



Technical Information

Positioning accuracy of rotary axes: a key factor in 5-axis machining

The rise of globalization and the resulting internationalization of markets have led to strong diversification in customer demands. The end-customer market increasingly expects variant diversity and ever greater product individualization. These trends have not gone unnoticed in the manufacturing technology sector. To compete with global providers, companies must offer innovative products with superior quality and functionality. This fact, combined with ever smaller lot sizes per variant, places growing demands on geometrical tolerances and the finish quality of visible and functional surfaces. At the same time, manufacturing companies must adapt to shorter product-to-market times and product life cycles.

One approach to achieving high variant flexibility in manufacturing is to use a machine tool for 5-axis machining. Universal workholding systems permit multi-sided, complete machining and enable high-level automation for output flexibility and excellent machine utilization. Being able to vary the tool orientation along the milling path allows complex geometries to be machined extensively using standard tools. During 5-axis machining, all five machine axes are moved relative to each other and are synchronously interpolated (three linear axes and two rotary axes). When the rotary axes are moved to a fixed position prior to machining and held there throughout, this approach is known as 3+2-axis machining.

Machine tools ought to be able to maintain the high required machining accuracy on the workpiece even under fluctuating environmental and machining conditions. Position feedback must therefore be evaluated based on both the measurement accuracy and its consistency over time. During 5-axis machining in particular, errors in the positioning of rotary axes have a significant effect on machining accuracy and translate directly to the workpiece.



Depending on the cost structure, customer requirements, and machining scenario of the machine tool, the power train of a given rotary axis is based either on a torque motor or on a servomotor combined with a mechanical transmission. The choice of encoder is particularly important for rotary axes with a mechanical transmission, which will be the main focus of this article. The simplest way to obtain position feedback for a rotary axis consisting of a servomotor and gear system is to use a motor encoder while accounting for the transmission ratio. This type of position feedback is referred to as semi-closed loop control. It does not account for errors arising in the mechanical transmission elements. These errors are not part of the feedback loop. In Semi-Closed Loop operation, cyclic loads that cause friction-induced heating of the transmission components are a particular source of significant positioning error. However, when position feedback is obtained from an angle encoder mounted directly on the axis of the rotary table, this configuration is known as closed loop control. In a Closed Loop system, nearly all of the mechanical transmission errors are taken into account by the position control loop.

The following discussion will show that having a gear system in the measurement chain has a significant effect on rotary table positioning and will compare this approach with that of an angle encoder integrated directly into the rotary table.

Reference encoder

A reference encoder was designed and built for determining the positioning accuracy of the rotary table. Figure 3 provides a schematic representation of the design. The reference encoder consists of an optical scale drum [1] read by four, non-contact scanning heads [2]. The drum was centered and mounted to the rotary table via an adapter [3] so that it would turn with the rotary table during the measurement. The scanning heads were arrayed in a holder [4] and connected to the clamped main spindle of the machine tool by means of the tool clamping system [5].

Configuration of the tested machine

The following measurement results were obtained on a high-end 5-axis vertical machining center featuring two linear axes and one rotary axis for the workpiece, and one linear axis and one rotary axis for the tool (see Figure 2). The range of traverse was approximately 600 mm x 600 mm x 500 mm. The test focused on the "C" rotary axis in the table, which was driven by a servomotor and worm gear.

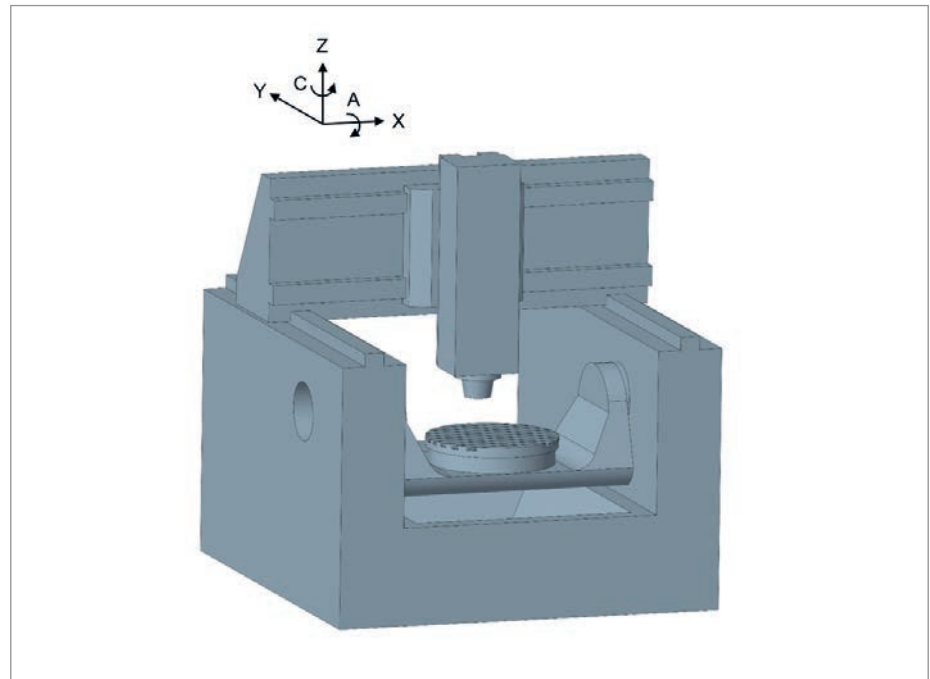


Figure 2: Schematic design of a machine tool for 5-axis machining

Figure 4 shows the reference encoder as mounted inside a machine tool. During the measurement, the rotary axes of the following components were in alignment: the rotary table, the scale drum of the reference encoder, and the main spindle. The reference encoder was qualified on a calibrated measuring machine and is able to ensure a high system accuracy of $\pm 0.5''$. This accuracy was attained within the wide mounting and operating tolerances of ± 1.0 mm radially and 0.4 mm for radial runout. Measurement series performed on the machine tool verified the reproducibility and quality of the reference encoder.

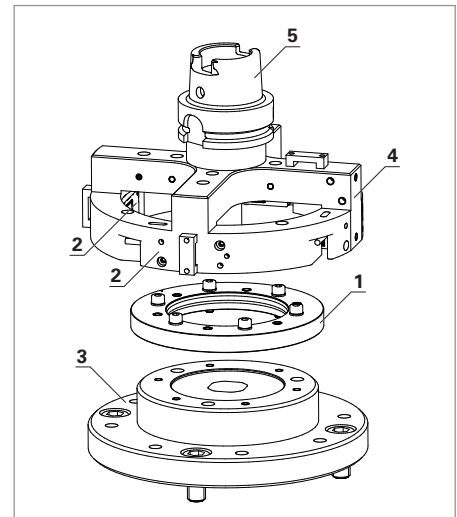


Figure 3: Schematic representation of the reference encoder

The benefit of this reference encoder lies in its generous mounting tolerances (especially its permissible eccentricity of ± 0.2 mm), which greatly facilitate installation and operation. The encoder's stated system accuracy refers to the complete reference encoder and is unaffected by external environmental factors. Measurements are also possible at any rotary axis position and in small stepping angles. No fixed value for the number of measurement positions or the equal distance between them was specified. It was not necessary to link the reference encoder with the machine control.

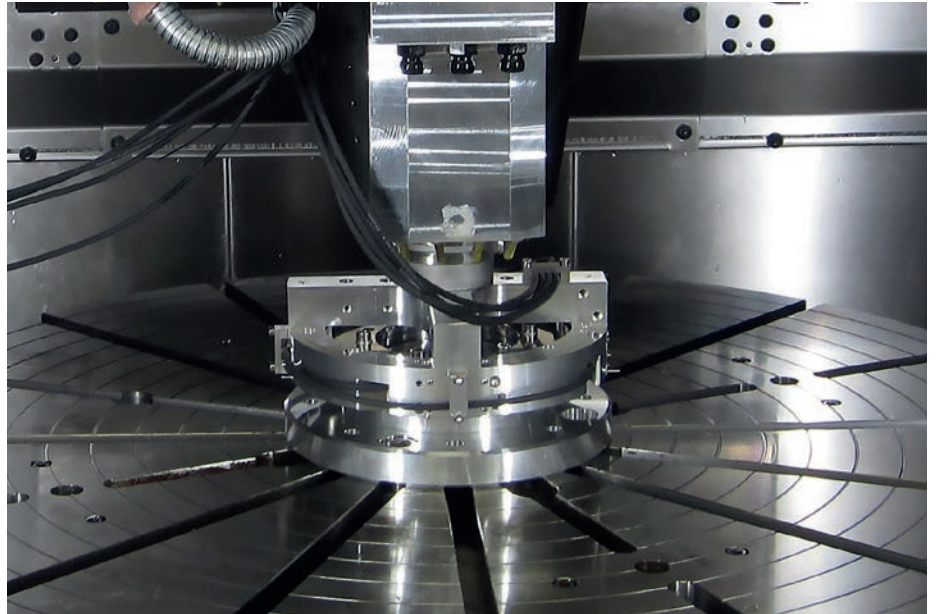


Figure 4: Reference encoder on the rotary table of a machine tool

Position measurement on rotary axes

Although direct drive systems with torque motors are widespread, a high proportion of machine-tool rotary axes still use a servomotor combined with a mechanical transmission. Reasons for this include the required level of machining complexity and the cost structure of the machine. When a servomotor is used, there are two ways to determine the angular position of the axis. The two position feedback configurations—Closed Loop (CL) and Semi-Closed Loop (SCL)—are schematically depicted in Figures 5 and 6.

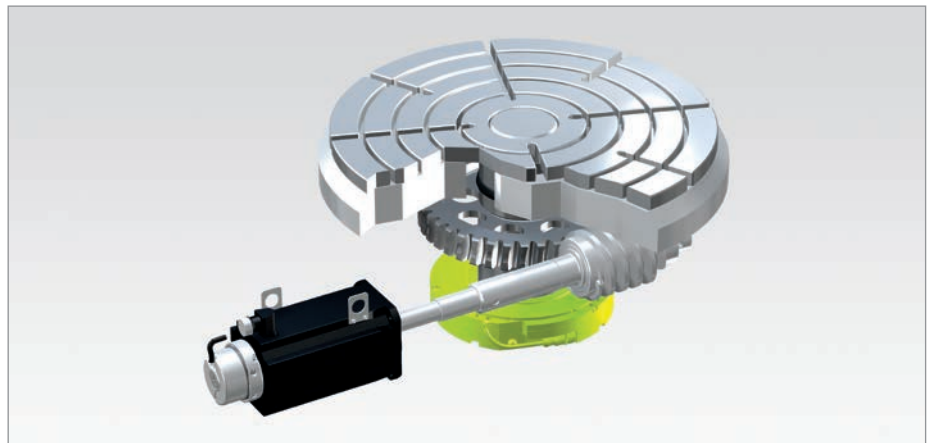


Figure 5: Closed Loop configuration

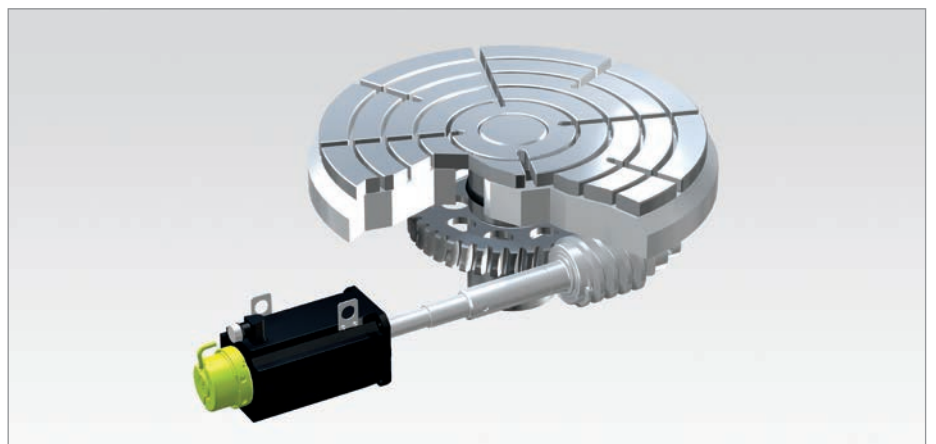


Figure 6: Semi-Closed Loop configuration

Compared with the Closed Loop setup, the Semi-Closed Loop configuration contains more sources of error due to the greater number of components located between the point of position measurement at the encoder and the affected rotary table. Particularly problematic in this context are geometric errors, elasticity errors in the mechanical transmission elements, thermal effects, and wear. Position measurement is also influenced by dynamic effects arising from the machining forces and vibrations. In a Closed Loop configuration, however, the positioning accuracy remains largely unaffected by the main error sources mentioned above since these errors are measured at their point of origin by the angle encoder and can be accounted for in the position control loop.

Although the measured rotary table is normally operated under Closed Loop control, this machine's control can be easily reparameterized to position the table under Semi-Closed Loop control. This allows for a direct comparison of the position error of the rotary table for both configurations (see Figures 7 and 8). For this comparison, 720 measuring positions evenly distributed along the circumference of the table were first approached from two directions: clockwise (CW) and counterclockwise (CCW). This high-resolution characterization of the position behavior revealed the constant, position-dependent, and non-systematic effects that influence rotary axis positioning. In the Closed Loop configuration, high positioning accuracy was attained across the measured angular

range of the axis, and the two directions of approach were barely distinguishable from each other. This measurement curve primarily reflects the behavior of the angle encoder used for position control. In the Semi-Closed Loop configuration, higher reversal error between the directions was apparent, as was a much larger variance within a single direction. This is primarily due to position-dependent errors in the mechanical transmission elements (i.e., play, friction, and gear-meshing effects). The larger amplitude of high-frequency vibration in the CW measurement compared with CCW also points to heightened wear in the gear flanks for this evidently preferred direction.

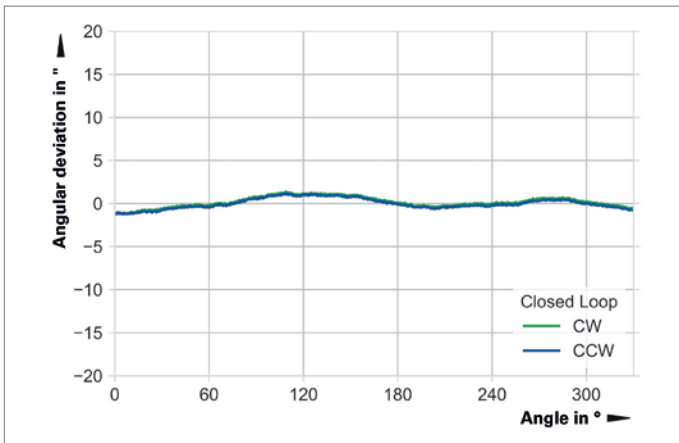


Figure 7: Position error from measurement of 720 positions under Closed Loop control

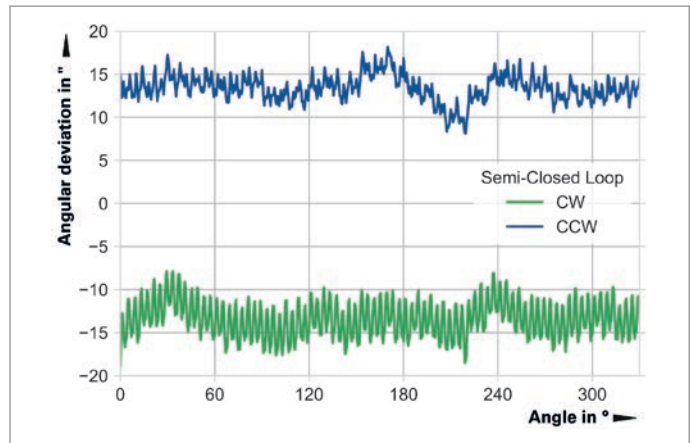


Figure 8: Position error from measurement of 720 positions under Semi-Closed Loop control

Determining the positioning accuracy of rotary tables with the reference encoder

All of the measurements presented here were performed on the machine tool described above. Its control enables the rotary table to be switched between Closed Loop and Semi-Closed Loop operation. In Closed Loop operation, position feedback was provided by an RCN 8310 angle encoder. In Semi-Closed Loop mode, the position of the rotary table was calculated based on the motor

encoder signal and the transmission ratio of the worm gear. Because these results were obtained on the same machine and with the same feed-axis power train, a direct comparison was possible. The positioning accuracy of the rotary table was determined using the standardized measuring procedures laid out in the ISO 230-2 and ISO 230-3 standards.

Static positioning accuracy as per ISO 230-2

First, the static positioning accuracy of the rotary table was determined in accordance with ISO 230-2. To this end, the 360° measuring range was subdivided into twelve, equidistant positions at 30° intervals. This represents the typical number of measuring points when an autocollimator with a polygon mirror is used. The measuring points were approached sequentially at a feed rate of 1000 °/min. The final position was then measured at standstill by the reference encoder for the rotary table. In order to

obtain a statistically meaningful result for the acquired parameters, this procedure was repeated five times each under clockwise and counterclockwise rotation. Similar starting conditions for the comparative measurements were created not only by using the same machine but also by initially deactivating the C-axis compensation tables stored in the control for both configurations.

Under Closed Loop control (Figure 9), the measured accuracy remained stable within

a range of $\pm 1.3''$, which is to be expected when an angle encoder is used. By comparison, the measurement results for Semi-Closed Loop operation (Figure 10) exhibited a lower rotary table positioning accuracy of $\pm 5''$ in each direction. In addition, a reversal error of 31'' was clearly detected under varied approach directions. During a second round of measurements, the positioning accuracy values determined for the twelve sampling points in each configuration (CL and SCL) were stored in a compensation table and activated.

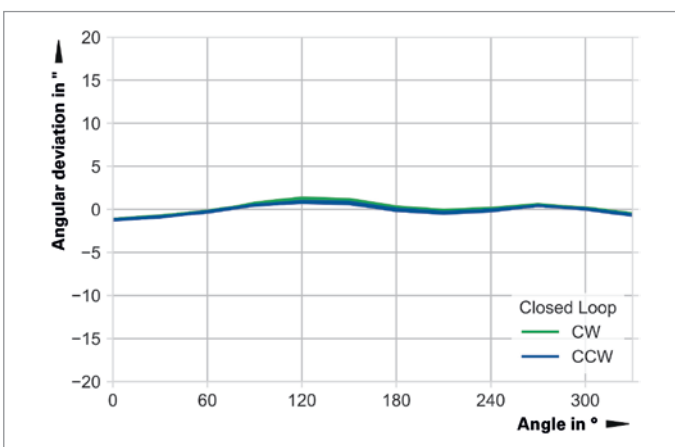


Figure 9: Position error as per ISO 230-2 under Closed Loop control (without compensation)

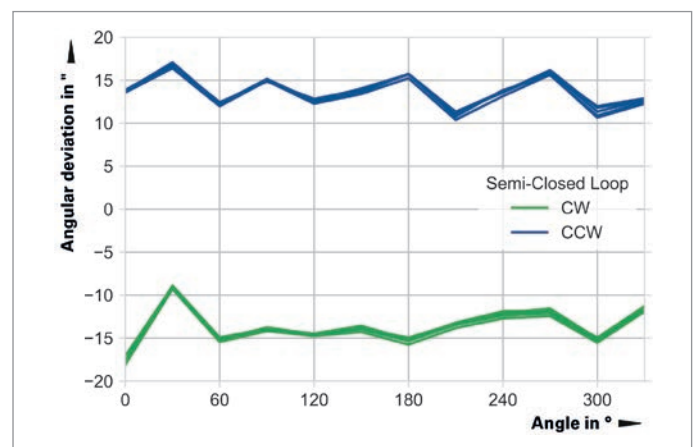


Figure 10: Position error as per ISO 230-2 under Semi-Closed Loop control (without compensation)

After parameterization and activation of the non-linear axis error compensation on the machine's control, the results from both control loop configurations were now available in a good and acceptable accuracy range (see Figures 11 and 12). The accuracy under Closed Loop control improved to $\pm 0.35''$. The Semi-Closed Loop configuration also performed well in this measurement, exhibiting a low position error of $\pm 1.4''$ across the measured range of rotation. However, a low reversal error of $1.0''$ was still noticeable. At this point, it is important to remember that the compensation values represent a discrete machine state, are valid for only the first measurement, and are stored as static values in a table. During operation, however, both the machine state and position uncertainty change in response to thermal and mechanical loads, as well as due to wear in the mechanical components.

Thus, over time, the use of static tables to compensate for position error will fail to attain the quality depicted in Figures 11 and 12.

The positioning accuracy behavior between the sampling points used for compensation can be seen from a repeated measurement under Semi-Closed Loop control using twelve sampling points and 60 measuring points. This is the typical number of sampling points generated during a measurement with an autocollimator and polygon mirror. The results from this additional measurement are shown in Figure 13. The plot shows a significantly higher position error of $\pm 4.5''$ and a reversal error of up to $4.0''$. In addition, high-level, non-linear effects are apparent between the selected sampling points. Like the short-range errors in Figure 8, these non-linear effects cannot be

modeled by the compensation values from Figure 10 and are thus unknown to the control. The use of compensation tables in Semi-Closed Loop operation does not ensure attainment of the positioning accuracy between the sampling points, and the results will deviate considerably from those in Figure 12. Therefore, this method of compensation is suitable only when the rotary table approaches previously known positions. This may be the case, for example, in 3+2-axis machining.

In theory, a much greater number of sampling points could be used in the control's static compensation table, but this would require an unreasonable amount of measurement work. Furthermore, during the machining process and even during measurement, the thermal state of the machine tool is subject to change. This will be discussed in the following.

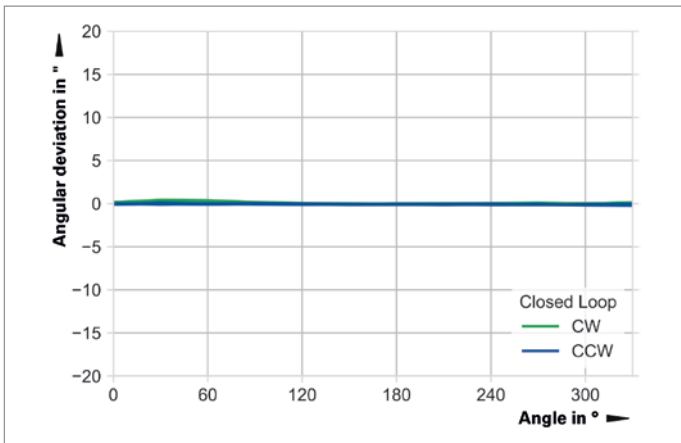


Figure 11: Position error as per ISO 230-2 under Closed Loop control (with compensation)

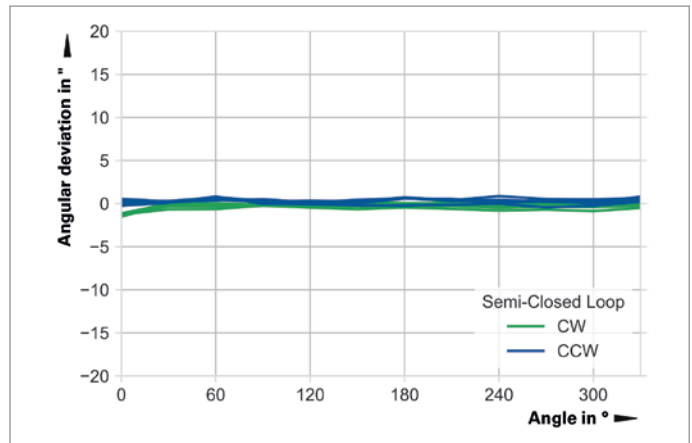


Figure 12: Position error as per ISO 230-2 under Semi-Closed Loop control (with compensation)

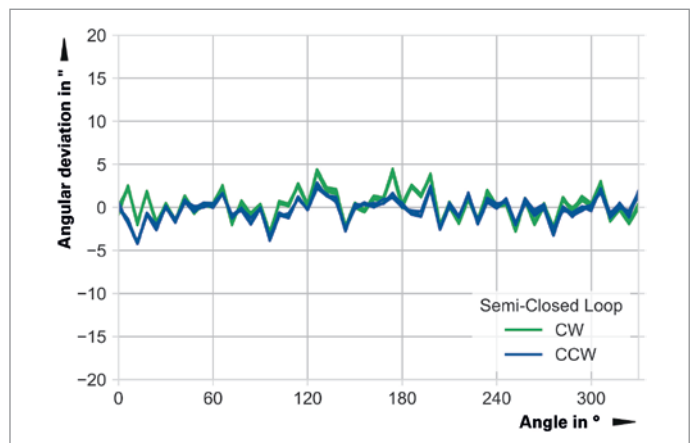


Figure 13: Position error as per ISO 230-2 under Semi-Closed Loop control (60 measuring points, with compensation)

Determining the effects of thermal drift as per ISO 230-3

A measurement as per ISO 230-3 for each configuration revealed the change in positioning behavior due to heat build-up in the power train of the rotary axis and its other mechanical components. For this measurement, compensation was activated in the machine's control based on the sampling points defined in the previous section. In addition, the effects of thermal position drift on the positioning accuracy of the rotary axis were determined in accordance with ISO 230-3. For this purpose, two positions were defined (0° and 180°) and likewise approached from two directions (CW and CCW). Between the individual measurements, a temperature increase for the measurement range (0° to 180°) was achieved through five cyclic movements at a feed rate of 3000 °/min. The measured values continued to be recorded until the thermal position drift of the rotary table stopped changing.

The measurement results in Figure 14 show that, when an angle encoder is used in Closed Loop control, the positioning accuracy remains stable even despite cyclic movement of the rotary table axis and the resulting temperature increase in the power-train components. In this configuration, the angle encoder measures the thermally-dependent position drift and feeds it back into the position control loop. The maximum value in this measurement was 0.5".

By comparison, the Semi-Closed Loop configuration exhibited a considerable change in positioning accuracy over time (Figure 15). This change involves two parameters: the amplitude, with a maximum of 8", and a very short time constant of approximately 2 minutes. In addition, a position drift component was superimposed at the 0° measurement position. This component arose from heat build-up in the structural elements of the machining center with a considerably longer time constant. As a result, the distance between both measuring points was also constantly changing.

In addition, the reversal error between the two approach directions rose to 3". Regardless of the maximum error acceptable in some applications, the short time constant is problematic in many machining scenarios. Examples include the machining of smaller lot sizes or the cyclic alternation between positioning of the rotary axis with subsequent standstill (machining in opposite orientations) and continuous motion of the axis. The replacement of a broken tool also falls within this time constant.

In the case of the measured rotary table, it has already been shown that the use of a compensation table is not helpful. The seemingly stable state of the position error reached after approximately 25 minutes will change every time the machine or feed axis comes to a standstill, such as during rechucking or the loading of a new workpiece. This translates into a high level of uncertainty for the attainable machining accuracy and will have a direct impact on workpiece accuracy during 5-axis simultaneous machining, and even during 3+2-axis machining.

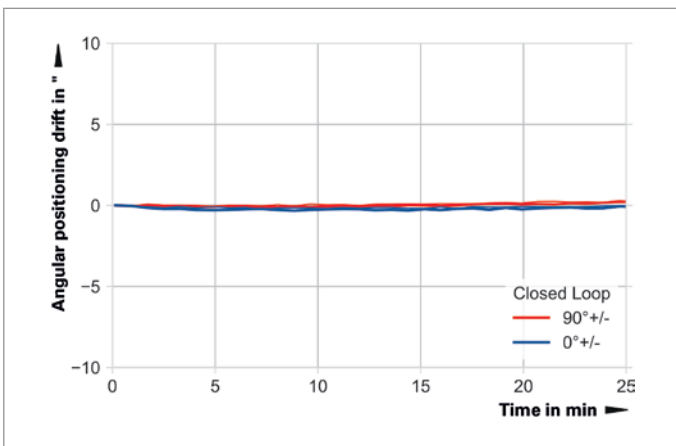


Figure 14: Position error as per ISO 230-3 under Closed Loop control (with compensation)

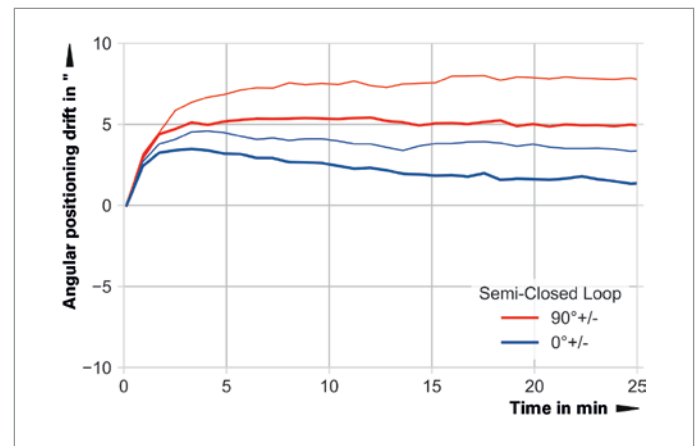


Figure 15: Position error as per ISO 230-3 under Semi-Closed Loop control (with compensation)

Conclusions

On the standard rotary table of a high-end machining center, it was shown that position errors as large as 8" occurred within 10 minutes under Semi-Closed Loop control. This is equivalent to a deviation of 20 µm on a radius of 0.5 m. The complex design of rotary tables consisting of a servomotor with mechanical transmission, combined with the difficulties associated with measuring the various errors caused by environmental factors, renders practical online compensation of rotary axis position errors largely impossible.

This was illustrated by means of a suitable reference encoder, which performed comparative measurements of the positioning accuracy of a machine tool's rotary table in Closed Loop and Semi-Closed Loop operation. Both the static positioning accuracy of the rotary axis and its stability under heating from a cyclic load were ascertained. Likewise, the effects of

measuring point compensation with twelve sampling points were determined and compared. In all of these measurements, the Closed Loop configuration exhibited stable behavior with high positioning accuracy and low reversal error. Under Semi-Closed Loop control, the initially inaccurate positioning behavior did see significant improvement from compensation, but this could not be maintained under cyclic loading of the power-train components. The change in behavior over time with increasing temperature in the mechanical transmission system was chiefly characterized by a very short time constant in the measurements shown. In practical terms, this rules out the possibility of compensation through the machine's control. It was also shown that, between the sampling points, high-level, non-linear effects arose that could not be covered by this method of compensation.

When the rotary axis is operated under Closed Loop control with angle encoders from HEIDENHAIN, the motion of the rotary axis is measured directly. This allows most of the influencing factors and time-dependent mechanical changes to be taken into account in the position control loop. These factors include mechanical transmission errors, thermal effects, and wear. The only exceptions are those errors that the angle encoders are able to measure but whose dynamic behavior exceed the dynamic performance of the position control loop. Absolute RCN angle encoders with an integrated bearing and stator coupling are well suited to high-accuracy rotary axes with mechanical transmission elements, as well as to direct-drive technology. These angle encoders combine a high system accuracy with easy mounting and high contamination immunity thanks to their enclosed design. If these encoders cannot be integrated for design reasons, then it is still possible to use modular angle encoders with optical scanning. With an correspondingly high number of signal periods, the ERA 4000 and ECA 4000 series likewise offer high positioning accuracy. In this case, the choice of rotary table bearing requires special attention regarding its stiffness and operating characteristics, because these traits directly affect the attainable measurement accuracy of the angle encoder and therefore the positioning accuracy of the rotary table. A rotary axis designed in this manner delivers the ideal conditions for 5-axis machining with high process reliability and throughput.

This article's comparison of Closed Loop control and Semi-Closed Loop control on rotary axes primarily applies to the rotary tables on machine tools. However, as mentioned at the outset, 5-axis machining involves two precisely positionable rotary axes. Similar measurements for the tilting axis of machine tools are currently underway and will be presented as well.



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