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Review Article

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Techniques of multi-degree-of-freedom measurement on the linear motion errors of precision machines

Abstract: Any axis of precision machines possesses six-degree-of-freedom (6-DOF) motion errors, also called the geometric errors, due to manufacturing tolerances and assembly errors, namely three linear and three angular errors. Conventional optical instruments allow measurement of only one or two errors at a time. In order to achieve fast measurement, many multi-degree-of-freedom measurement (MDFM) systems have been developed over the past 20 years, from three-degree-of-freedom (3-DOF) to 6-DOF. This article summarizes reports of optical measurement techniques of MDFM systems for precision linear, planar and XYZ stages. Comments are also given for the applicability to practical uses.

Keywords: diffraction grating; laser interferometer; linear motion; multi-degree-of-freedom measurement; planar motion.

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1 Introduction

Any axis of precision machines possesses six-degree-of-freedom (6-DOF) motion errors, also called the geometric errors, due to manufacturing tolerances and assembly errors, namely three linear and three angular errors. The structural design of most precision machines, such as machine tools and coordinate measuring machines (CMM) has inherent Abbe errors [1]. It defines that the measuring apparatus is to be arranged in such a way that the distance to be measured is a straight-line extension of the graduation used as a scale. Bryan further made a generalized interpretation that if the Abbe principle is not possible in the system design, either the slide-way that transfers the displacement must be free of angular motion or the angular motion data must be obtained to compensate the Abbe error using software [2]. Methods of testing machine tool accuracy have been suggested in some well-known books in the early stage as guidelines [3, 4]. ISO also specifies the standard methods of testing machine tool and CMM accuracy [5–7]. Those are mainly for one-degree-of-freedom (1-DOF) or two-degrees-of-freedom (2-DOF) measurement methods. The first laser interferometer-based apparatus for measuring five geometric errors was developed by Hewlett Packard [8], but can only measure 1-DOF each time with specified optics. The special feature of such kinds of laser interferometer system is to measure the out-of-plane moving object. In other words, the reflective mirror has to be moved along its normal axis. Technical overviews of the optical methods available for dimensional metrology of laser interferometer based systems in large-scale machine tools and CMMs, are summarized by Schwenke [9], Estler [10] and Slocum [11]. For a basic three-axis machine, the measuring time for the total of 21 geometric terms requires several days, which is time consuming. The variation of ambient conditions will affect the machine's structure as the well as measured results if the time elapse is too long. The need of MDFM for fast accuracy calibration of precision machines has thus been studied since 1990. The main approach is to split the beam of laser displacement interferometer into two or three parallel beams, which are reflected back by corresponding mirrors or corner cube reflectors (CCRs) mounted on the moving stage. The straightness or angular errors of the stage will result in the lateral shift or tilted angle of the returned beams that can be detected by position sensitive detectors or autocollimator kits. Typical examples of 6-DOF measurement systems

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were proposed by Shimizu [12], for machine tools in 1994, and Huang [13], for CMMs in 1995. After this time, many other reports of laser interferometer-based MDFM systems in different optical configurations have been proposed for various applications. These techniques will be reviewed in the following sections.

In addition to the trend of laser interferometer-based MDFM systems, another trend is based on the laser grating encoder, also called the grating interferometer. In 1992, Teimel described the operating principle and characteristics of grating interferometers [14]. It is known that laser wavelength is sensitive to the ambient condition and has to be corrected with respect to the refractive index of air [15, 16]. The grating pitch is relatively more stable in ambient conditions so that the readings of grating interferometer fluctuate less than the laser interferometer [17, 18]. In contrast to the laser interferometer, the special feature of the laser grating encoder is to detect the Doppler shift of two diffracted beams when the grating is moved perpendicularly to the laser beam and in the direction of grating pitch, called in-plane motion. In other words, the grating has to be moved in the direction perpendicular to its normal axis. However, due to the inevitable 6-DOF motion errors of the grating, the generated diffractive beams are also sensitive to the straightness and angular motions of the grating. Based on this phenomenon, detecting the change of the laser spot at the corresponding sensing position of each diffractive beam of interest could make the MDFM system possible. In practice, it is difficult to make the grating in a large size; it is normally attached to medium to small sized precision machines. This kind of laser grating encoder-based MDFM system has been developed since 2000 [19]. A thorough survey report was given by Lee in 2013 [20]. Some typical examples are collected in the book written by Gao in 2010 [21].

In this paper, a general review of MDFM techniques on the linear motion errors of precision machines is studied, including the laser interferometer-based and the laser grating interferometer-based in-plane motion errors. The basic principles of displacement, straightness and angular error measurements will be introduced in Section 2. The MDFM systems will be reviewed for linear, planar and XYZ motions in the following sections.

2 Basic principles of 1-DOF and 2-DOF measurements

As mentioned above, normal 6-DOF geometric errors of a moving stage consist of the positioning error along the moving axis, two straightness errors perpendicular to the moving axis, and three angular errors along three perpendicular axes, as shown in Figure 1.

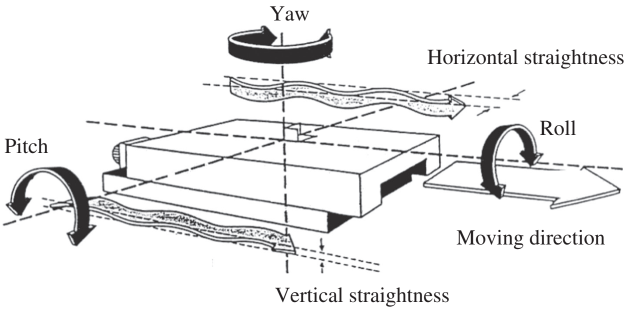

Figure 1 6-DOF geometric errors of a linear moving stage.

2.1 Displacement measurement

In micro- and nano-measurement technology, laser interferometers are commonly used to detect the out-of-plane displacement of the stage, as they provide a means for attaining high metric resolution and precision, even over long measurement ranges. There are two types of laser interferometers on the market; both are based on the principle of Michelson interferometer. Heterodyne laser interferometers with dual frequencies are the basis of metrology and control in high accuracy displacement measurement applications [8]. Homodyne laser interferometers have some advantages in terms of ease of use, simple structures and lower cost [22, 23]. However, the stability, resolution and accuracy of the homodyne laser interferometer is susceptible to its environment, vibration, the structural design of equipment and other factors. Its accuracy can be improved using a polarization state technique [24]. Figure 2 shows an example of the polarizing homodyne laser interferometer in which a CCR is mounted onto the moving stage. A partially polarized laser beam impinges on the polarizing beam splitter PBS1 and is split into two beams: the transmitted P-beam and the reflected S-beam. The P-beam will be reflected back by the moving CCR (object beam) and the S-beam is reflected back by the reference CCR (reference beam). The quarter waveplates (QWP) Q1 and Q2 prevent the diffraction beams from going back into the laser head because each polarization state will be changed by 90° after passing a quarter waveplate twice. The two returned beams are combined at PBS1 and converted into left and right circularly polarized beams by Q3. With the phase shift module composed by NPBS, PBS2 and PBS3, the interference fringe with 90° phase shift can

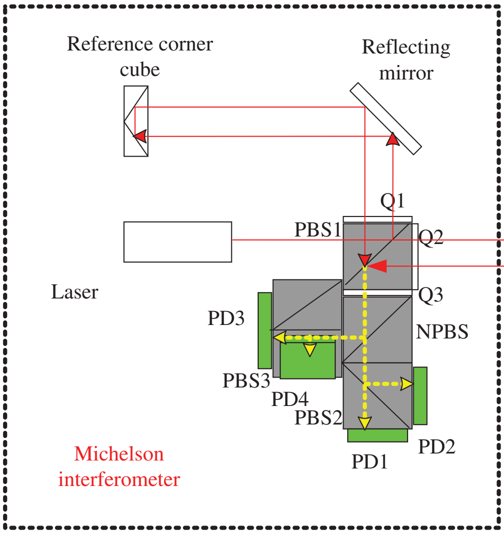

Figure 2 Michelson interferometer-based polarizing homodyne laser interferometer.

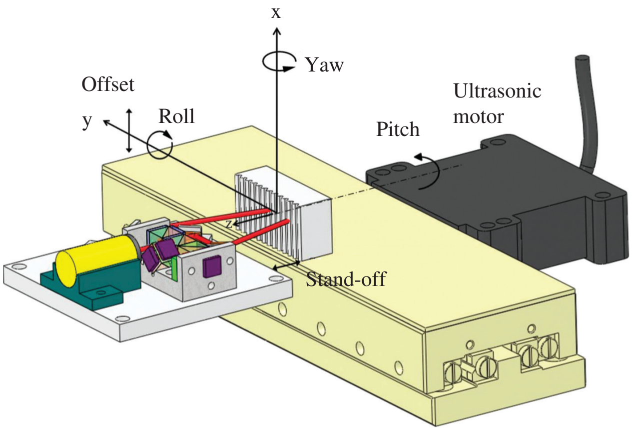

Figure 3 Littrow type laser grating interferometer [26].

be detected by photo-detectors PD1 to PD4. Because of the optical path difference (OPD) of the object beam and the reference beam, an interfering fringe pattern will appear. When the moving CCR moves one-half wavelength the interference signal has a phase variation of one period (360°). Normally for a stabilized laser, the resolution can reach 1 nm and accuracy can be in the order of 10 nm for long displacement. The measurement uncertainty is largely determined by the ambient condition; for good temperature control, it can be <±10 nm.

For the in-plane displacement measurement, laser-grating interferometers are often used to attain nanometer resolution. Its unit length is the grating pitch, which has the advantage of immunity from temperature variation. Limited by the physical dimension of the grating scale, its maximum measuring range is about 100 mm. The basic principle is to join two diffracted beams and analyze the phase shift of the interfering fringe due to the in-plane motion of the grating. Various optical configurations have been proposed, such as the Littrow type [25–27], dual laser frequencies method [28, 29], quasi-common-path [30, 31], common-path [32, 33], and wavelength-modulated phase-shifting [34]. Gao developed a two 1-D grating system to be able to measure the in-plane displacement and out-of-plane straightness error of the object grating [35, 36].

Figure 3 shows a Littrow type laser grating interferometer for measuring the in-plane (along Y-direction) displacement of the grating, which is mounted onto the linear stage driven by the ultrasonic motor. The optical configuration is similar to Figure 1 except that the two split beams at PBS1 are directed by proper mirrors so that their incident angles are equal to the +1st and –1st diffraction angles of the grating. The diffracted beams of the +1st order and –1st order then proceed along the same input paths. Because of the Doppler shift caused by the grating's lateral motion, the diffraction beams will have a phase shift proportional to the motion speed of the grating. When the grating moves a half pitch (d/2), the beat frequency signal has a phase variation of one period (360°). Normally for grating interferometer, the resolution can reach 1 nm and the accuracy is in the order of 20–30 nm for short displacement. The uncertainty is largely affected by the angular errors of the stage and the travelling distance. The example shown is in the range of 15 nm [26].

In recent years, some works expanded the grating from 1-D to 2-D, called a planar grating, and measured the XY planar motions simultaneously [37]; an example is shown in Figure 4, [38]. Two sets of 1-D sensor units are used, one for each directional displacement. In practice, the optical module has to be embedded in the XY stage and mounted underneath the 2-D grating. The available space is limited causing extreme difficulty in setup and alignment.

2.2 Straightness error measurement

Hewlett-Packard introduced the first commercial straightness interferometer in 1973 using a dual-frequency laser in association with a Wollaston prism and a large angled reflection mirror [8, 39]. There are other researchers developing heterodyne interferometric systems for measuring lateral motion with different optical configurations [40–42]. Although the interferometer-based system has high accuracy, resolution and stability, it is too bulky and of a high cost. It is not possible to expand the system for a MDFM system. The most commonly used method is the laser straightness measurement system consisting of a

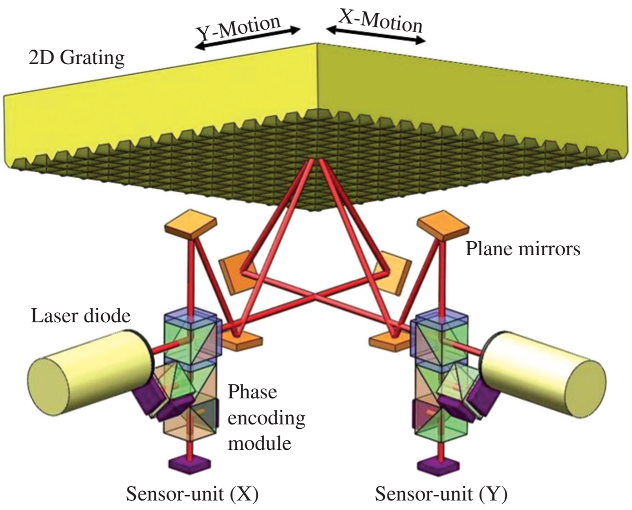

Figure 4 Planar grating interferometer [38].

collimated laser diode and a four-quadrant photodetector (QPD, also known as PSD or QD), as shown in Figure 5. The laser beam is treated as a reference line and the QPD is a target. When the QPD is moved with the stage, any vertical or horizontal straightness error of the stage will result in the laser spot movement in the opposite direction. Dual directional straightness errors can thus be easily obtained. Considering that the electrical lines of QPD will be dragged or pushed during motion that may cause signal noise, some users would like to replace the QPD by a CCR and move QPD to the laser side. In addition, the angular drift of the laser beam can be minimized by using a fiber-coupled collimating lens [43, 44]. Normally the QPD can reach the resolution to 0.1- 0.01 μm and accuracy <0.5 μm. Uncertainty is <±1 μm.

2.3 Angular error measurement

Two types of angular error measurements are commonly adopted for use, one is the based on the principle of laser interferometry and the other is on the autocollimator. The optical setup of the laser angular interferometer is modified from laser displacement interferometer by directing two beams to the same moving mirror or a pair of moving CCRs [8, 45, 46], as shown in Figure 6 [47]. It can be seen that the stationary optical setup is similar to Figure 1. The yaw motion of the mirror or the CCRs will generate OPD of the two parallel beams, yielding the phase shift of interfering fringe. For the pitch motion measurement, the system has to be rotated to the vertical direction. Normally for a laser angular interferometer, the resolution can reach 0.01 arc-sec and accuracy can be <0.1 arc-sec for long displacement. Uncertainty is around ±0.1 arc-sec.

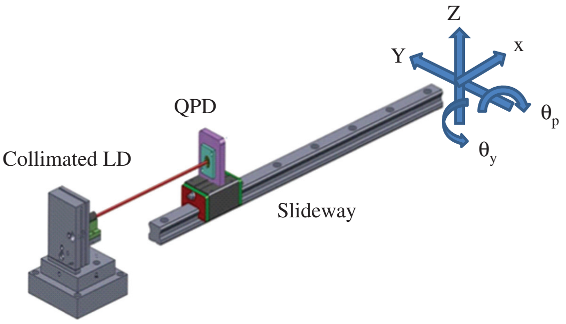

Figure 5 Straightness error measurement.

It is known that the laser angular interferometer can only measure pitch or yaw error sequentially. Although it has the merits of high accuracy and high resolution, it is, however, very expensive. Except those of ultra-precision machines like wafer steppers [18] or nano-positioning stages [48] that require very fine angular error measurement, most of precision machines admit the resolution to 0.1 arc-sec and accuracy <1 arc-sec in angular error measurement. A substituted method using autocollimator at low cost and for pitch and yaw simultaneous measurement is commonly accepted [49–52]. According to the principle of the optical autocollimator as shown in Figure 7(A) [53], the tilted angle (θ) of the plane mirror will result in the lateral shift of the focused spot by $2f\theta$, where f is the focal length of the focusing lens. Figure 7(B) shows of an example of the design of the optical system. The built-in QPD is used as the beam spot position detector to detect the amount of spot shift. The two tilted angles of the plane mirror can then be calculated simultaneously. Normally for a self-assembled autocollimator, the resolution can reach 0.1–0.01 arc-sec and the accuracy in the order of 0.1–0.5 arc-sec or less. Uncertainty is around ±0.5 arc-sec.

For the roll error measurement, a simple method is to use two parallel straightness measurement kits [54]. As shown in Figure 8, two parallel laser beams can be generated from two separate lasers or one laser with optics. The roll motion of the stage causes the difference in Z-straightness of the two QPDs. Dividing this difference by the distance of two laser beams, we can easily obtain the roll error. It is noted that such a setup can also measure vertical and horizontal straightness errors of the stage, being a 3-DOF sensor. Another concept is to rotate a QWP in the path of a laser beam so that elliptical polarized light is produced in heterodyne phase detection. The roll angle is sensitive to the polarizing angle [55]. Similarly, It is also possible to rotate a rectangular prism on which a beamsplitter is attached to face the incoming beam. The roll motion of the prism will produce differential spot shift on

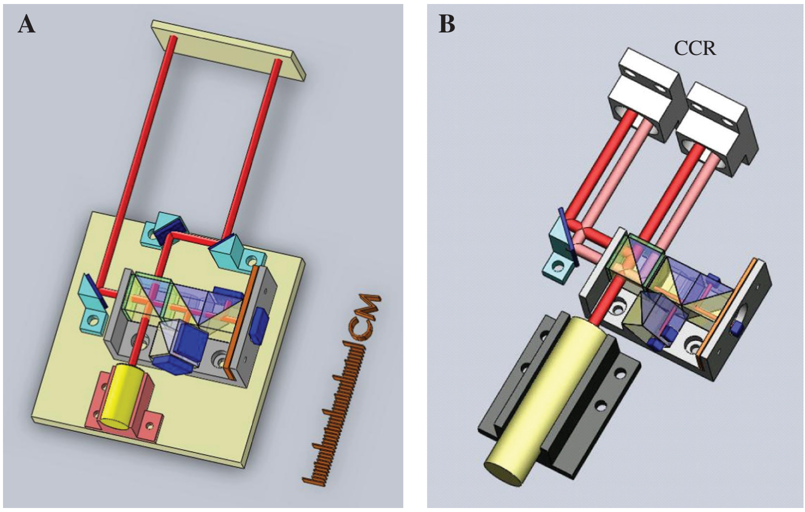

Figure 6 Laser angular interferometer.
(A) Plane mirror reflector, (B) corner cube reflectors [47].

two OPDs [56]. Normally for the roll sensor made by differential QPDs, the resolution can reach 0.1 arc-sec and accuracy about 1 arc-sec. Uncertainty is around ±1 arc-sec.

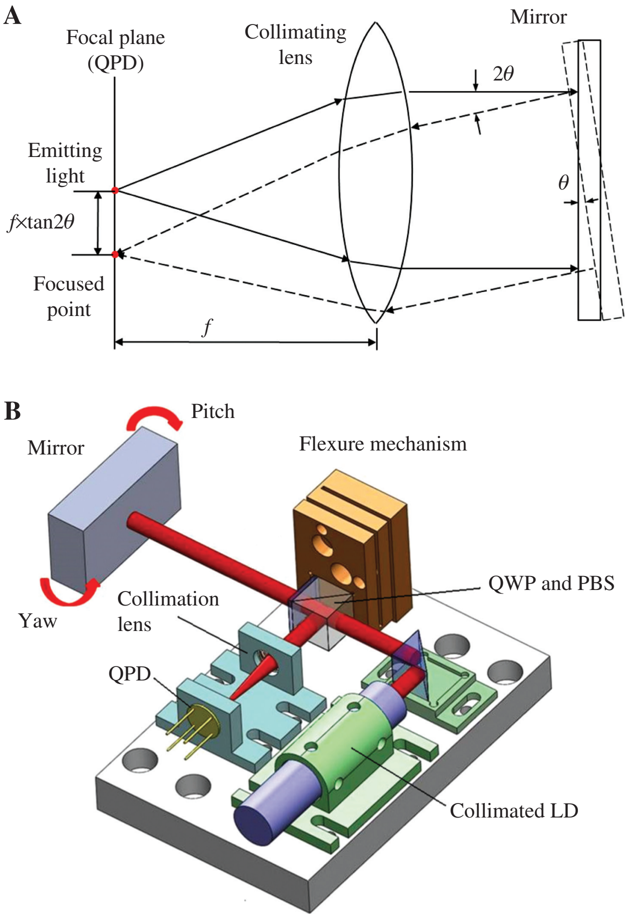

Figure 7 Autocollimator.
(A) Principle and (B) measurement system design.

In this section, some basic 1-DOF and 2-DOF error measurements were introduced. Most of the MDFM systems are a combination of the above-mentioned techniques. Some others have various concepts that are discussed in the following sections.

3 MDFM methods of linear stages

3.1 Three-DOF measurement

The 3-DOF errors can be in any combination of the 6-DOF error terms. For the out-of-plane motion, the combination of linear interferometer and autocollimator can achieve the 3-DOF measurements in displacement, pitch and yaw. An example is shown in Figure 9, which integrates the optical modules of a Michelson interferometer from Figure 2 and an autocollimator from Figure 7, both sharing the same laser source. The interferometer can be

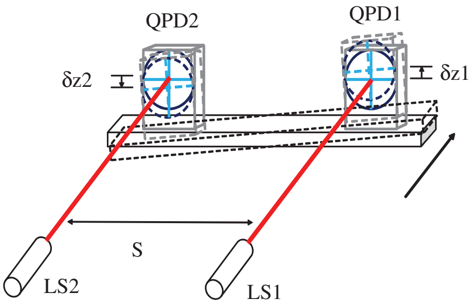

Figure 8 Roll error and two straightness errors measurement setup.

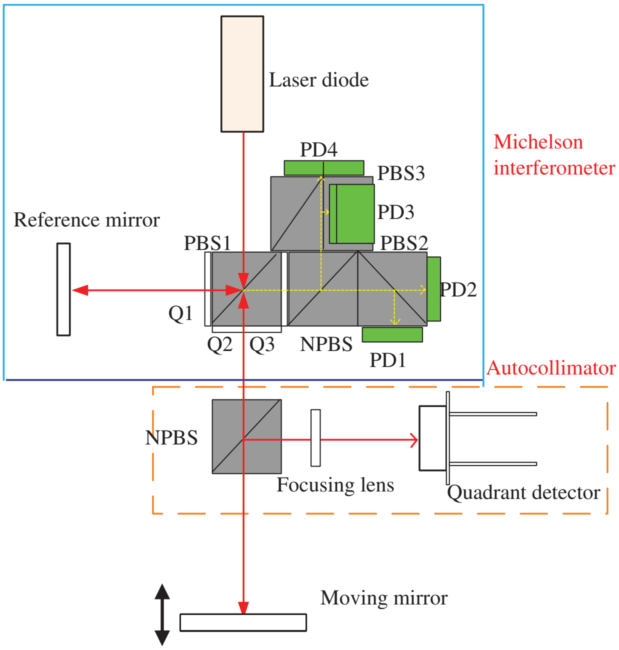

Figure 9 Displacement, pitch and yaw measurements.

a commercial laser interferometer system [57, 58] or a self-assembled Michelson interferometer [59, 60].

Another type of approach is to replace the moving mirror by a linear grating. Huang combined the ±1-orders of the diffractive beams to form a laser grating interferometer and used the 0-order beam to form an autocollimator. A 3-DOF (displacement, yaw and roll) laser linear encoder for an in-plane high precision stage was thus developed [61].

For the three-angle measurement system, Gao used an out-of-plane moving grating to generate 0- and ±1-orders of diffractive beams. By combining these beams, the pitch, yaw and roll errors can be measured simultaneously [62, 63]. Tenjimbayashi generated three parallel beams onto a moving body mounted with four components. One of the beams is returned and received by a QPD to measure pitch and yaw errors; the other two beams are transmitted and received by the other two QPDs for roll detection [64]. It is possible to use the system for the measurement of three angular errors of the linear stage.

3.2 Four-DOF measurement

For the 4-DOF measurement, the combination of the principles of straightness error measurement (Figure 5) and autocollimator (Figure 7) described in Section 2 could yield two straightness errors, pitch and yaw measurements at one setup. Kuang [65] proposed to mount the optical module consisting of one CCR, one beam splitter (BS) and one QWP on the moving stage. The two straightness errors and the two angular errors are detected by two QPDs. Huang [66] presented a high resolution, compact size and low cost system for simultaneously measuring 4 DOF. A collimated laser beam is emitted to the moving stage on which an optical module consisting of one cube beam-splitter, two critical angle prisms and two PDs are mounted. The pitch and yaw error measurements are based on a new method of the internal reflection effect at an air/glass boundary. The horizontal and vertical straightness errors are detected by the two PDs. The method can largely reduce the inherent non-linearity of reflection hence the accuracy could be greatly enhanced.

The other type of 4-DOF measurement method is to measure one linear error and three angular errors of an in-plane motion grating. Based on the principles of the diffractive theorem and optical triangulation, Liu [67] developed a simple measurement system for the simultaneous measurement of pitch, yaw, roll and displacement of the linear stage with the use of just two QPDs. The repeatability is, however, not good enough. He further added a collimator lens and detected the 0- and +1-order diffractive beams with two QPDs. The vertical straightness error and three angular errors are measured simultaneously [68]. By adding a DVD pickup head for detecting the focus error signal (FES) of the zero-order diffractive beam, the new system was able to measure the horizontal straightness error and three angular errors [69].

3.3 Five-DOF measurement

There are various combinations of the 5-DOF measurement systems:

a. Three linear errors, pitch and yaw errors. This type of 5-DOF measurement normally splits the main laser beam from the displacement interferometer to two or three parallel beams. With the use of autocollimator and QPD-straightness principles, two additional straightness errors, and pitch and yaw angular errors are measured simultaneously. Huang [70] and Liu [71] used a commercial laser interferometer as the light source. Jywe [72] integrated a miniature laser interferometer with a DVD pickup and straightness measuring optical system to build up a 5-DOF measurement system. Kang [73] built up a complicated optical system based on laser collimator and interferometry techniques. Using multi-reflection and lens magnification, the resolution of linear displacement has twice of the current linear interferometer and the resolution of straightness error can be improved to 0.01 μm.

b. Two straightness errors and three angular errors. Huang [74] presented a method for measuring a 5-DOF system of a stage with monolithic prism and a phase-sensitive detection technique. The specially designed wide monolithic prism can generate three parallel beams reflected by the stage. Using three PSDs to detect the three reflected beams, the straightness, pitch, yaw and roll can be simultaneously measured. The system is quite simple in the optical structure.
c. Displacement, straightness, and three angles. Differing from the above-mentioned 5-DOF measurement methods, Liu [75] integrated the circular polarized interferometric technique with the three-dimensional diffracted ray-tracing method to develop a novel laser encoder with 5-DOF measurement system, including the in-plane displacement, out-of-plane straightness and three angular errors (pitch, yaw and roll).

3.4 Six-DOF measurement

Early in 1994, Shimizu [13] proposed a simultaneous 6-DOF measuring method using three parallel laser beams as references. The positional error is measured with the conventional laser interferometric system. The other five errors are measured with three parallel laser beams split from the conventional system. Three sets of QPDs are fixed on the moving part to detect the positioning deviation of laser beam caused by the table motion errors.

Lee [76] presented the development of a 6-DOF geometric error measurement (6GEM) system that can be applied to the simultaneous measurement of six geometric error components of the moving axes of a meso-scale machine tool (mMT). A pigtailed LD and a cube BS are mounted on the moving axis. Based on the beam shift and triangulation method, 6-DOF motions of the axis can be detected by three QPDs assisted by a fixed cube BS. The system is very simple but the range of the travel is limited to 8 mm. Similar to this method, Wang [77] presented a modified optical system so that the travel range was increased to ±35 mm in X-Y and ±50 mm in Z.

Fan [78] integrated three laser Doppler displacement meters (LDDMs) to generate three parallel beams that could directly measure the displacement, pitch and yaw errors. Adding two QPDS, the two straightness errors and roll error could be obtained. Although the structure is simple, the total cost is high.

Lau [79] presented a 6-axis measurement by a novel 5-DOF and a precision laser roll detector. The roll detector uses single laser beam and polarizing prism. The system has been commercialized by API Co., Rockville, MA, USA.

Feng [80] built a simple and compact system for simultaneously measuring the 6-DOF geometric motion errors of the linear guide. It is an extension of the 5-DOF system [74]. A special feature of this system is the common-path method for measuring the laser beam drift so that the beam drift can be compensated.

Lee [81] presented the method of a 6-DOF measurement in a linear stage by employing a single unit of an optical encoder. The proposed optical encoder consists of a linear grating, a corner cube, four separate two-dimensional position-sensitive detectors, four photodiodes and auxiliary optical components. It was constructed to simultaneously measure the three translational errors and three angular errors. With a single travel of the stage, it provided a 6-DOF motion error with a high resolution, <0.03 arc-sec within ±200 arc-sec, 20 nm within ±400 μm and 0.4 nm within 40 mm for angular errors, ΔY and ΔZ, and ΔX, respectively, at the same time.

4 MDFM methods of XY stages

The XY stage can be stacked-up by two linear stages in orthogonal directions or constructed by the coplanar type of XY stages. Many coplanar stages are constructed by H-type linear guides or two pairs of linear motors in X and Y directions.

4.1 Three-DOF measurement

Most of the measured 3-DOF errors of XY stages are two displacements and the roll angle. For the out-of-plane motion measurement, laser interferometer is commonly used. One axis is measured by a laser linear interferometer and the other axis is measured by a dual-beam laser interferometer for XY-positions and Z-roll error measurements [82–84]. Figure 10 shows a typical example of this kind.

For the in-plane motion measurement, the planar grid is commonly adopted as the scale unit in each axis. Gao [85, 86] fabricated an angle grid with two-dimensional sinusoidal waves on its surface. The XY-positions and roll rotation of the platen can be obtained from the two two-dimensional angle sensors. The same group [87] also developed a three-axis surface encoder for stage motion measurement with sub-nanometer resolution. Four sets of

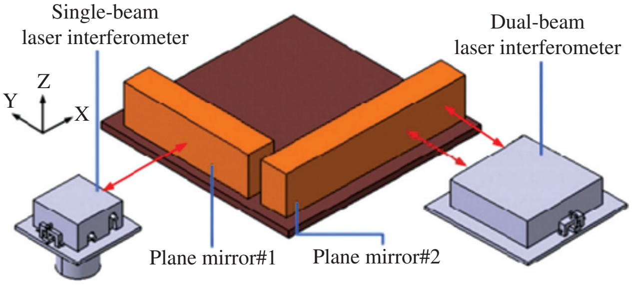

Figure 10 X, Y and roll measurements of an XY stage [82].

interference signals, which were generated by superimposition of the X and Y-directional ±1 order diffracted beams from the two gratings, were employed for evaluation of the X-, Y- and Z-directional displacements of the optical sensor head with respect to the scale grating.

4.2 Five-DOF measurement

Combining the principles of laser linear interferometer and autocollimator for displacement, pitch and yaw measurement in each axis, as shown in Figure 9, Jywe presented a new precision measurement system for the simultaneous measurement of 5-DOF motion errors (two linear positions, as well as pitch, roll, and yaw) of a nano-XY stage [88]. Jaeger [48] developed a 3-D ultra-precision nanopositioning stage that applied five-beam laser interferometers to measure 5-DOF motions (except the roll) of the stage. Angular errors are automatically compensated with three PZTs.

4.3 Six-DOF measurement

For the out-of-plane motion, Fan [89] presented a 6-DOF simultaneous measurement system for the accuracy of an X-Y stage. The system employs four laser Doppler scales for X, Y, pitch and roll measurements, and two quadrant photo detectors to detect the Z straightness and the yaw rotation of an optical reflection device mounted on the top of the X-Y stage. The system configuration is shown in Figure 11. Extended from the similar method, Kao [90] employed one 2-axis, one 3-axis and one 4-axis interferometer to build an all-interferometer-based 6-DOF measurement system for a lithography wafer stage, as shown in Figure 12.

For the in-plane motion, Kim and Bae [91–93] proposed a simple system that, using a laser source to project a divergent beam onto the 1-D grating target, the 0- and ±1-order diffractive beams are received by three QPDs.

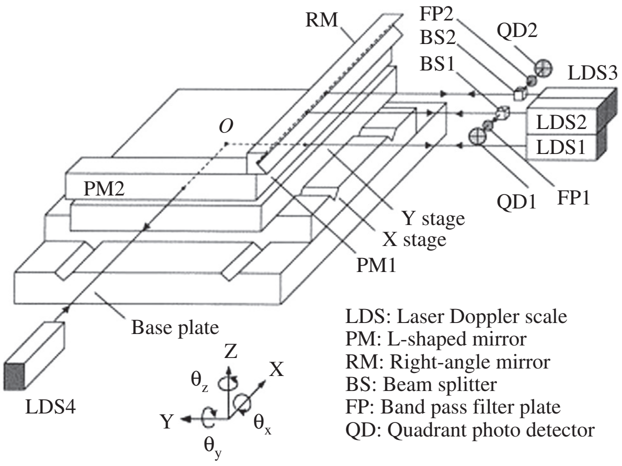

Figure 11 Six-DOF measurement system for XY-stage [89].

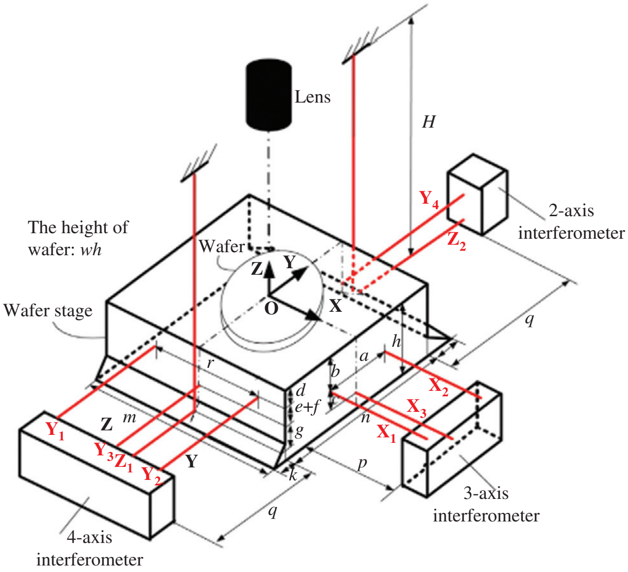

Figure 12 All interferometer-based 6-DOF measurement system for XY-stage [90].

Adding the convex lens to adjust the movement and the intensity distribution of the diffracted rays, it can improve the performance of the measurement system. Figure 13 shows its optical structure.

5 MDFM methods of XYZ stages

It is known that all geometrical errors of each axis are measured to construct the volumetric errors of the machine within the working volume in Cartesian coordinates [4, 11–13, 94]. The volumetric error at any functional point, such as cutting, measuring, handling, etc., of the

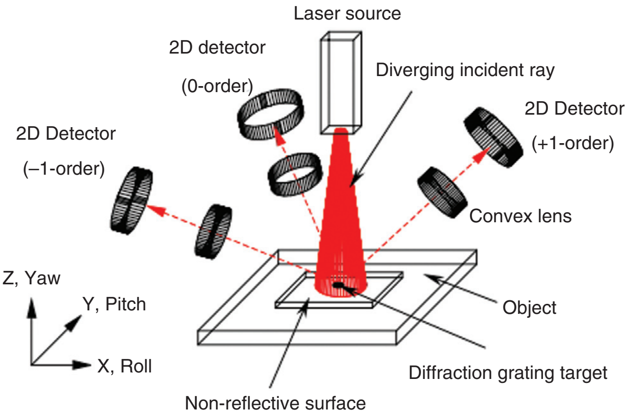

Figure 13 6-DOF measurement system for in-plane motion [93].

machine is defined as the positional offset of the actual point from the ideal point in 3D space. In 1986, Lau first developed a 3D laser tracking system at NBS in the USA for the calibration of trajectory accuracy of robots [95]. In that system, a laser interferometer is accurately pointed by means of a two-angle servo-system, to a reflector attached to the robot's wrist. The measurement of the 'length' of the laser beam and the two angles of the pointing device convert the position of the retroreflector in Cartesian coordinates. With a single measuring station, all linear errors (position and straightness) of the robot's trajectory can be measured. Repeatability of the system is ±12 µm over an area of 25×35 cm. The system has been modified with an active target and commercialized by API Co. as a Laser Tracker for the volumetric error calibration and compensation of machine tools [96]. Equipped to Siemens 840D (Siemens AG, Munich, Germany) and Fanuc 30–35i (Fanuc Co., Oshino-Mura, Japan) controllers, volumetric errors of the machine tools can be compensated by 70%.

The displacement measurement of the commercial Laser Tracker is still limited by the precision of the point of rotation. NPL of UK and PTB of Germany developed a novel tracking interferometer, named LaserTracer, that employs a high accuracy sphere with form errors below 50 nm as the optical reference for the interferometric measurement [97, 98]. The system has been commercialized by eTALON AG. [99]. For calibration purposes with high accuracy, it is based on the principle of sequential multi-lateration whereby spatial coordinates are determined solely from measurements of displacement of a moving probe relative to a number, probably as many as eight, of fixed measuring stations, as shown in Figure 14. In contrast to a single station that measures linear errors, the multilateration techniques are very accurate in length measurements. With high quality targets and refractive index compensation a length measurement uncertainty of $U=0.3\ \mu m+L\times0.5\times10^{-6}$ (k=2) can be realized. It is able to calibrate on-the-fly linear and rotary axes of machine tools and CMMs [100]. All 21 geometric error terms can be obtained.

6 Discussion

It has been mentioned in the Introduction that the need of MDFM systems is to to reduce total calibration time of all geometric errors of precision machines for industrial

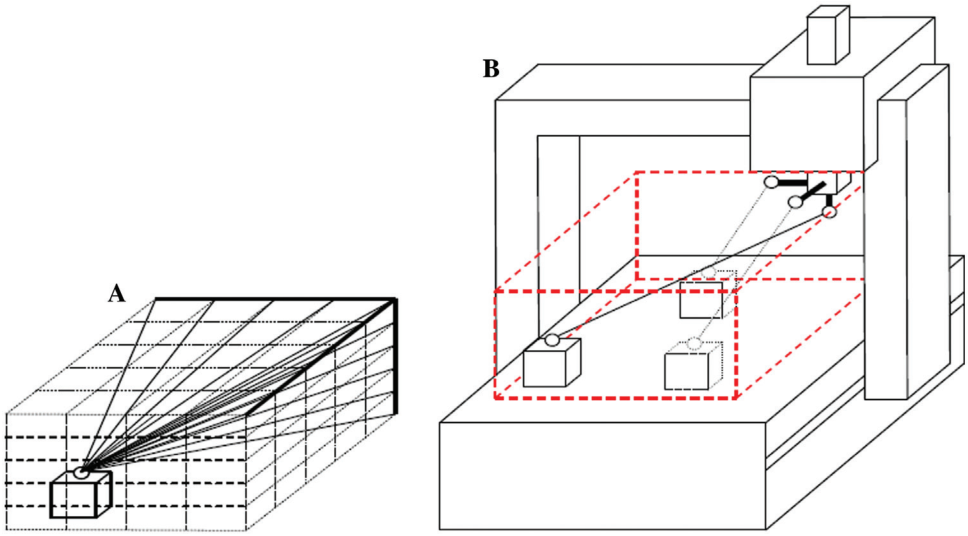

Figure 14 LaserTracer on the work-piece table.
(A) Spatial grid at a single station, (B) at three tracking positions [98, 99].

applications. For the out-of-plane motion, the reflection mirror type with laser interferometer and autocollimator for 3-DOF measurement, and the QPD type for straightness measurement, are easier to be implemented, as the setup is less complex. Nevertheless, commercial MDFM systems are still rare. In this report, only the 6-DOF system [79] and laser Tracker [96] produced by API Co., and the LaserTracer [99] by eTALON AG, were found.

However, for the in-plane motion with diffraction grating technology, direct industrial application is still difficult, as the angular errors will cause the tilting of diffractive beams yielding to a variation of sinusoidal signals [26]. In addition, the alignment technique during the installation of the planar grid underneath the moving table is extremely difficult. It can be seen that most of the reports only demonstrated experiments with very short traveling length. It is expected that the technology of robust signal processing of distorted sinusoidal waves is need to solve this problem.

Most of the published literature on MDFM systems are built up by the author's group and are still at the laboratory stages. Even if the studied stage have long strokes, such as 100 mm or longer, experimental works only demonstrated with very short travels, such as several millimeters or even much shorter to micro scales. Therefore, this paper emphasizes on the developed MDFM technologies, rather than measurement uncertainty of each system. Because most MDFM systems are composed of similar principles in 1-D and 2-D measurements, as expressed in Section 2, the general measurement resolution, accuracy and uncertainty are added in the examples of Section 2. Only some cases in Section 3 to Section 5 are mentioned these quantitative data.

7 Conclusions

This article summarizes reports of optical measurement techniques of MDFM systems for precision linear, planar and XYZ stages. Both the out-of-plane and in-plane measuring methods are studied and compared. This review covers the state-of-the-art optical systems from 3-DOF to 6-DOF measurement techniques. The feasibility of industrial applications is also discussed.

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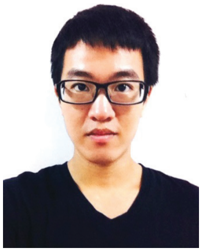

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