Chapter

Geometric Accuracy, Volumetric Accuracy and Compensation of CNC Machine Tools

Jiri Marek, Michal Holub, Tomas Marek and Petr Blecha

Abstract

The production of geometrically and dimensionally defined workpieces is what the user expects from a machine tool. Deviations from these prescribed dimensions and geometry are due to machine inaccuracies. Therefore, it was necessary to develop tests and tests on the properties and parameters of machine tools that can detect these. Every new machine tool undergoes these tests.How to perform and evaluate these tests is determined and recommended primarily by standards and regulations. When testing the properties of machines, it is not only about knowing and knowing how to measure machines, but also how I can analyze and apply the obtained results. Is it necessary to do a mechanical intervention of the machine or is it enough to compensate the software?

Keywords: geometric accuracy, volumetric accuracy, compensation, machine tools

1. Introduction

The production of geometrically and dimensionally defined workpieces is what the user expects from a machine tool. Deviations from these prescribed dimensions and geometry are due to machine inaccuracies. Therefore, it was necessary to develop trials and tests of machine tool properties and parameters that can detect these errors. Every new machine tool, a newly developed machine, or a machine overhauled is subjected to these tests [1].

Testing of machine tools is an important part of the product life cycle-machine tool. Tests of machine tools can be divided into three groups. The first group of tests is associated with a contractual obligation between the seller and the buyer of the machine. They are, therefore, a part of the contract. Acceptance tests usually take place in two steps—first, directly at the machine manufacturer and then, after the machine is assembled, at the customer. These tests aim to verify the declared properties of the machine. The prototype tests serve to verify the properties of newly designed and manufactured machines. Prototype tests extend the acceptance tests with a series of measurements to provide important information, especially to machine designers. The proposed and expected properties of the new product are examined and the unknown properties, which cannot be expected when the product is being developed, are revealed. Statistical acceptance (process competence test) is used for exacting customers, where it is necessary to maintain the quality of the workpiece in the long term [2].

How to perform and evaluate these tests is determined and recommended primarily by standards and regulations. When testing the properties of machines, it is not only about knowing and being capable of how to measure machines (what kind of equipment to use, what method and procedure), but also how to analyze and apply the results in future. Is it necessary to do a mechanical intervention into the machine or is it sufficient to compensate the machine software? [1].

The inspector should be able to answer these and other questions related to machine tool diagnostics. Machine diagnostics is not only a knowledge of the measurement method, but also a set of knowledge that the inspector must know. The first is the knowledge of the measuring equipment itself and its management, monitoring its properties, accuracy, and ensuring a regular calibration (if necessary). Next, it is the knowledge of working with these devices (procedures) and what standards and regulations apply to the measured quantity, the machine, and the device itself. However, it is also important to know the measured machine, without which we cannot adequately perform diagnostics and propose suitable measures to improve the accuracy of the machine [1].

The publication [3] describes the effects of an improperly selected method of measuring the volumetric accuracy of a machine tool. Various methods of placing the temperature sensors on the machine were carried out. These are then reflected in the size of individual machine errors, but also in the resulting volumetric accuracy in the range of 8–12%. This is an example of a different approach to measuring of volumetric accuracy, which is, in this case, affected by the human factor.

2. Effects influencing CNC machine tool operation

The machine tool must be seen as a technical system, which must always be considered in a comprehensive way, with all the impacting effects. In operation, the CNC machine tool is influenced by a number of effects. By this, we understand the effect not only of the ambient where it is installed, but also the influence of the operator on the machine itself and its impacts on the ambient. These influences affect the properties that all machine tool users call for, namely run stability, repeated machining accuracy, and trouble-free operation. We must assess machine tools in a comprehensive, hierarchical, and structured way. The deviations in the dimensions of the machined component provide the user with direct information on the accuracy of the parts from which the machine is assembled, on the care devoted to the assembly and, last but not least, on its construction. The workshop environment where the machine is installed affects the machine tool by [4]:

- vibrations;
- impurities;
- heat.

On the other hand, the machine can have the same effects on the environment. The machine can cause vibrations (not common), exhaust gases from the supply of coolant and cutting fluid to the cutting site and can also cause ambient warming. By impurities we do not mean coarse dirt and excessive dust, but the standard ambient of normal workshop operation. Heat flow and radiation from the ambient have an immediate effect on the machine installation site and can adversely affect the machine operation. Coldness or sudden temperature changes are equally unfavorable. In cases where this does not impede the operation of the machine (e.g., thermal protection failure, functionality of motion mechanisms) and the temperature changes (sudden temperature difference) are not too high, the machine can be operated satisfactorily. This state can be compared to a temperature steady state (tempered state). Therefore, manufacturers usually report the temperature range at which their machine operates. Rather, a sudden change in the temperature field is detrimental [4].

In addition to these external effects, several factors, referred to collectively as production accuracy (production uncertainty), affect the operation and, in particular, its machining accuracy. When machining a workpiece over time, its dimensions vary within or outside the given and permitted limits. Workpiece dimensional variations are caused by three main factors affecting the machine tool and the manufacturing process [4]:

- temperature influence;
- static rigidity of the machine-tool-workpiece system;
- dynamic compliance of machine-tool-workpiece system.

Every CNC machine tool is exposed to temperature effects, both even and uneven, during its operation and also in its sleep mode. Due to this temperature effect, temperature deformations arise which lead to a change in the position of the workpiece relative to the tool and thus to inaccuracies. This will be striking if we are focused on the stability of the machined dimension in case of a smaller series of workpieces, respecting the shape and position errors defined on the machined parts. The causes of heating up the individual parts of the machine tool can be found either in the machine itself (passive resistors in the motion axes or the cutting process itself) or outside it. The thermal stability of machine tools today is one of the most important factors for maintaining the specified tolerances on the workpiece [5].

Almost all the mechanical work that is done in the cutting process turns into heat. In addition, losses occur in the machine motion groups. Heat is dissipated from the place of origin (cutting process or in drives, guides) by [5]:

- conduction;
- convection;
- radiation.

Heat dissipates from the cutting process by:

- chip;
- workpiece;
- tool;
- ambient.

It follows that almost all the heat is stored in the machine tool and must be dissipated or stabilized. Uneven heating up of machine tool parts can occur, which can lead to thermal expansion and deformation. This results in fluctuations of workpiece dimensions and tolerance variations in shape and position. All temperature effects cause a temperature increase during machine tool operation, which then stabilizes at a certain value—the so-called steady temperature, which is different for each machine. Therefore, some manufacturers insist on this condition and then recommend machining. However, they must ensure that there is no sudden change in temperature. The harm caused to the machining process may not be the temperature itself, but rather harms of temperature changes during machining. For this reason, in addition to efficient cooling, some manufacturers also heat their machines [5].

This state is called a thermally stabilized machine tool. The cold machine tool heats up slowly, because we cannot achieve smooth operation and even workload of the machine tool at the beginning of machining. This is because machining must often be interrupted and this causes cooling. Therefore, at first, the machine is thermally stabilized by heating to the operating temperature and then by controlling and maintaining its temperature. Our aim is that, in spite of the thermally stabilized state of the machine, the changes in temperature and its manifestations of thermal deformation could affect as little as possible the position of the tool relative to the workpiece and thus the machining accuracy by [5]:

- selecting a thermo-symmetrical machine design;
- increasing the efficiency of all nodes and elements, thus minimizing losses that change into heat;
- placing heat sources efficiently so that they do not affect the design of the machine;
- dissipating the heat by cooling, chip removal, or by dimensioning the surfaces for efficient heat dissipation;
- compensating the machine;
- checking the air flow and its temperature, or shielding the external thermal radiation.

Undesirable and harmful side effects of time-varying loading can be vibrations, and thus also the accompanying phenomenon of these vibrations—noise of the machine or its parts. Vibrations deteriorate the working conditions of the working process, deteriorate the quality of machined surface, and reduce the tool edge life. The vibrations that occur in machine tools are called forced and self-excited vibration. The source of forced vibration in machine tools is the periodic force.

Forced vibrations are dangerous for the machine construction itself if their frequencies or higher harmonic frequencies of this force, e.g., from the cutting process, are equal to the eigen frequencies of the machine-tool-workpiece system.

If the source of the forced vibration is caused by the cutting process, the suppression of subsequent vibrations can be accomplished by selecting the cutting conditions. However, it should be borne in mind that, for example, the eigen frequencies of the workpiece can sometimes vary considerably depending on the depth of the chip being removed.

Similarly, the eigen frequency of the machine or the eigen frequency of tool clamping in the spindle may not be suitable. Another way how to suppress the forced vibration is by fixing the machine on a flexible foundation or by using a vibration absorber. On the other hand, self-excited vibrations limit the machining quality. The self-excited vibration of the machine arises without an external power supply (excitation source), since this is due to the interaction between the workpiece and the tool. If there is an excess of energy obtained, i.e., if this energy is greater than the energy consumed, self-excited vibrations occur. This is manifested as a chatter of the machine; this is caused by a number of mechanisms. Self-excited vibrations occur during roughing and finishing operations. This does not mean that if less chip is removed, self-excited vibrations are avoided. For example, self-excited vibrations may occur when removing a chip of small depth on a vertical lathe (0.3 mm) with a large load of the ram on the tool tip (1500 mm) [5].

Self-excited vibrations occur suddenly; stable conditions of cutting process can also suddenly change to unstable ones. Stable conditions become unstable when a certain value of chip depth, which is called a limit chip depth, is exceeded. The basics of the self-excited vibration theory were developed in the 1950s at VÚOSO Praha, founded by Tlustý, Poláček, and others. The theory was based on equality of energy in the feedback system. Energy is generated by the cutting process, which is the source of excitation, and consumed by vibrations (inertial mass, springs and absorbers that can replace the system) [5].

3. Types of accuracy of CNC machine tools

Under the term accuracy of machine tools, you can imagine several partial features of the machine. Accuracy will be taken differently from the perspective of the designer and from the perspective of the metrologist. From the metrological point of view, accuracy describes how close the measurement result is to the true value of the quantity. In the field of machine tools, we can talk about several types of accuracy, while the determination of accuracy is only qualitative (small, medium, and high). These are **geometric, working, and production accuracies**. Each of these accuracies has its own justification [6].

These basic three types of accuracy of CNC machine tools are complemented by other types of accuracy, namely **positioning accuracy, interpolation accuracy, volumetric accuracy, and thermal expansion**.

3.1 Geometric accuracy

Geometric accuracy describes the geometric structure of a machine tool from which the properties of functional parts affecting its working accuracy can be evaluated. It also describes the production quality of the machine and its assembly in an unloaded state. The tests are carried out on machines working under no load or under finishing conditions of machining [6].

Geometric accuracy of axes, their measurement and evaluation are given by the standard ČSN ISO 230-1. This section applies only to accuracy tests. It does not deal with the functional tests of the machine (vibrations, jerky movements of parts, etc.) or the determination of characteristic parameters (revolutions, feeds), as these tests are to be performed prior to the accuracy tests. Geometric tests consist of verifying the dimensions, shapes, and positions of components and their relative alignment. They include all operations that affect a part of the machine, such as planeness, alignment, intersection of axes, parallelism, squareness of straight lines or planar surfaces. They relate only to dimensions, shapes, positions, and relative motions that may affect the accuracy of the machine operation [7].

According to the standard, there are six geometric errors in linear (according to ČSN ISO 230 - 1) and rotary (according to ČSN ISO 230 - 7) axes, namely three translational errors—positioning error, horizontal and vertical straightness error and three angular errors. A typical three-axis CNC machine tool contains 21 geometric errors—3 × 3 translation errors, 3 × 3 angular errors. To these errors, the errors of the relative squareness of the linear axes are added. All of these errors can adversely affect the overall positioning accuracy of the machine and thus also the accuracy of the machined parts. Errors usually occur when the actual position differs from the position displayed on the machine control unit. Errors increase with dynamic effects arising from the interpolation of axes [4].

In the case of three-axis kinematics, we can find 21 error parameters, 18 translational errors and 3 parameters of squareness of individual machine axes. These errors, including spindle errors, are shown for the three-axis vertical milling machine in **Figure 1**. The kinematic chain of the three-axis machine tool presented below corresponds to W (Workpiece) -X-Y-Z-T (Tool) [8].

The error description for one linear X-axis and one rotary C-axis is given in **Table 1**.

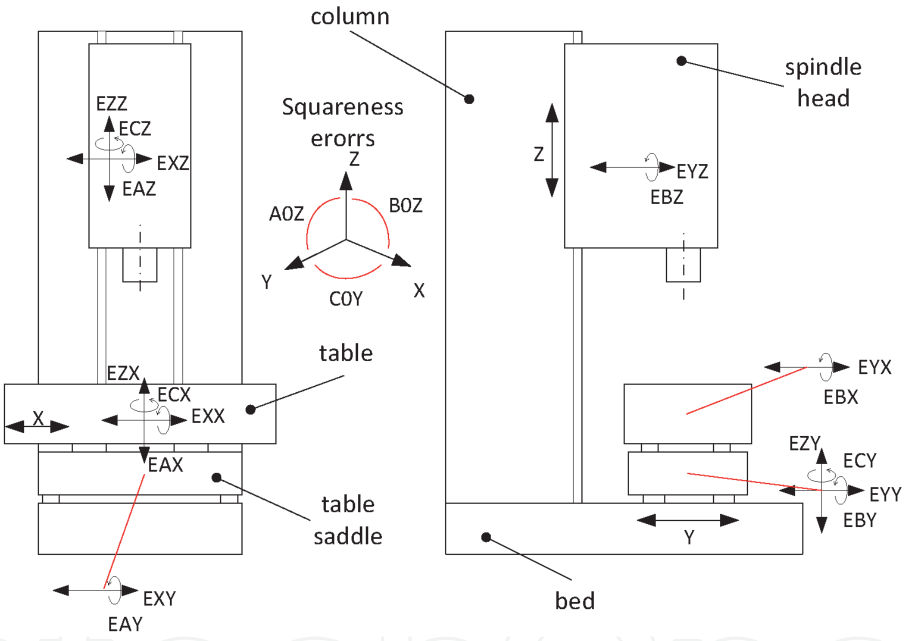

Figure 1.
Scheme of deviations of three-axis kinematics at the machine MCV 754 QUICK, KOVOSVIT-MAS [8].

Linear axis X	Rotary axis C
EXX – positioning error	EXC – radial motion in X direction
EYX – straightness error in Y direction	EYC - radial motion in Y direction
EZX - straightness error in Z direction	EZC - axial motion of C axis
EAX – angular roll error	EAC - tilt error motion around the X of the C axis
EBX - angular pitch error	EBC - tilt error motion around the Y of the C axis
ECX - angular yaw error	ECC - angular positioning error

Table 1.
Error description for one linear axis.

As early as in 1932, German professor Georg Schlesinger published a book "Inspection Test on Machine Tools," which became the basis for a unified system for assessing the accuracy of machine tools. In this book, he introduced guidelines for the use of devices and equipment for machine tool inspections. Measurement procedures and tolerances for permitted deviations are also given. The name of prof. Schlesinger is used to informally call the geometric accuracy tests of machine tools.

The devices and aids most commonly used to measure geometric errors in machine tools are, for example, granite rulers and cubes, dial gauges, digital inclinometers, autocollimators or laser interferometers, which are increasingly used for measurement. The principle of light interference as a measuring tool dates back to 1880, when Albert Michelson developed interferometry. The Michelson interferometer consists of a light source of one wavelength (monochromatic light), a silver-coated mirror and two other mirrors. Although modern interferometers are more sophisticated and measure with accuracy of the order of 1 ppm and higher, they still use the basic principles of the Michelson interferometer [4].

The straightness measurement shows deflection (bent component) or misalignment in the machine guides. This may be due to wear, an accident that may have damaged them, or poor machine foundations that cause the axis or the entire machine to drop.

Squareness is measured by comparing the straightness of two nominally orthogonal axes. Measurements can be carried out using different fixtures and devices with different arrangements. Measuring prisms, mandrels, or granite cubes may be included among fixtures while dial gauges and lasers among devices [4].

Planeness measurement is performed to check the planeness of CMM tables and machine tools, plate fields and surfaces. It determines whether there are any significant peaks or valleys and quantifies them. If these errors are significant, corrective operations are required. A certain number of measuring lines are required to measure the planeness of the surface.

3.2 Positioning accuracy

This parameter describes the accuracy and repeatability of positioning in linear and rotary numerically controlled axes. "Determination of accuracy and repeatability of positioning in numerically controlled axes" is described in the standard ISO 230-2/6 (ISO 230-2 Test code for machine tools—Determination of accuracy and repeatability of positioning numerically controlled axes; ISO 230-6 Test code for machine tools—Determination of positioning accuracy on body and face diagonals), but very often the directive VDI/DGQ 3441is also used [6].

Positioning accuracy is the most common form of measurement made with a laser interferometer (**Figure 2**). The laser system measures linear positioning accuracy and repeatability by comparing the position displayed on the machine with the actual position measured by the laser system.

A more advanced device for measurement of positioning accuracy of the machine is the Laser Tracker, which allows for immediate evaluation of the x, y, and z deviations. The geometric accuracy of the machine and the accuracy of positioning can be evaluated simultaneously (**Figure 3**) for an already assembled and activated machine. For this reason, the aforementioned accuracies are usually considered simultaneously [9].

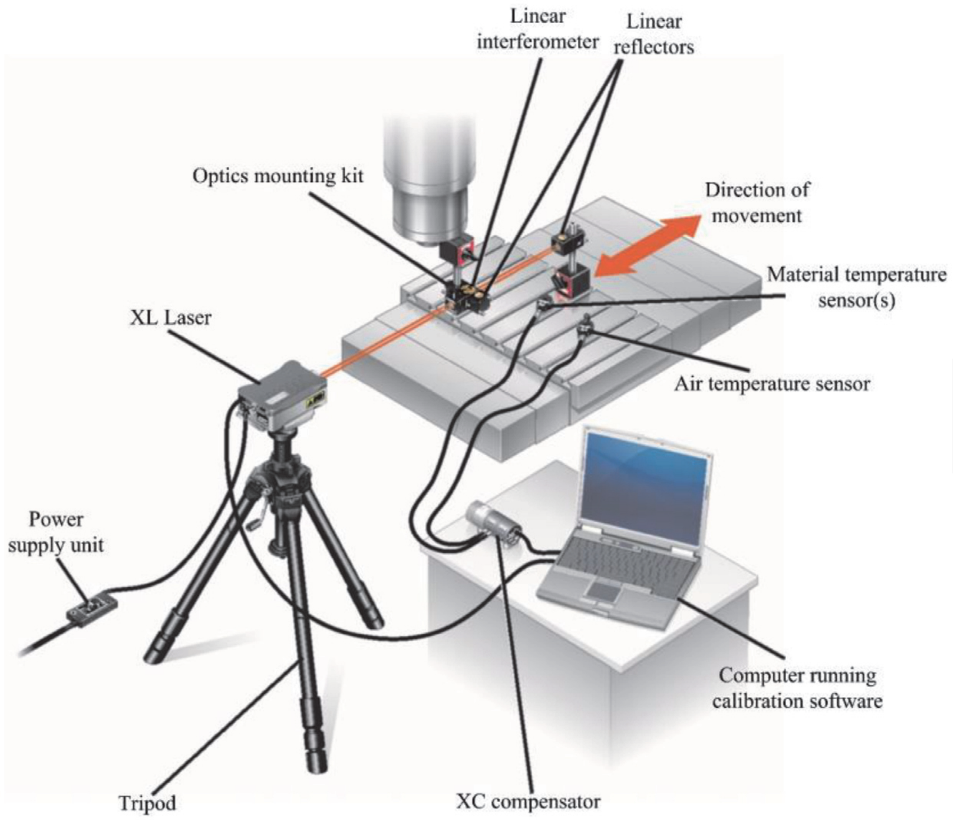

Figure 2.
Setting of measuring system for measurement of positioning accuracy [Renishaw].

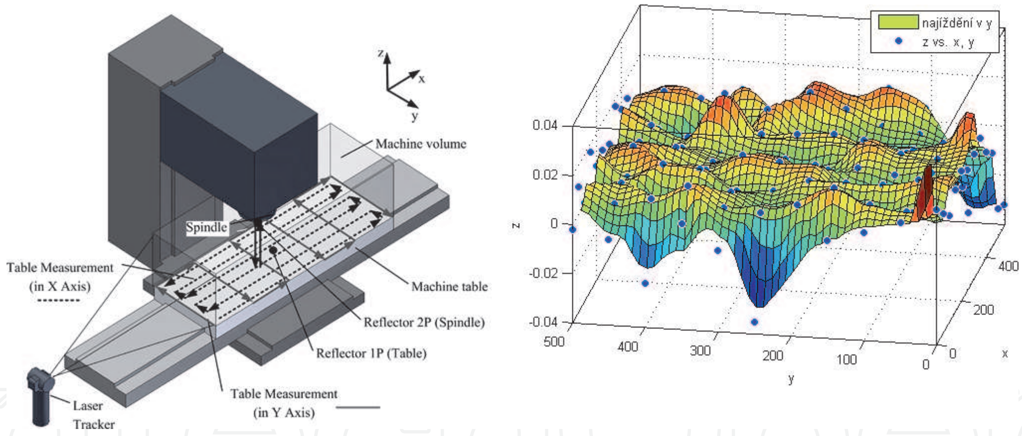

Figure 3.
Synergy when evaluating geometric and positioning accuracy using a laser tracker [9].

3.3 Interpolation accuracy

Theoretically, if the CNC machines were perfectly accurate, then the circular path of the machine would exactly match the programmed circular path. In practice, however, any of the errors (measuring error, straightness, clearance, reverse error, etc.) will cause the radius of the circle to deviate from the programmed circle. If we are able to accurately measure the actual circular path and compare it with the programmed (nominal) path, we would get a scale of the machine tool accuracy. Measurement and evaluation of circular interpolation accuracy are the subject of, for example, the standard ČSN ISO 230-4. The aim of the tests is to provide a method for estimating the properties of contour forming of numerically controlled machine tools. These errors are affected by the geometric errors and dynamic behavior of the machine at the feed used. Results are visible on machined parts under ideal machining conditions if the diameter and feed are the same for both machining and interpolation testing [1, 7].

3.4 Volumetric accuracy

Advanced and highly progressive methods include the assessment of volumetric accuracy and its subsequent compensation. The purpose of these advanced compensations is to minimize the tool center point (TCP) deviation at any point in the machine measured workspace. TCP volumetric deviation is defined as the sum of partial deviations in the individual axes [6].

Volumetric accuracy of machine tools is represented by a vector map of error deviations in the workspace. In the standard ISO 230-1, the concept of volumetric accuracy for a three-axis center is defined as the maximum range of relative deviations between the actual and ideal position in the X, Y, Z directions and the maximum range of deviations orientation for directions of A, B, C axes for motions in X, Y, Z axes in the specified volume, where the deviations are the relative deviations between the tool and the workpiece on the machine tool for specified alignment of the primary and secondary axes [1, 10].

The LaserTRACER measuring device (**Figure 4**) is mainly used for measuring of volumetric accuracy and subsequent volumetric compensation. The principle of the LaserTRACER measurement is based on measurement of beam lengths (HeNe laser wavelengths, 632.8 nm) and calculation of the measured point in the workspace by the method of sequential multilateration.

With this method, it is necessary to measure gradually from multiple locations on the machine (it is recommended to measure from at least four LaserTRACER positions). The method is presented as an analogy to the GPS system [10].

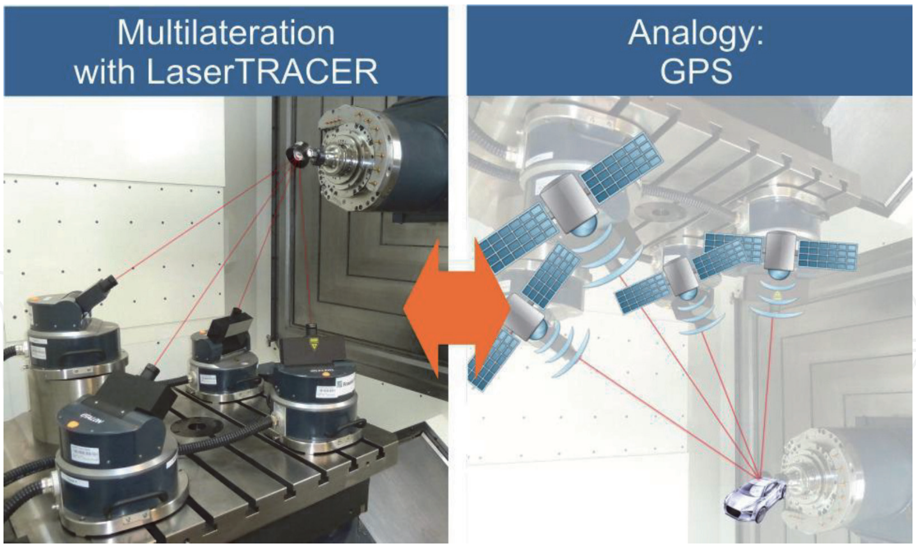

Figure 4.
Principle of measurement with LaserTRACER [etalon].

3.5 Working accuracy

This is a property of a machine tool that expresses the quality and productivity of a potential workpiece production. Working accuracy is expressed by the production of a test workpiece or a series of test workpieces. The working accuracy of the machine is affected by the accuracy of the relative tool path [6].

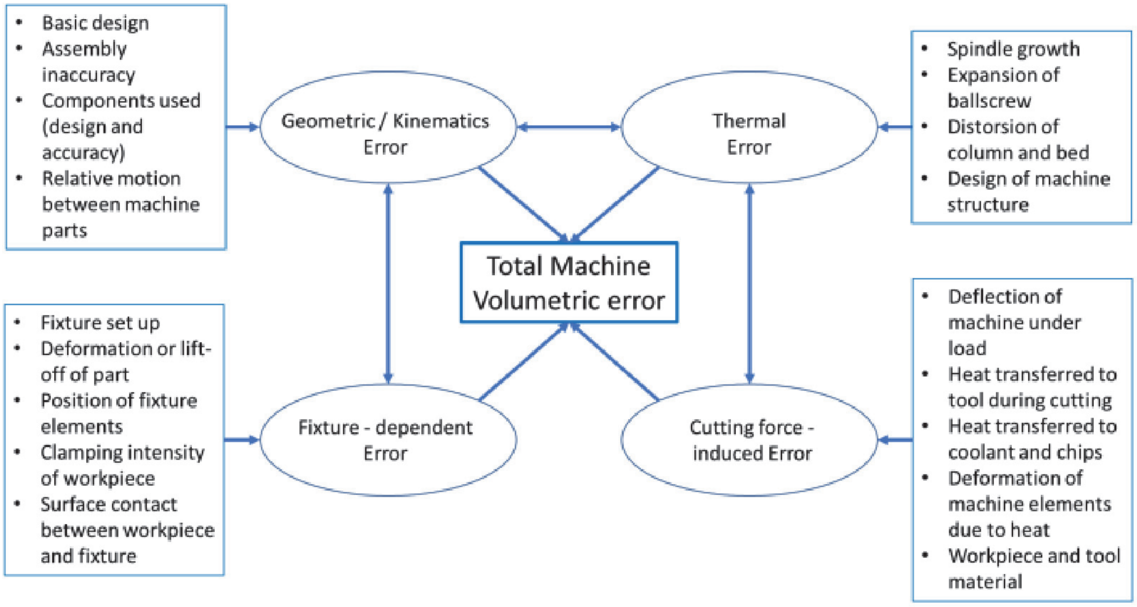

Figure 5.
Overview of the error budget in a machine tool and the factors affecting it [11].

- geometric accuracy of the machine;
- tool positioning accuracy relative to the workpiece (positioning accuracy);
- resistance of the machine to elastic deformations (caused by cutting forces, workpiece weight, etc.);
- resistance of the machine to thermal expansion (“thermal stability”);
- selection of cutting conditions, etc.

An overall summary of factors affecting the accuracy of the machine tool is shown in **Figure 5**. The resulting error in the Cartesian coordinate system is shown by Eq. (1) as a spatial error between the programmed and the actual TCP position [6].

Test workpieces to be tested for working accuracy are given, for example, by ISO 10791–7. Here, a test workpiece for three-axis machining is designed. Furthermore, test workpieces are aimed at continuous five-axis machining. An example is the test workpiece defined by the directive VDI NCG 5211-1.

3.6 Production accuracy

Production accuracy describes the production process accuracy evaluated on the workpiece. Production accuracy is influenced by geometrical accuracy, positioning accuracy, working accuracy, and also by the errors of machine operator (incorrectly adjusted tool, poorly clamped workpiece) and by changes of ambient conditions. Variations in the dimensions of the test workpieces during the production process provide direct information on production accuracy [6].

Production accuracy is usually monitored by SPC (statistical process control). This method has already been overcome in some production processes with 100% product control. Due to the spectrum of workpieces of medium-sized and large CNC machine tools, the SPC method can still be considered valid [6].

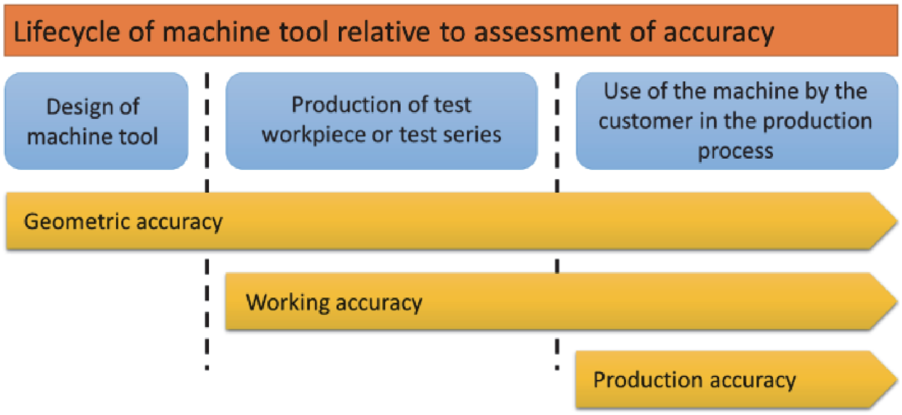

Figure 6.
Relationships between individual accuracies of a CNC machine tool throughout its life cycle.

The three main influences that affect the machine tool and the production process and cause workpiece dimensional variations can be more closely assigned to [4]:

- production technology 15%,
- working accuracy of the machine 25%,
- measurement 15%,
- ambient conditions 20%,
- machined part 5%,
- machine operator 20%.

The above-mentioned partial accuracies of the machine tool can be divided into individual parts of the life cycle (**Figure 6**). Production accuracy can, therefore, be monitored at the phase of customer's machine use and is influenced by both the working accuracy of the machine and long-term stability of geometric accuracy.

4. Example of basic compensation: positioning accuracy

One of the possibilities of compensating the error of linear and rotary axis is to use the so-called interpolation compensations, which include the compensation of leadscrew errors and measuring system errors [12]. In the SIEMENS control system, errors are referred to as LEC and MSEC (*LEC*-Leadscrew Error Compensation and *MSEC*-Measuring System Error Compensation). Compensation values are entered into the system in the form of tables, which are either manually entered or subprograms can be generated using various software solutions, which automatically load and write the table into the machine control system. Here, it should be taken into account that this automatic table loading can only work for given versions of the machine control system with the appropriate service pack. The MSEC compensation is also referred to as ENC_COMP in the machine control system and, through this parameter, the compensation is gradually set and activated. The abbreviations depend on the type of machine control system.

Only unidirectional compensations can be made by ENC_COMP compensation. In the event that a clearance error is found from the test, it is possible to use the Backlash compensation in combination with ENC_COMP.

4.1 Backlash

During the transfer of force between the movable part of the machine and its drive—e.g., a ball screw and its mounting—there are clearances (gaps) at different load directions. Conversely, a complete clearance-free mechanical adjustment will dramatically increase machine wear and heat generation. Mechanical clearances cause deviations in the reverse path of axes or spindles with indirect measuring systems. This means that if the direction changes, the axis will travel depending on the gap size. These clearances are compensated by the function listed below as Backlash.

Backlash can be entered into the control system in several ways. The first option is to use the machine parameter and enter the value as a constant for the selected axis.

The second option is to use the SAG compensations and the CEC table, which will be described in the next step and eliminate the clearance error by bidirectional compensation. The advantage of the first solution is to specify only one constant. In the case of non-linear behavior, it is preferable to enter the clearance in the form of a CEC table.

To use the MSEC compensation, the table for the Siemens control system will be as follows:

```
%_N_AX_EEC_INI
CHANDATA(1)
$AA_ENC_COMP[0,0,X1]=0.003    ; first compensation value (interpolation point
                                0):+3μm
$AA_ENC_COMP[0,1,X1]=0.01     ; second compensation value (interpolation
                                point 1): +10μm
$AA_ENC_COMP[0,2,X1]=0.012    ; third compensation value (interpolation
                                point 2): +12μm

$AA_ENC_COMP[0,800,X1]=-0.0   ; last compensation value (interpolation point
                                800): 0μm
$AA_ENC_COMP_STEP[0,X1]=1.0   ; Distance between two compensation values
                                1.0 mm
$AA_ENC_COMP_MIN[0,X1]=-200.0 ; Start of compensation -200.0 mm
$AA_ENC_COMP_MAX[0,X1]=600.0 ; End of compensation +600.0 mm
$AA_ENC_COMP_IS_MODULO[0,X1]=0 ; Compensation without modulo
M17                              function
```

5. Example of basic compensation: sag compensation

In the previous paragraph, compensation in one MSEC axis was described [12]. In a large number of cases, MSEC compensation is insufficient and it is advisable to introduce corrections of two dependent axes. The sag compensation is performed when the weight of the individual machine elements leads to the positioning displacement and inclination of the moving parts, as this causes the related machine parts—including guide systems—to bend. The compensation error of angle is used

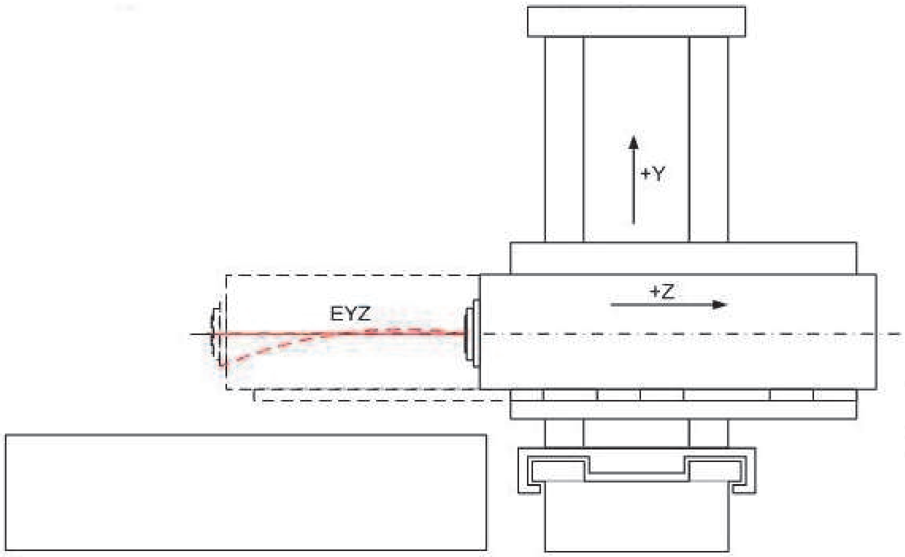

Figure 7.
Error EYZ of horizontal machine tool.

when the motion axes are not properly aligned at the correct angle (e.g., vertical). As the deviation from the zero position increases, the positioning errors also increase. Both types of errors can occur as a result of shifting the weights of individual machine parts, replaceable heads, workpiece diversity, and machine compliance. Measured correction values are calculated based on the relevant standards or own algorithms and are stored in the machine control system in the form of a compensation table during commissioning.

During machine operation and motion of axes, the corresponding value is interpolated between the values of the "interpolation points" table. For each motion in a continuous path, there is always both the base axis and the compensation axis. If the perpendicular y-axis is not in the continuous path of the x-axis and the y-axis, this inaccuracy is compensated by the x-axis in the continuous path. **Figure** 7 shows the principle of compensation on an example of a horizontal machine tool. The straightness error of EYZ is largely due to the machine compliance, while, through the ram travel, the sag occurs which is caused by the load of the assembly spindle-ram-slide-accessory.

This compensation provides a wide range of options for elimination of geometric errors. Here, an example will be given to compensate a sag, e.g., caused by changing the load of the replaceable heads, where there may be significant differences in their weights. If the machine is without a replaceable head, the sag is shown in **Figure** 7. If a milling head with a certain weight is used, the travel will be more loaded; therefore, a greater deformation will occur.

To use the SAG compensation for sagging compensations, the table for the Siemens control system will be as follows:

```
%_N_NC_CEC_INI
CHANDATA(1) ;
$AN_CEC[0,0]=0       ; first compensation value (interpolation point 0); for Z:
                      ±0μm
$AN_CEC[0,1]=0.01    ; second compensation value (interpolation point 1); for Z:
                      +10μm
$AN_CEC[0,2]=0.012   ; third compensation value (interpolation point 2); for Z:
                      +12μm
```

```
$AN_CEC[0,100]=0     ; last compensation value (interpolation point 101); for Z:
                       ±0μm
$AN_CEC_INPUT_AXIS[0]=(AX2)     ; base axis Y
$AN_CEC_OUTPUT_AXIS[0]=(AX3) ; compensation in Z axis
 $AN_CEC_STEP[0]=8        ; distance between interpolation points 8.0 mm
$AN_CEC_MIN[0]=0          ; start of compensation Y=0 mm
$AN_CEC_MAX[0]=800.0         ; end of compensation Y=800 mm
$AN_CEC_DIRECTION[0]=0     ; table applies to both directions of Y axis motions
$AN_CEC_MULT_BY_TABLE[0]=0;
$AN_CEC_IS_MODULO[0]=0    ; compensation without modulo function
M17 ;
```

If we use the SAG compensations for bidirectional axis compensation, the table for the Siemens control system will be as follows. The parameters of both the base axis and the compensated axis will be the same and match the axis designation. The direction parameter will be first set to 1 and then to −1. As an example of a horizontal boring machine, for the Z axis of ram travel, it will be as follows.

```
%_N_NC_CEC_INI ;
CHANDATA(1) ;
$AN_CEC[0,0]=0     ; first compensation value (interpolation point 0); for Z: ±0μm
$AN_CEC[0,1]=0.01 ; second compensation value (interpolation point 1); for Z:
                      +10μm
$AN_CEC[0,2]=0.012     ; third compensation value (interpolation point 2); for Z:
                          +12μm
$AN_CEC[0,10]=0        ; last compensation value (interpolation point 11); for Z:
                         ±0μm
$AN_CEC_INPUT_AXIS[0]=(AX3)     ; base axis Z
$AN_CEC_OUTPUT_AXIS[0]=(AX3) ; compensation in Z axis
$AN_CEC_STEP[0]=75          ; distance between interpolation points 75.0 mm
$AN_CEC_MIN[0]=0.0          ; start of compensation in Z=0 mm
$AN_CEC_MAX[0]=750.0      ; end of compensation in Z=750 mm
$AN_CEC_DIRECTION[0]=1     ; table applies to only positive direction of Z axis
$AN_CEC_MULT_BY_TABLE[0]=0     ;
$AN_CEC_IS_MODULO[0]=0              ; compensation without modulo function
$AN_CEC[0,0]=0     ; first compensation value (interpolation point 0); for Z: ±0μm
$AN_CEC[0,1]=0.01     ; second compensation value (interpolation point 1); for Z:
                         +10μm
$AN_CEC[0,2]=0.012     ; third compensation value (interpolation point 2); for Z:
                          +12μm
$AN_CEC[0,11]=0     ; last compensation value (interpolation point 11); for Z:
                      ±0μm
$AN_CEC_INPUT_AXIS[0]=(AX3)     ; base axis Z
$AN_CEC_OUTPUT_AXIS[0]=(AX3) ; compensation in Z axis
$AN_CEC_STEP[0]=75     ; distance between interpolation points 75.0 mm
$AN_CEC_MIN[0]=0.0     ; start of compensation in Z=0 mm
$AN_CEC_MAX[0]=750.0     ; end of compensation in Z=750 mm
$AN_CEC_DIRECTION[0]=-1     ; table applies to only positive direction of Z axis
$AN_CEC_MULT_BY_TABLE[0]=0     ;
$AN_CEC_IS_MODULO[0]=0     ; compensation without modulo function
M17 ;
```

Furthermore, SAG compensations are used to compensate squareness error. The squareness compensations of the Siemens control system are entered using CEC tables, where one axis is determined as the base axis and the other as compensated. An example will be given to compensate the squareness of, for example, the Y and Z axes of a horizontal machining center. From the measured values obtained, for example, from measurements with a laser interferometer, ballbar or calibration cubes and dial gauges, we obtain information on the size and orientation of squareness, which may be, for example, 22.4 μm/m. It is necessary to respect the machine coordinate system and orientation of axes when preparing the measurements. Otherwise, for the verification measurement, the resulting error value will be multiplied. For a ram travel (Z axis), this means that for a travel length of 750 mm, the measured error of 22.4 μm/m must first be converted by a ratio of 750/1000 mm. After multiplying by the measured value, we obtain the value for entering the correction into the machine control system. In this case, the value at the 750 mm position will be 16.8 μm.

For the above example, the compensation table for travel of the ram axis Z will be as follows.

```
%_N_NC_CEC_INI ;
CHANDATA(1) ;
$AN_CEC[0,0]=0     ; first compensation value (interpolation point 0); for Z: ±0μm
$AN_CEC[0,100]=0.0168 ; last compensation value (interpolation point 11); for Z:
                        ±16.8μm
 $AN_CEC_INPUT_AXIS[0]=(AX3)     ; base axis Z
$AN_CEC_OUTPUT_AXIS[0]=(AX2) ; compensation in Y axis
$AN_CEC_STEP[0]=750        ; distance between interpolation points 750.0
$AN_CEC_MIN[0]=0.0        ; start of compensation in Z=0 mm
$AN_CEC_MAX[0]=750.0        ; end of compensation in Z=750 mm
$AN_CEC_DIRECTION[0]=0    ; table applies to for both directions of Z axis
                            motions
$AN_CEC_MULT_BY_TABLE[0]=0     ;
$AN_CEC_IS_MODULO[0]=0     ; compensation without modulo function
M17 ;
```

6. Example of advanced compensation: volumetric compensation

The DMU 75 monoBlock® machine (**Figure 8**) is kinematically adapted to have three linear motions in the tool (X = 750, Y = 650, Z = 560 mm) and two rotary motions in the workpiece (swinging about the X axis and rotation around the Z axis). It is equipped with the Heidenhain TNC 640 control system. This machine has a positioning accuracy of 8 μm per axis.

The measurement and compensation of the volumetric accuracy of the linear machine axes are shown in **Figure 9**. After compensation, the workspace was improved by approx. 60%.

Before verification measurement of the volumetric accuracy, the machine was measured by a DBB device to verify the successful activation of volumetric compensation. **Figure 10** shows an improvement in the accuracy of circular interpolation on the shape of roundness (especially squareness); therefore, the machine was verified by the LaserTRACER to detect an improvement in overall volumetric accuracy [13].

After compensating the volumetric accuracy of the linear axes, the rotary axis that is the first in the kinematic chain from the workpiece to the tool, i.e., the C axis, must first be measured. This axis was measured with an example of the results in **Figures 11** and **12** [13].

Figure 8.
View of DMU 75 monoBlock ® [DMG Mori].

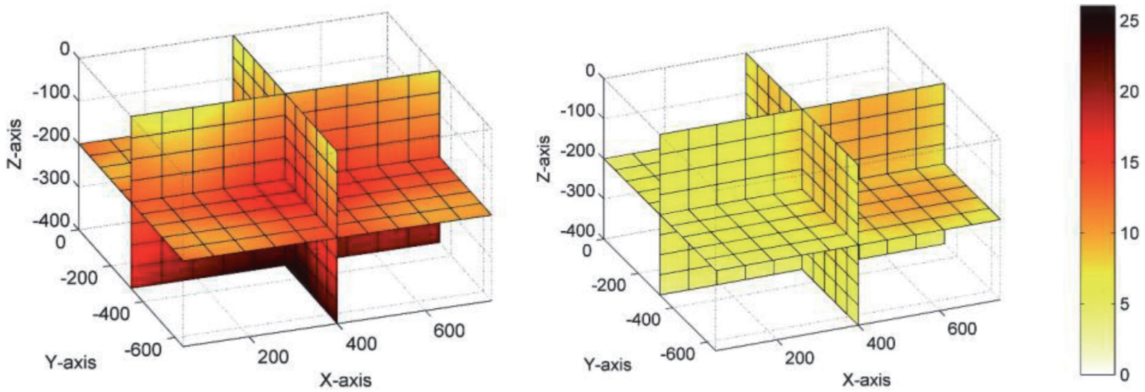

Figure 9.
Results of volumetric accuracy measurement of linear axes before and after compensation [13].

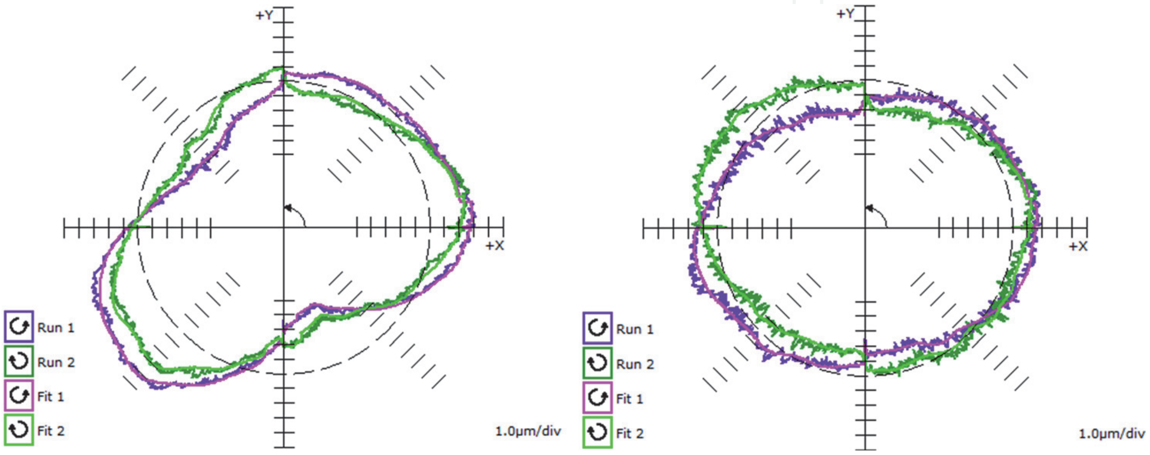

Figure 10.
Accuracy of circular interpolation in XY plane before and after volumetric compensation [13].

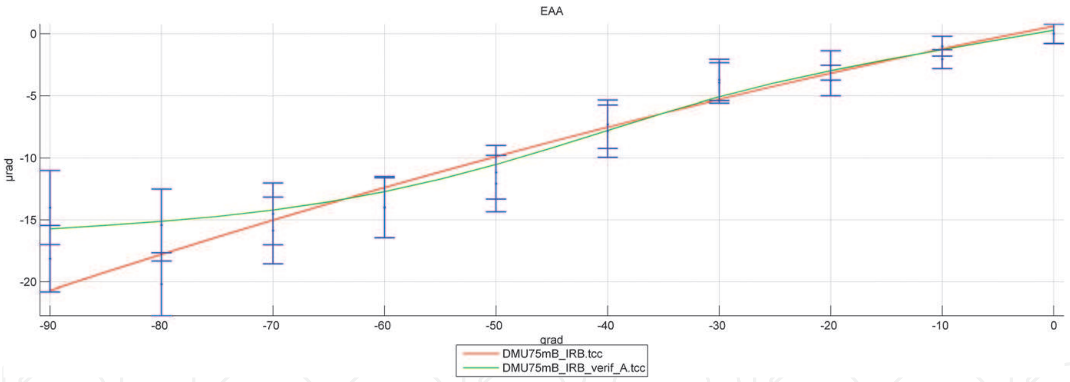

Figure 11.
Error of EAA axis A [13].

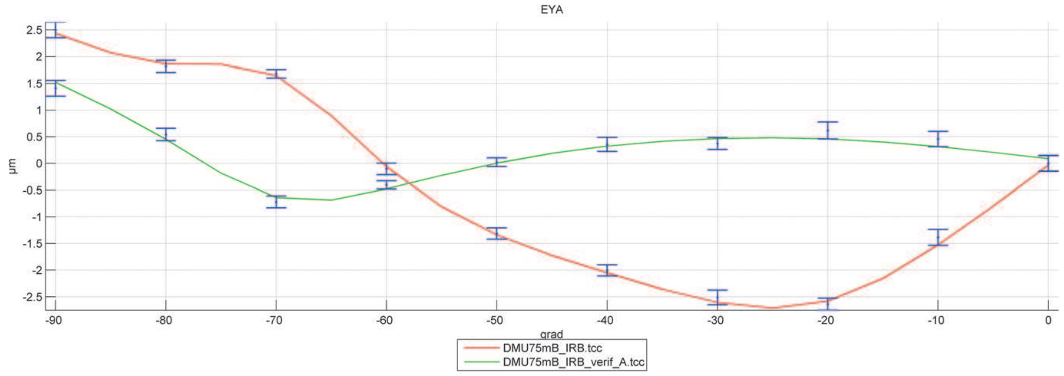

Figure 12.
Error of EYA axis A [13].

7. Conclusion

The aforementioned accuracies are related to one another and it cannot be assumed, for example, that the desired working accuracy can be achieved by poor geometric accuracy. **Figure 13** shows cascading of these accuracies.

Figure 13 shows a machine tool with linear axes. If there are rotary axes on the machine, it is necessary to check the linear axes first and then check the rotary axes. These are also checked for geometrical, positioning, and volumetric accuracy. If all

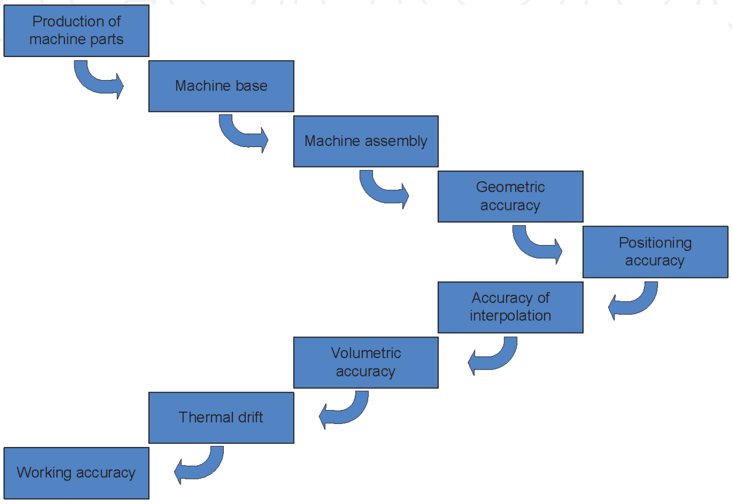

Figure 13.
Cascading of accuracies in machine tools [13].

the accuracies are within the required tolerances, the working accuracy related to the machining of the workpiece can be stepped to. Individual accuracies are described in the following section.

Acknowledgements

These results were obtained with the financial support of the Faculty of Mechanical Engineering, Brno University of Technology (Grant No. FSI-S-20-6335).

Author details

Jiri Marek*, Michal Holub, Tomas Marek and Petr Blecha
Institute of Production Machines, Systems and Robotics, Brno University of Technology, Brno, Czech Republic

*Address all correspondence to: marek@fme.vutbr.cz

References

[1] Marek T. Měření a kontrola obráběcích strojů. In: Konstrukce CNC Obráběcích Strojů IV. Praha: MM Publishing, s.r.o.; 2018. pp. 336-350. ISBN: 978-80-906310-8-3

[2] Marek J. Konstrukce CNC Obráběcích Strojů III. Praha: MM Publishing, s.r.o.; 2014. ISBN: 978-80-260-6780-1

[3] Holub M, Andrs O, Kovar J, Vetiska J. Effect of position of temperature sensors on the resulting volumetric accuracy of the machine tool. Measurement [Online]. 2020;**150**: 107074. DOI: 10.1016/j.measurement. 2019.107074. ISSN: 02632241

[4] Marek T, Marek J. Mít Sondu Nestačí. Brno: Renishaw s.r.o.; 2017. ISBN: 978-80-87017-20-3

[5] Marek J. Stavba CNC Obráběcích Strojů—Souvislosti a Fakta. Praha: Grumant s.r.o.; 2017

[6] Holub M. Geometric accuracy of machine tools. In: Measurement in Machining and Tribology [Online]. Materials Forming, Machining and Tribology. Cham: Springer International Publishing; 2019. pp. 89-112. DOI: 10.1007/978-3-030-03822-9. ISBN: 978-3-030-03821-2

[7] ČSN ISO 230-1 Zásady Zkoušek Obráběcích Strojů - Část 1: Geometrická Přesnost Strojů Pracujících bez Zatížení Nebo za Dokončovacích Podmínek Obrábění. Praha: Úřad pro Technickou Normalizaci, Metrologii a Státní Zkušebnictví; 2014

[8] Holub M, Blecha P, Bradac F, Kana R. Volumetric compensation of threeaxis vertical machining centre. MM Science Journal [Online]. 2015;**2015**(03): 677-681. DOI: 10.17973/MMSJ.2015_10_201534. ISSN: 18031269

[9] Knobloch J, Holub M, Kolouch M. Laser tracker measurement for prediction of workpiece geometric accuracy. In: Engineering Mechanics. Vol. 1. Svratka: Institute of Solid Mechanics, Mechatronics and Biomechanics; 2014. pp. 296-300. ISBN: 978-80-214-4871-1. ISSN: 1805-8248

[10] Holub M, Kol. GTS—Testování Obráběcích Strojů. Brno: VUT Brno – UVSSR; 2016

[11] Ramesh R, Mannan MA, Poo AN. Error compensation in machine tools—A review. International Journal of Machine Tools and Manufacture [Online]. 2000;**40**(9):1235-1256. DOI: 10.1016/S0890-6955(00)00009-2. ISSN: 08906955

[12] Holub M. Kompenzace geometrické přesnosti CNC obráběcích strojů. In: Konstrukce CNC Obráběcích Strojů IV. Praha: MM Publishing; 2018. pp. 352-364. ISBN: 978-80-906310-8-3

[13] Marek T. Predikování Vybraných Vlastností Rotačních Kinematických Dvojic Obráběcích Strojů [Online]. Vysoké Učení Technické v Brně. 2019. Available from: https://www.vutbr.cz/studenti/zav-prace/detail/122509