Comparison of laser-interferometric

With the rising precision of machine tools the demand for more precise and more efficient measurement systems increases. At present, several systems with different measurement procedures are available. This article describes three systems for the geometrical characterisation of machine systems: TRAC-CHECK and TRAC-CAL by ETALON AG, and MT-Check by IBS Precision Engineering. A qualitative comparison is made regarding the possibilities of compensation for measured geometrical errors as well as the measurement execution. Furthermore, a metrology frame for the characterisation of the dynamic tool path accuracy, which has been developed at Fraunhofer IPT, is presented briefly.

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The machining accuracy of machine tools depends on numerous influences. By stressing the machine, thermal deformation and the static and dynamical stiffness take effect. Further inaccuracies in the fabrication and assembly of the machine parts cause geometrical and kinematic deviations, also in the unstressed state [1]. This paper deals with the characterisation and compensation of the geometrical errors. These errors refer to the movements of a unidirectional axis and describe the deviations between the nominal and actual movement.

According to [1], for a translational axis the positional deviation, the straightness deviations (in both lateral directions), rolling, yawing and pitching are the relevant errors (see Figure 1). Including the deviations for rectangularity, a conventional three-axis machine system has a total of 21 geometrical errors.

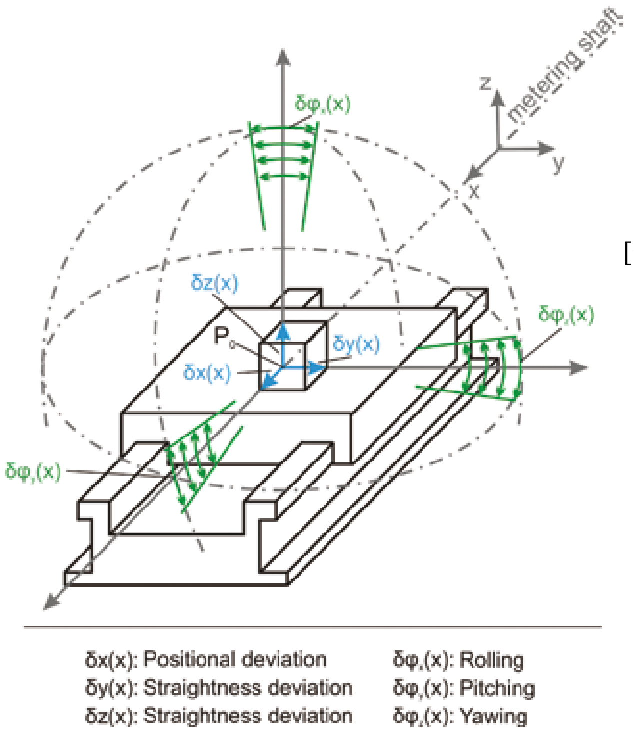

Figure 1. Geometrical deviations of a translational axis [1].

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tactile and measurement systems

Possibilities of compensation

The final target of the machine characterisation is to compensate for the measured geometrical errors. For this purpose, several compensation strategies have been developed, to be implemented in the control unit of the machine. In general, the measured data is stored in the control unit for the calculation of error motion commands. Depending on the compensation strategy, different ways of describing the errors are required. Following [2] and [3], two different examples of strategies, the space-grid compensation and the volumetric compensation, are briefly explained below.
The space-grid compensation is based on a three-dimensional grid, filling out the workspace, which is defined by the lengths of the axes. The crosses of the grid describe nominal workspace positions. For each of these positions, a three-dimensional error vector is stored in the control unit, which represents the deviation between the nominal and the actual position. The control unit uses these vectors in the generation of the motion commands.
The volumetric compensation is based on various mathematical functions, which describe the specific geometric errors of an axis (e.g. positional deviation, rolling, etc.) depending on the nominal axis position. To compensate for the geometrical errors, the control unit solves the corresponding equations and includes the specific influences into the generation of the motion commands.

Three measurement systems

In the context of recent work, the Fraunhofer Institute for Production Technology IPT examined and compared measurement systems for the characterisation of geometrical axis errors. The focus was set on the system LaserTRACER including the evaluation software TRAC-CHECK and TRAC-CAL by ETALON AG and a system by IBS Precision Engineering called MT-Check. In reference to [4], [5], [6] and [7] the functionality of these systems is briefly outlined below.

The LaserTRACER is a laser-interferometer-based measurement system for machine tools and coordinate measuring machines; see Figure 2. The laser beam follows a pentaprism reflector which has to be mounted near the tool centre point. In order to do this, two drives, controlled by using a photosensitive diode, afford the flexible and rapid tracking. On the basis of the modifications of the laser beam length the geometrical deviations are detectable. The LaserTRACER contains a Class 2 Laser with a wavelength of about 632 nm and offers a measurement range from 0 to 6 m and an accuracy of measurement of about 0.3 µm + 0.3 µm/m.
Depending on the software used, different measurement routines can be executed whereby different deviations are quantifiable.

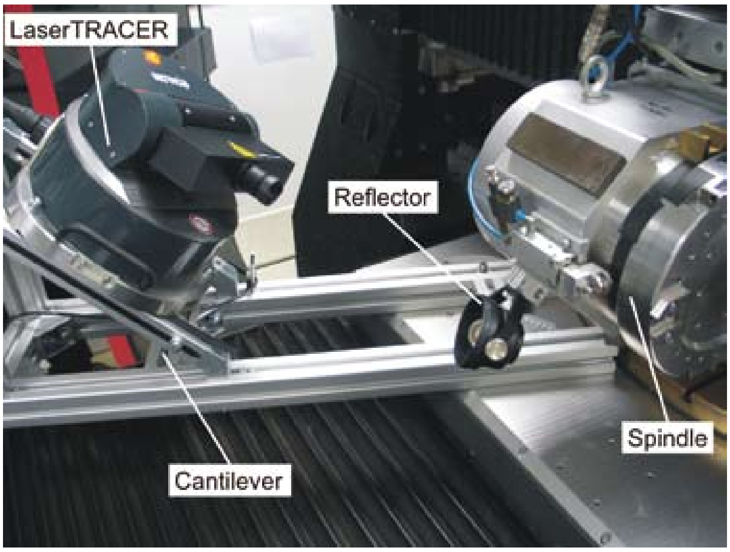

Figure 2. LaserTRACER and reflector installed on an ultra-precision machine tool.

For a three-axis system, the software TRAC-CHECK enables the determination of positional deviation of an axis and also deviations of rectangularity of a Cartesian coordinate system. In order to execute the measurement, straight lines with discrete measuring points have to be defined at which the modifications of the laser beam length are recorded. By defining a line along the axis the positional and straightness deviations are detectable,

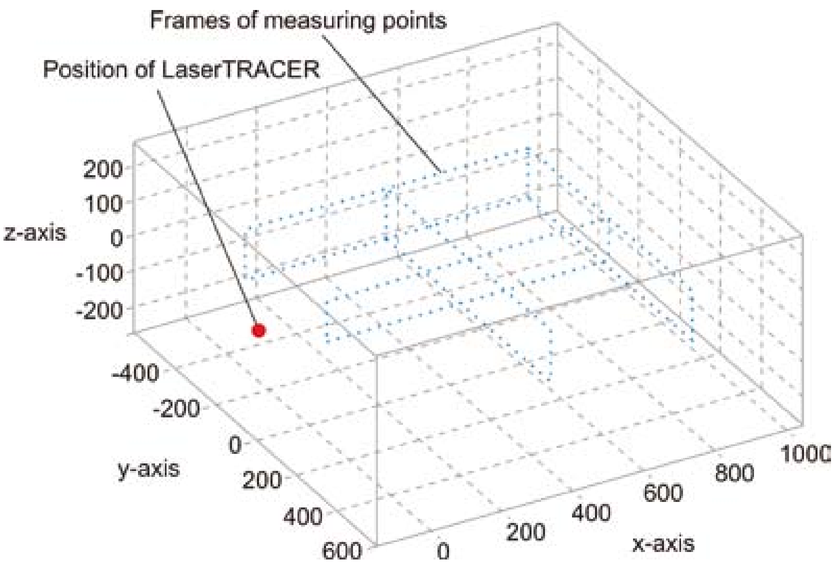

Figure 3. Frames of measuring points.

whereas by defining a diagonal line the deviation of the rectangularity can be measured.
Also for a three-axis system, the software TRAC-CAL enables the determination of positional, straightness and rectangularity deviations, and also the rolling, pitching and yawing of each axis, so all 21 geometrical errors are detectable. For this purpose, at least six positions of the LaserTRACER have to be defined. Frames of measuring points, contained in the workspace of the machine, have to be measured from each position; see Figure 3.

The system MT-Check by IBS Precision Engineering is based on an electro-mechanical probe for the data acquisition and a ball beam as an etalon; see Figure 4. Three eddy current sensors with a calibrated measurement range of 1.0 mm are included in the probe. Each of them measures against a plate which is mounted with springs. This design allows a tactile measurement. The specific arrangement of the sensors enables the acquisition of a three-dimensional signal according to a Cartesian coordinate system. The ball beam contains several ceramic balls, which have calibrated positions and diameters that are highly constant (22 mm, roundness < 0.5 μm). The system accuracy is better than 2 μm and it offers a measurement range from 0 to 0.5 m. Using larger ball beams, the measurement range can be raised up to 1.5 m. In order to execute the measurement, the probe has to be fixed in or near the tool holder. The ball beam has to be clamped along the relevant axis. Before the measurement can be conducted the coordinate systems of the machine, the probe and the ball beam have to be aligned by the control unit. During the measurement, the probe touches each of the balls. The signals of the three sensors correspond to a deviation vector in the Cartesian coordinate system. The software evaluates this data and provides the positional and straightness deviations.

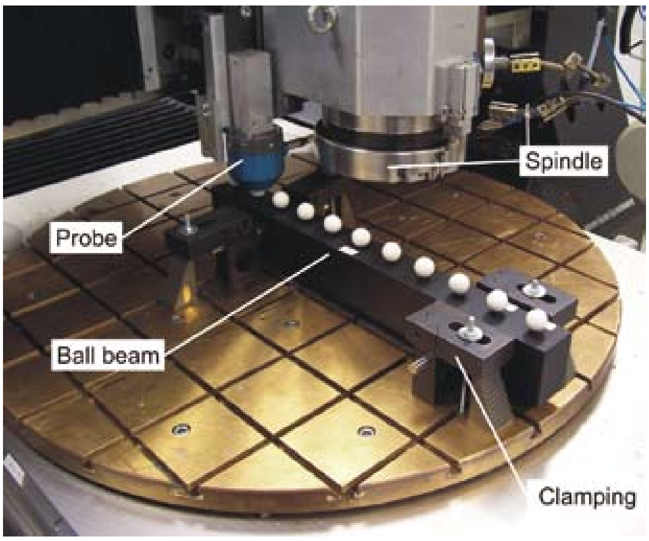

Figure 4. MT-Check installed on a machine tool.

Measurement setup and results

In order to test and compare the three measurement systems, the ultra-precision planing machine UHM (stroke of the axes: 1.800 x 900 x 200 mm³) of Fraunhofer IPT was characterised with TRAC-CHECK, TRAC-CAL and MT-Check. A discussion of all measurement results does not fit in the scope of this article. Therefore, only the positional deviation of the x-axis is considered. Furthermore, only the half-length of the x-axis was measured because of the following reasons. The UHM is a machine with a low portal (located at the centre of the x-axis) on which the y- and z-axis are mounted. The x-axis has to be moved through this portal. On the x-axis (workpiece table) the LaserTRACER is fixed. Because of its size, it is not possible to move the axis trough the portal. Therefore just half of the x-axis is measurable. Using the MT-Check, only half a meter of the x-axis is measurable because of the ball beam length (see Figure 4). Additionally, it has to be mentioned that due to the geometry of the UHM and the size of the LaserTRACER, the LaserTRACER had to be fixed with a cantilever on the x-axis to avoid collisions (see Figure 2).
The measurement results are shown in Figure 5.

Discussion

Each of the diagrams in Figure 5 shows different results for the positional deviation of the x-axis. This can be ascribed to the different measurement procedures and evaluation algorithms of the systems.
TRAC-CHECK employs a simple laser-interferometric measurement of lengths. The straightness deviation and the rolling, pitching and yawing of the x-axis influence the measured position but these influences are not separated from the positional deviation. Because of this, the positional deviation measured with TRAC-CHECK corresponds to an overall deviation of the x-axis.
The evaluation algorithms of MT-Check distinguish the influences of the positional and straightness deviations, whereas the contributions of rolling, pitching and yawing of the x-axis are incorporated in the measured positional and straightness deviation.
A separation of the 21 geometrical errors is achieved by measuring with TRAC-CAL. All the different deviations are determined independently from each other.

Thus, the measured positional deviations differ from each other according to the measurement system used. In general, the measurement systems produce different descriptions of the deviations.
A reasonable comparison of the measurement results is possible by adding the individual deviations to an overall positional deviation. This requires the knowledge of all the relevant geometrical parameters of the measurement setup, such as distances between the etalons or the LaserTRACER positions and the centres of rotation of the rotary errors.
In order to use the measurement data for compensations by the control unit, the description of the deviations has to suit the compensation method. For example, for the volumetric

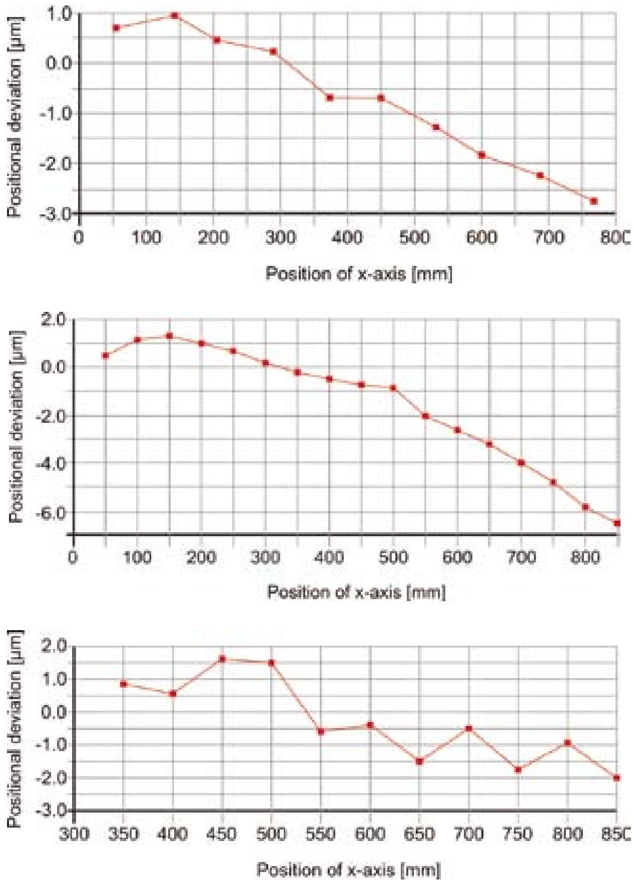

Figure 5. Positional deviation of the x-axis, averaged over five forward and backward cycles, from measurements on three systems.
(a) TRAC-CHECK.
(b) TRAC-CAL.
(c) MT-Check.

compensation each of the possible deviations has to be determined as an independent mathematical function, whereas the space-grid compensation refers to an overall positional deviation.

Comparison

During the measurements, several observations concerning the execution by each of the systems were made.
The installation of the instruments for measurements with the LaserTRACER needs just a few minutes. No precise adjustments of the instruments are required. However, generating the measurement strategy (frames of measurement points, positions of the LaserTRACER) can be very time-consuming, especially if the geometry of the axes or the machine is disadvantageous. Examples of a disadvantageous geometry are short axis length, low portals or a tight housing. In generating the strategy, the user has to avoid collisions during the measurement process and has to take into account that the quality of the measurement results depends on the strategy. The execution and evaluation of the measurement can be conducted comfortably because of automatic routines. However, it is hard to understand and reproduce the evaluation of the measurement data. The effect of possible errors in measurement is not easy to detect in the results, so that a second or third measurement is needed to confirm the results.

The installation of the instruments for measurements with MT-Check requires several time-consuming adjustments by the control unit. Moreover, the measuring length is limited by the length of the ball beam. On the other hand, this fact is favourable in case of the measurement of machines with a disadvantageous geometry (see above). No time-consuming development of measurement strategies is needed, however. Because of automatic routines, the measurement execution and evaluations also can be conducted comfortably.

In general, three conclusions can be drawn:

- For machine systems with a small workspace or a disadvantageous geometry the MT-Check system is more useful, whereas for large machine systems the LaserTRACER systems are easier to operate.
- To get a complete description of all the geometric deviations (e.g. to use for a volumetric compensation) a characterisation with the LaserTRACER or TRAC-CAL is more efficient. For a quick measurement of only one axis or for some test measurements the MT-Check system may be preferred.
- The application of the measurement systems based on the LaserTRACER is sometimes difficult and requires a skilled user, especially because of measurement strategy development, which has a strong influence on the quality of the results.

Metrology frame

Next to the geometrical deviations, several dynamic effects influence the machining accuracy. These effects depend on a lot of factors like the tool path speed respectively acceleration or the weight that is moved along the axes, and cause deviations of the tool path.
At Fraunhofer IPT, a metrology frame was designed in order to characterise the three-dimensional path accuracy of highly dynamic milling machines. It was developed for the integration on a three-axis machine. Use of this frame allows the metrological determination and optimisation of the dynamic properties, the parameters of the drive control and the adjustment of the damping system of the decoupling axes.

Figure 6 shows the design of the metrology frame. The frame is made up of slides equipped with air bearings. The possible stroke of the axes is 180 x 180 x 80 mm³. In each direction the Heidenhain high-resolution metrology system LIDA is used to measure the tool path. The lightweight construction limits the weight to be moved to a mere 4 kg. The design allows the tool path to be measured as close as possible on the tool centre point. Including an estimation of the displacement due because of the bearing stiffness, a maximum deflection of the frame of less than 2 µm can be expected.

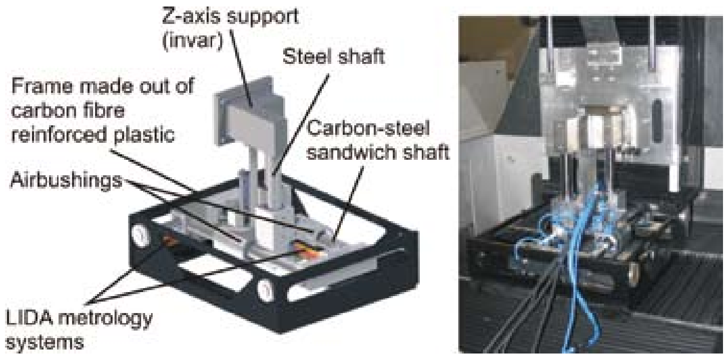

Figure 6. Design of the metrology frame.

The measurements with the metrology frame have to be executed as follows; see Figure 7. At first, the static accuracy can be characterised by measuring discrete points on the tool path. Further, the path accuracy can be determined at different path speeds and control parameters.

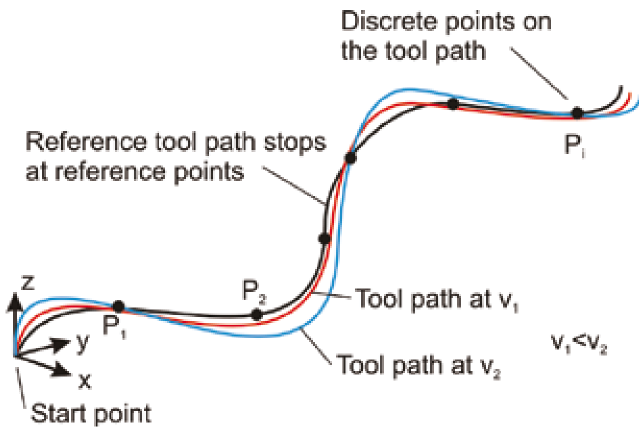

Figure 7. Approach for the characterisation of the tool path.

Analysing the measurement results, strategies for a minimisation of the deviations and an optimised setup of the decoupling systems can be derived. Moreover, it is possible to adjust NC programs for the workpiece machining in order to minimise the path deviations at high path speeds.

Summary

The axes of a machine system have geometrical deviations. In order to quantify these errors, complex measurement systems have been developed that facilitate a quick and complete characterisation. The comparison of three current systems shows that depending on the machine system (large/small) and the measurement task different systems are preferable. Furthermore, the description of the deviations differs from one system to another.
A metrology frame designed by Fraunhofer IPT allows the determination and compensation of tool path deviations caused by dynamical effects.

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Author's note

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