modeling. A great variety of instruments recommended by the ISO 230 series generally have shortcomings such as long measuring period and low measuring efficiency, which make the overall measurement and compensation of machine tools error can’t really be implemented and become a technical bottleneck that restricts the improvement of measurement accuracy and manufacturing level. Therefore, how to achieve the high accuracy and fast measurement of multi-error parameters has become one of the key problems that need to be solved urgently for the error compensation of machine tools.

Due to the mechanical and thermal deformations of the machine structure, motion errors of movable parts during machine running, and assembly error accumulated in a machine tool, the final machining accuracy disagrees with the output obtained from the embedded scales. In addition, the final machining error is a comprehensive interaction of various error sources including random errors such as vibration, tool wear, and environmental factors. It can be considered that the machining error is finally reflected directly in the machining quality of the products and indirectly in the relative position between the tool and workpiece. Progress in machine tools and measuring instruments requires the consideration of machine tool elements as well as setting and machining conditions, and it is essential to ensure the machining accuracy by providing the correct relative position between the cutting tool and workpiece. In-process and on-machine measurements constitute the simplest method for achieving high accuracy and small uncertainty values, as well as reducing the measurement procedures. Nevertheless, the system requires optimal trade-off between machining time and measurement performance. The conventional approaches focus on achieving good measurement performance without a clear trade-off and on the practical benefit of introducing in-process and on-machine measurements.

"Industry 4.0" represents an initiative for the future development of machine tools. The conception aims to combine the manufacturing industry and measurement technology to make production more flexible, where the flexibility offers the possibility to manufacture customized products through efficient manufacturing processes. As demand fluctuates and batch sizes fall, efficiency in process adjustment and production control operations become crucial. During production, machine tool performance, cutting tool conditions, cutting parameters, and workpiece geometry and properties change all the time. The integration of online machining, inspection, and monitoring is a final solution to addressing the problems mentioned above. Efforts have been made in online adjustment of cutting parameters and emergency actions and online tool path compensation. Advanced sensors and sensor systems such as dynamometers, accelerometers, AE sensors, and current and power sensors have been adopted for intelligent monitoring of machining process. However, more work should be devoted to online process control, information fusion, and optimization for dynamic and complex machining conditions.

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