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Accuracy behavior of five-axis machines: classification and influence of individual error components

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Abstract

Due to increased output and variant flexibility in manufacturing, five-axis machining is more productive than three-axis machining in many ways. It offers the ability to produce more complex parts with less intervention by the machine operator and is indespensable in mold and die production. However, the use of two additional axes introduces new sources of error, causing a reduction in attainable workpiece accuracy. Topics such as thermal stability and fast recalibration take on greater significance. Thermal stability is particularly important because axis drift has a much greater effect on five-axis machined parts than on three axes machined parts.

For this article, four different five-axis machining centers with a similar kinematic structure and different cooling designs were investigated. The first task was to choose a suitable measuring device for analyzing the kinematic behavior of the machine structure over time. The R-test device was found to be the most suitable option because it permits observation of the translational and rotational location errors of all the axes, as well as the positioning error of the linear axes. During various long-duration tests performed on all four machine tools, the main error components were observed over time and compared with a norm based on the IT tolerances. During these tests, the machines were subjected internal and external heat sources. This article provides an overview of the main thermal error effects identified on these machines and how they affect five-axis machine accuracy. When thermal stability is attained, kinematic calibration can dramatically increase five-axis accuracy. This effect was demonstrated on a test workpiece that reveals kinematic errors through visible marks.

Machine tool, five axis machining, thermal behavior, kinematic calibration, test workpiece

1. Five-axis machining

The ease-of-use of five-axis machining technology with modern CAM tools gives the machine user a wide range of possibilities for the economical production of complex parts. In contrast to three-axis machining, the assumption that the accuracy of neighboring features on a workpiece are mainly affected by the neighboring accuracy of the machine tool proves to be invalid. As five-axis machines become ever easier to program, the more difficult it will become to know the attainable workpiece accuracy. This conflict is based on the fact that five-axis machining allows neighboring features on a workpiece to be machined in completely different machine axis positions. A small workpiece may be moved through the entire axis workspace of the machine. Consequently, machining an accurate part requires a consonance of the controllers, kinematic model, and actual machine kinematics.

2. Thermal behavior of machine tools

When it comes to setup and calibration, a central issue is the need to reduce or eliminate the differences between the kinematic description and the actual machine. It is already possible to achieve acceptable volumetric calibration results for five-axis machines. Various approaches using different measuring devices can be found in the literature [1, 2, 3, 4]. Nevertheless, even with perfect calibration, thermal drift during machining remains one of the most influential uncertainties in machine tools accuracy and influences it 5- to 10-times higher than all other effects [5]. New technologies such as trochoidal milling lead to high feed rates, thereby generating internal heat. To deal with this problem, techniques such as warming-up cycles, recalibration, thermal compensation, and the cooling or temperature control of machine components are employed in order to reduce the amount of thermally induced error.

2.1. Structural behavior during thermal load

A common method for resetting thermal drift during machining involves measuring a single point in the workspace or on the workpiece and then resetting the workspace reference point. Yet this approach is generally not appropriate for five-axis machining. A change in workpiece position must be separated into the reference point shift and the adjustment of the machine tool's kinematic chain. Any detected thermal drift must be corrected through some kind of recalibration.

In order to determine the most significant sources of inaccuracy in five-axis machining, four different medium-sized machine tools with different cooling designs were investigated. The R-test was found to be the best-suited device for characterizing the machine kinematics within a short measuring period.

2.2.Observation of machine kinematics through the R-test

The R-test is a measuring device that measures the position of a sphere in the tool holder relative to the table. This method achieves a volumetric measuring accuracy better than 0.5 µm. The data collected at various machine axis positions can then be used to identify different machine parameters.

With the R-test mounted at a single eccentric position on the machine table, the table is turned and swivelled into different rotary axis positions. Maintaining the same position of the sphere in the tool holder relative to the table provokes compensation movements in the linear axes. Their measurement allows the identification of a kinematic model containing the location errors for all axes. These errors consist of four translational location errors of the rotary axes, four rotational location errors of the rotary axes, and three rotational location errors of the linear axes. The change in linear axis positioning error can be determined as well. This type of model was chosen for its robustness, its low condition number (20 - 50), and its ability to describe the main fluctuating thermal effects. Figure 1 shows the R-test and a sample workspace, along with the measuring positions and measured deviations scaled by a factor of 2000.

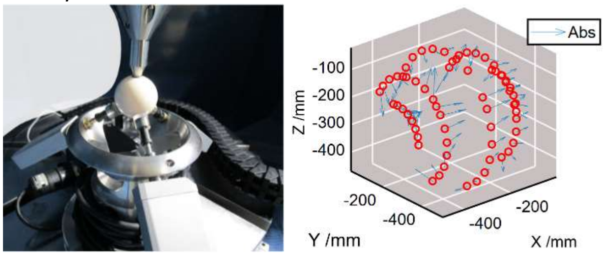

Figure 1: R-test and measuring points in the workspace

To verify some of these identified parameters, other devices such as a laser interferometer and a 2-D reference grid encoder were used for cross-checking the results through direct measurement. The discrepancies were quite small and could be mainly explained by the measuring uncertainty of all the devices.

3. Thermal measurements

The thermal investigation of four different machines was performed as illustrated in Figure 2. The measurement of about 50 different positions with the R-test in the workspace was carried out recurrently in different thermal states over a period of approximately one to three days. During the measurement, all of the positions were measured twice (forwards and backwards) so as to reduce measuring noise.

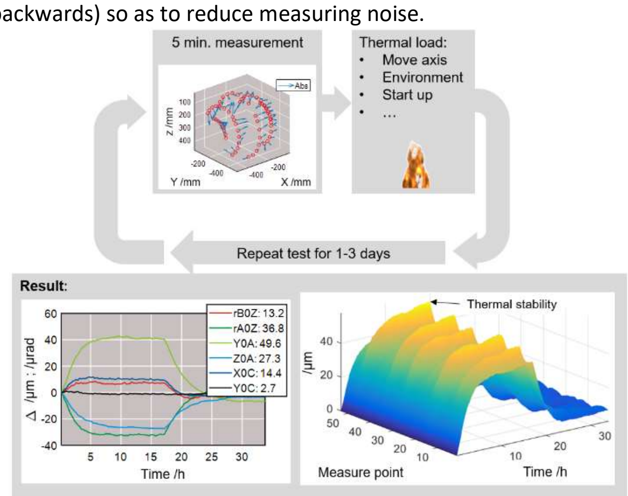

Figure 2: R-test process of thermal test

Between measurements, different thermal loads were induced through moving axes or changes in environmental temperature. The uniform ratio between the measuring period and the thermal loading period was approximately 5 minutes-to-15 minutes. This ratio was kept constant for all four machines.

The key results of the thermal investigation were the sequence of the main varying kinematic parameters over time and the fluctuation of 3-D errors over time in all positions. Examples of both metrics can be seen above in Figure 2. The maximum variation of the measured normal deviation during a single test is referred to as the thermal stability. This value describes only the variation of measured deviations, assuming that the machine exhibits no kinematic error at the beginning of every test. This emulates a perfectly calibrated machine at the beginning of every test.

4. Comparison of different machine cooling designs

Table 1 lists all four of the investigated machines and some of their characteristics. All of the machines have their rotary axes on the workpiece side of the machine. With the exception of Machine D, all of the them were medium-sized machines exhibiting a workspace diagonal at or near 1m.

The machines featured different structural cooling designs. In Machine A, none of the structural components were cooled except the spindle, and a temperature-controlled cutting fluid. All of the other machines were partly or fully temperature-controlled with a water cooling system as listed in Table 1. The reference temperature for the cooling system was constant only for Machine D.

Table 1: Four different machine tools

Machine	Kinematics/ workspace diag.	Struct. Cooling	Ref. temp.	Scaling factor (IT)
A	AC table / 1.2m	No	Env.	1.09
B	AC table / 1.0m	Partly	Env.	0.99
C	BC table / 1.0m	Yes	Env.	0.98
D	BC table / 0.5 m	Yes	22°C	0.73

4.1 Weighting machine accuracy by IT tolerances

Any comparison of the achievable accuracy of differently sized machines must take the workspace accuracy into account. A standard approach for achieving comparable accuracy based on the size of a manufactured part is the IT tolerance table in [6]. The current formula is:

$$IT = K \cdot \left(0.45 \cdot \sqrt[3]{D} + 0.001 \cdot D\right);\ D\ in\ mm, \qquad (1)$$

where IT is the standard tolerance value in µm and K the factor of the corresponding standard tolerance. *D* is the range of the size to be manufactured. For basic tolerances, *K* is usually greater than 1. For the scaling of the workspace, *K* is selected to be 1/5.5, which, when *D* = 1 m, yields *IT* = 1. This value is the scaling factor for the measured deviations referenced to the workspace diagonal and is listed in Table 1 for the different machines. In order to achieve the scaled thermal stability for the comparison of different machine tools, the determined thermal stability is divided by this scaling value

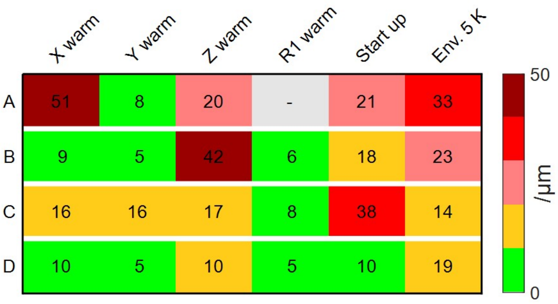

Figure 3: Scaled thermal stability for different machines

Figure 3 shows the attained scaled thermal stability of the machines. This diagram represents a measuring period of around 900h. The different thermal loads are as follows:

X,Y,Z warm: Warming of the linear axes for 15 h at a feed rate of 10000 mm/min, followed by a 15 h cool-down period.

R1 warm: Warming of the first weight-loaded rotary axes for 15 h at 90 ° position, followed by a 15 h cool-down period to 0°.

Start up: Starting of the machine from a cooled state, followed by measuring for 24 h and interrupted by standstill.

Env. 5 K: Measuring interrupted by standstill for at least three days. When possible, the machine tool was subjected to temperature variations by means of a temperature chamber. The resulting deviations were scaled by 5 K. This range was defined by the observed maximal daily environment variation during measurements in usual shop floor conditons.

Prior to each test (except for “Start up”), the machine was brought to a standstill and powered-on for 24 h. As can be seen, in most of the warming-up cycles, the machine tool with no structural cooling exhibited a thermal stability of above 20 µm. In contrast, a constant reference temperature for structural cooling (Machine D) most effectively reduced the deviation caused by internal heat sources. In a thermally uncontrolled environment, it appears advantageous to base the cooling medium temperature on the environmental temperature. The environmental influence is thereby relatively low.

4.2 Main driving error-effects for accuracy

To examine the reason for the attainable thermal stability, the identified kinematic parameters were investigated over time. Figure 4 shows the summarized effect, of different error types, on the scaled thermal stability. The denotation is in accordance with ISO notation in [7]

T0R: Translational error of rotary axes (Y0A,Z0A,X0B,Z0B, …)

R0R: Rotational error of rotary axes (B0A,C0A,A0B,C0B, …)

R0T: Rotational error of transl. axes (B0X,C0X,A0Y,C0Y, …)

ETT: Positioning error of linear axes (EXX,EYY,EZZ)

For Machine D, the ETT could not be identified due to the small mounting radius of the R-test.

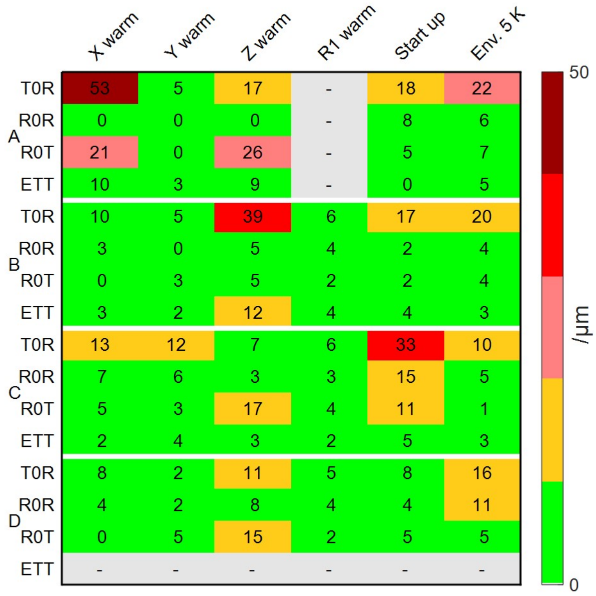

Figure 4: Error-effects on thermal stability

The main influence on the scaled thermal stability is the T0R (mean: 14.5 µm). On temperature-controlled machine structures, this error is significantly smaller. Unlike in three-axis machines, the T0R is critical in five-axis machining. In practice, the T0R can be significantly reduced through recalibration during machining. This is usually done by probing a reference sphere placed on the machine table at different positions of the rotary axes. This can be performed under full automation, such as with the KinematicsOpt cycle [8].

The second largest influence is the R0T (mean: 6.2 µm). Like the T0R, the R0T exhibits greater variation on non-temperature-controlled machines.

Although R0R is measurable, it has, on average, only a very small effect on the scaled thermal stability (mean: 4.6 µm).

The ETT (mean: 4.2 µm) has the smallest effect on the scaled thermal accuracy. This can be traced not least to the fact that all of the machines are equipped with linear encoders. Even within changing environment, the ETT remains sufficiently small.

Thermally caused deviations can be characterized by more than just their maximum value. The change in thermally caused deviations and characteristic values over time, such as time constants, are also important factors for stable machining. The time constant of a body is a product of its mass, thermal capacity, and thermal resistance. The identified time constants were therefore also divided by the scaling factor in Table 1 in order to account for the varying machine sizes.

As an example, the “X,Y,Z-warm” tests were compared in terms of the time constants T of the best observable parameters from the group T0R, R0T, and ETT. The R0R values were too small for detecting properly time constantes.

Table 2 shows that the highest time constants were observed in Machine A. However, thermal stability was most rapidly achieved in the temperature-controlled Machine D with a constant reference temperature. The increase in the time constant can be explained by the higher thermal resistance of a water-cooled surface compared to air-cooled surface.

Regarding the scaled time constants, the period of time required in order to stabilize Machine A for machining can be much longer than that of Machine D. In addition to the time-consuming thermal stabilization of Machine A, the scaled thermal stability in Figure 3 is even worse.

Table 2: Identified scaled time constants

Machine	T of T0R in h	T of R0T /h	T of ETT /h	Mean T
A	1.9	1.6	2.4	1.8
B	1.8	1.3	2.0	1.6
C	2	1.2	2	1.6
D	1	1.4	-	1.2

5. Testing five-axis accuracy on a test workpiece

The R-test is well suited for determining the thermal stability of a machine tool and for characterizing its thermal behavior. In order to evaluate five-axis accuracy in a manufacturing environment, a test workpiece for five-axis shaft milling was introduced. This workpiece is easy to mount, fast to machine, and reveals the five-axis accuracy through observable marks immediately after milling. Its shape is based on various Platonic bodies. The main idea is to produce K+1 faces on each side of the Platonic body, where K is the number edges of each side. The center face is given the same orientation as the standard face of the Platonic body. All of the other faces are gently sloped toward the edges that connect them to the standard Platonic body. Figure 5 shows three examples of this test workpiece.

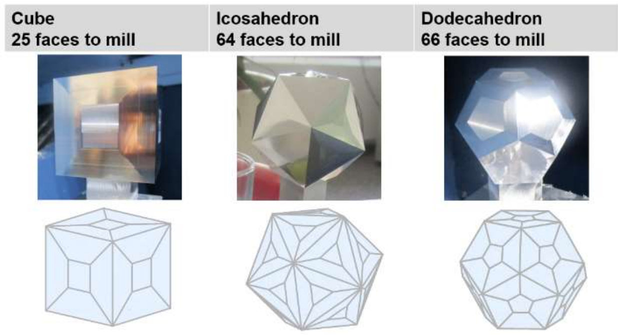

Figure 5: Test workpieces based on Platonic shapes

The defined slope angle directly influences the visible marks on the surface of the test workpiece. The flatter the angle of the faces, the more visible the marks become. Figure 6 shows the theoretical effect on a single triangle face of an icosahedron. The resulting gain factor is reciprocal to the chosen slope angle. With an angle of 1 °, deviations of 10 µm are readily observable to the naked eye since the resulting error on the workpiece is magnified by a factor of 60, to 0.6 mm. Even easier to observe are the non-merging edges in each corner of the triangle. Due to the shape of the icosahedron, the inner triangle also becomes eccentric relative to the outer triangle.

All of the faces on the test workpiece are machined by swarf cutting; hence, the thermal expansion of the spindle has no influence on the accuracy of this part. To machine the test workpiece, the direction of swarf milling of the surrounding faces is along the outer edge of the Platonic body. The direction of the central face can be chosen as desired. Thus, all of the faces are machined in different tool orientations. When the workpiece is placed eccentrically relative to both rotary axes, wide ranges of linear and rotary axis movements are necessary in order to machine this small part. Due to the fixed magnitude coupled with the slope angle, the test workpiece can be made quite small in order to achieve comparable manufacturing results on machine tools of different size.

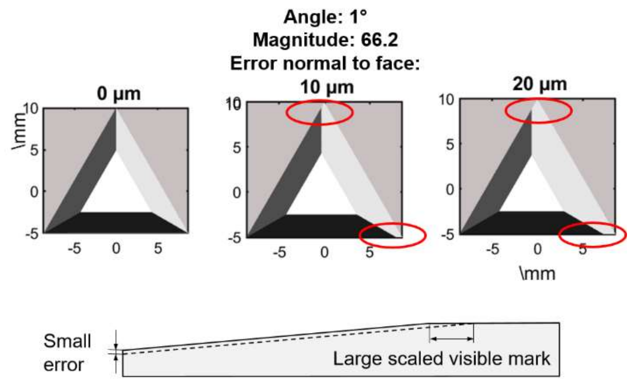

Figure 6. Visual effect, caused by normal deviation of the light-gray face

To demonstrate the potential of kinematic calibration, a test workpiece based on the icosahedron was milled on Machine B. Immediately prior to machining, the machine was calibrated in the following two ways:

1. Standard calibration: calibration of the four T0R with a standard cycle [8]
2. Customized calibration: calibration of the T0R, R0R, R0T, and component errors of the B axis with touch probe and four different positions of the calibration sphere on the machine table.

KinematicsComp [9] was used for the customized calibration and enables the compensation of all kinds of volumetric errors on machine tools. After implementation of the calibration methods, the test workpieces were machined. The machining time per workpiece was 15 min, including the roughing process. A picture of both parts can be seen in Figure 7. As is apparent from the image, the part machined with standard calibration exhibits much larger deviations between the non-merging edges. The size of the central triangle also strongly varies. Although customized calibration did not yield a perfect part, a significant improvement was noticeable.

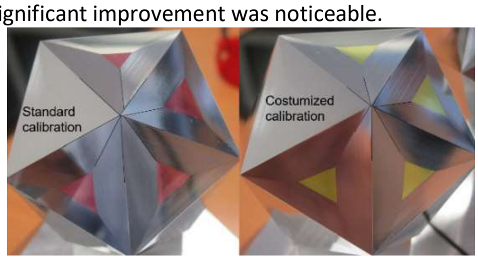

Figure 7: Test workpiece (icosahedron) for different calibration types

6. Conclusion

Compared with three-axis machining, five-axis machining offers a wider range of manufacturing capabilities (including greater flexibility) but leads to lower attainable accuracy.

Four different machine tools and their thermal behavior under different conditions were discussed. It was shown that structural cooling significantly reduced the amount of thermal drift as well as the time required to thermally stabilize the machine tool. This was observed through the use of the R-test measuring device and a new scaling method for comparing the different machine sizes. It was determined that the T0R and R0T are the main driving effects on the scaled thermal stability. T0R, in particular, can cause 1:1 errors on a five-axis milled workpiece. Yet in three-axis machining, TOR is merely a reference-point shift, whose error effect is easy to avoid.

Even when thermal stability is achieved, five-axis machining still involves higher calibration demands due to its large axis movements relative to the size of the workpiece. Also discussed was how a small, simple test workpiece based on Platonic bodies can be used to check the machining accuracy of a five-axis machine tool. This method immediately reveals the accuracy of a five-axis machine tool in the form of visible marks on the manufactured surface. A gauging process on a CMM was therefore unnecessary for a qualitative evaluation of the achievable accuracy.

7. Outlook

The test workpiece enables a qualitative evaluation of the achievable accuracy. For a quantitative evaluation, a subsequent gauging process on a CMM could be employed. In this case, the slope angle can be set to zero, thereby allowing the milled faces to be gauged. By milling the central face (white face in Figure 6) with a positive offset relative to the surrounding faces (gray faces in Figure 6), the test workpiece can be machined in the same manner as described above. The cube-shaped workpiece is especially well suited for this process because nearly all of its faces can be probed with just three axes. If the machine tool has sufficient three-axis accuracy within a small probing volume, the probing process can even be performed directly on the machine tool. A subsequent analysis could use the probed deviations for kinematic calibration purposes.

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