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5-Axis Machining: Getting a Grip on the Accuracy of Rotary Axes

Understanding challenges to accuracy and being able to judge measurement concepts help in gaining an insight into measuring technology and machine tools. That can be important, for example, when selecting a suitable machine tool for your own applications, especially if production quality has a high priority. In this article, we are placing emphasis on the accuracy of rotary axes.

In contrast to conventional 3-axis machines, 5-axis machining has completely new demands in terms of axis accuracy. It is not only a question of the precision of individual axes here, but of their accuracy in the working space. As a result, however, the number of error sources is significantly increased by the higher number of mechanical components in the machine design. Depending on the specific machine design, angle measurement is of particular importance here.

What sources of error exist?
The many mechanical components of a machine are all possible sources of errors. These are all stressed by the enormous dynamics of the working processes.

Typical causes for inaccuracies are:

- Wear caused by high mechanical loads, for example, or collisions during machining
- Elasticities in transfer elements, e.g., the worm shaft, or instabilities of the bearings
- Geometric errors e.g. radial eccentricity of mechanical transfer elements or incorrectly installed components

How can sources of error be avoided or reduced?
During the design of a machine, sources of error in connection with the rotary axes should be ruled out as far as possible. As a part of the kinematic influences, different mechanical and control-oriented designs of rotary axes should be compared.

Rotary axes feature complex mechanics with various components subjected to possible sources of error. Optimal compensation would have as a prerequisite the recognition of all

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Did You Know...

...that multiple HEIDENHAIN components and systems, including HEIDENHAIN's iTNC 530 contouring control, are critical components of innovative ultra-precise waterjet cutting machines? Because an ultra high-pressure waterjet machine's ability to erode and cut through stone or metal is highly dependent on a smooth, consistent velocity, its measurement and feedback components must be reliable and in sync. This is why Stone Contour Systems in Colorado uses HEIDENHAIN components for their customer solutions serving the tile and stone industry.

Besides using the HEIDENHAIN control, these Stone Contour machines also include the LIDA 487 exposed linear scales that provide the precision positional feedback to the iTNC530. The 20 micron signal period of the 1vpp signal enables some very precise tuning and the resultant tight control loop is applied to linear motors from ETEL a HEIDENHAIN sister company providing direct drive linear motors that are inherently contaminant tolerant). This system translates to super smooth velocity profiles with dramatically higher feedrates and better finishes being easily attainable when the waterjet's motion can be controlled with such precision.

Stone Contour waterjet cutting machines are highly regarded and also unique in the level of positional accuracy applied to what is commonly regarded as a crude process. Part accuracies of +/-.0005" are readily attainable with no sacrifice in cutting speeds.

Frequently multi-axis saws are combined with waterjets to allow almost limitless shapecutting with high throughput.

Stone Contour Systems' Contourjet 510 with HEIDENHAIN's iTNC 530 control and scales, and ETEL's linear motor.

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Did you know *continued from Page 1*

Because of this, the iTNC 530 was a natural control choice for these multiprocess systems. "The iTNC 530 adapts easily to complicated pallet and toolchanging systems allowing many processes to be combined in a single coordinate system," said Craig Lally, President of Stone Contour Systems. "This includes Wet Routers utilizing diamond tooling, as polishing tooling wears quickly and often necessitates very dynamic tool management."

The organized and efficient interface of the iTNC 530 control allows multiprocess systems to be operated more gracefully than PC controls that are more common in the industry. The flexibility of programming in HEIDENHAIN conversational (.h) or ISO G code (.i) accommodates any operational situation. Shops new to CNC can easily program in this method with FK (free contouring) function being especially useful in countertop design.

Those with existing CAD/CAM can quickly be adapted to the iTNC 530 with definable M codes and cycles to match their other equipment. The NC interface is clean enough to be foisted upon even the most novice operator. OEM definable soft keys can command any system process or cycle allowing complicated operations to be reduced to a single, graphical soft key.

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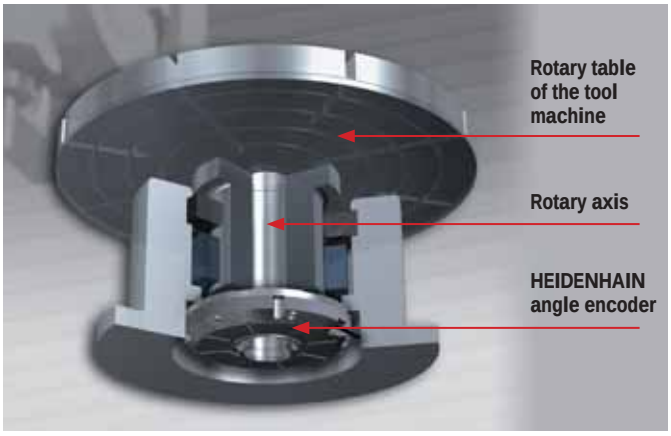
possible error sources for every situation. And exactly that is not possible.

A possibility for getting a grip on position deviations of rotary axes is the use of a suitable HEIDENHAIN angle encoder. For better understanding of the effect, here are two basic strategies for the design of rotary axes in control loops:



– "Semi-Closed Loop"
If the position of the rotary axis is measured solely via the rotary encoder on the motor, then we refer to a "semi-closed loop". Not only is the lack of accuracy of the motor encoder significant with this arrangement, but many other errors also play a part such as wear, elasticity deviations and geometric errors of the mechanical transfer elements.

– "Closed Loop"
If an angle encoder mounted directly on the rotary axis is used for position measurement, most sources of error can be avoided. This method is known as the "closed loop" method. Use of an angle encoder with integral bearing is recommended in this respect so that the previously described elasticity deviations do not lead to additional angle deviation. When using an angle encoder with integral bearing, it is presumed that the minimal angle error of an axis lies within the system accuracy of the angle encoder (the accuracy of an angle encoder of ± 2'' corresponds to a deviation of ± 5 µm for a table diameter of 1 m).

Of course spatial deviations also accumulate due to elasticity of the axes. Angle encoders with integral bearing and a hollow shaft have an additional advantage: an integrated coupling that compensates for shifts of the axis midpoints without additional angle errors. On the other hand, angle encoders without integral bearing would lead to eccentric deviations and would therefore provoke additional angle errors.

Are direct drives a positive trend?
With respect to accuracy, direct drives have several advantages and hardly any disadvantages. In the mid-term, an extensive transition from mechanical transfer elements with servo motors to direct drives (torque motors) can be expected. The decisive advantage is the very stiff coupling of the drive to the feed component without any other mechanical transfer elements. This is of true significance for a high level of contour constancy and optimal surface quality.

With the use of direct drives, an additional rotary encoder for speed definition is required. Position and shaft speed are defined by the angle encoder mounted directly to the rotary axis: a "closed loop". Since there is no mechanical transmission between the speed encoder and the feed unit, the angle encoder must have a correspondingly high resolution and signal quality in order to allow exact speed control, particularly at slow speeds.

Conclusion
System errors can be avoided with the selection of suitable measuring technology. That applies in particular to rotary axes. Because of their complexity, accuracy is a major challenge.

Especially with interpolated 5-axis machining and direct drive technology, encoders that do not convert unavoidable spatial deviations into large-scale angle errors are recommended. This challenge can be mastered with angle encoders (with integral bearing, integrated coupling and absolute position measurement) directly mounted on the rotary axis (such as the RCN model).

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The best solution is angle encoders with integral bearing, integrated coupling and absolute position measurement, directly mounted to the rotary axis.

Angle encoders
The term angle encoder is typically used to describe encoders that have an accuracy better than ± 5". In contrast, rotary encoders are encoders that typically have an accuracy worse than ± 12". Angle encoders are found in applications requiring precision angular measurement to accuracy within several arc seconds.

These include rotary tables and swivel heads on machine tools, C axes of lathes, measuring machines for gears, printing units of printing machines, spectrometers, telescopes, etc.

The following mechanical design principles can be defined:

- Angle encoders with integral bearing, hollow shaft and integrated stator coupling
- Angle encoders with integral bearing for separate shaft coupling
- Angle encoders without integral bearing

For comparison: Accuracy of linear axes
As with angle encoders, linear encoders can also significantly increase the accuracy of feed axes. And here as well – as is often the case with HEIDENHAIN – many influences are rendered unimportant by the design: If a linear encoder is used for measurement of the slide position, the position control loop covers the complete feed component.

Play and inaccuracies in the transfer elements of the machine have no influence in this case on the accuracy of the position measurement. Measurement accuracy really only depends upon the precision and installation location of the linear encoder.

Distributor Profile: AMI Finds Ways to Grow Cleveland, OH

Focusing on high technology in both product offering and marketing has given HEIDENHAIN distributor Automation & Metrology Inc. (AMI), headquartered in the Cleveland, Ohio area, a leg up in the industry. Originating in 1987 by a former HEIDENHAIN employee, AMI has grown to become a key distributor for HEIDENHAIN in a relatively short period of time, with two current Ohio locations, Cleveland and Cincinnati.

AMI partners Mark Contorno and Dave Denman

"We pride ourselves on providing high quality HEIDENHAIN product, installation and service for all types of machines in not only the Midwest or tri-state area, but also outside of our immediate geographic," said AMI partner, Mark Contorno, who purchased the business in 2003 with Dave Denman. "Our business has grown five-fold since joining the firm a decade ago. Dave and I have strong strategies in place and have operated consistently with double-digit growth." AMI's customer base – while in machine tool, aerospace, bearing manufacturing and medical equipment – varies in their requirements, they have all come to expect the commitment to integrity and service exhibited by AMI.

Both currently in their 30s, Mark and Dave embrace new technologies and are always finding ways in which to work with them. "Besides the regular use of online marketing opportunities using the HEIDENHAIN name to reach prospects, we also are firm believers in regular communication to our existing customers," said Mark, "Our customers are always being updated on the latest HEIDENHAIN technology being offered. We invest in regular visits to our customers which keeps our name fresh in their minds when a new application comes up."

Although AMI approaches the market with young eyes, they are well rooted in ways of the past. "Richard Walsh, the previous

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owner, helped us understand what it takes to run a successful small business," said Mark. "This is truly paying off during these difficult economic times. And Rick Glos (now retired HEIDENHAIN vice president) was a great influence to me as I started out representing HEIDENHAIN."

What makes Automation and Metrology successful? "We believe that our 'claim to fame' is our knowledge and ability to handle repairs within 24 hours," said Mark. "For example, because of our full stock and in-house equipment in our Cleveland and Cincinnati offices, a customer can come in with an encoder issue and we can rebuild it while he waits. For jobs further away, we pride ourselves on the ability to be on site on any national job within 24 hours, and fix the problem quickly."

Not going unnoticed, AMI has received multiple awards from HEIDENHAIN, including two HEIDENHAIN Distributor of Year President awards (2007 and 2003), as well as ten HEIDENHAIN Distributor of the Month awards over the years. "We are thrilled to work with HEIDENHAIN and it is our first choice when we retrofit any machine. AMI has offered other brands in the past but over the past number of years, we have migrated to the HEIDENHAIN brand exclusively" said Mark. "The product is always being developed and this has given us a competitive edge in our market."

Not only does AMI have great confidence in the product, they also believe in the management. "The management and the support are outstanding. Our company knows we can pick up the phone and get our problems solved, whether it is a technical, delivery or support issue. Just for these reasons alone, it has made it easy for us not to offer any alternative to HEIDENHAIN."

Because of AMI's dedicated focus on motion control technology, they cite strong knowledge of the HEIDENHAIN product line, which often saves their customers money. "Without this knowledge, you are just a quoting machine," said Mark. "We specify the right components for the job and get the installation or repairs right the first time. We are strong believers in examining old technology and enhancing it with new and all that that has to offer."

For more information about AMI, visit www.auto-met.com

Going to Great Lengths with HEIDENHAIN Scales

By Chris Weber, Product Manager, Machine Tool

When it comes to big machines, and I mean really big machines, feedback requirements can be challenging. Traditional feedback methods included systems such as "rack & pinion", low accuracy magnetic tapes, draw wire encoders, and glass butted to glass, but all of those systems involved compromises, typically with regards to accuracy and long term stability. For over 20 years, HEIDENHAIN has been making sealed linear encoders for lengths of up to 100 ft and beyond, and doing so without compromise.

HEIDENHAIN's longest scale systems are the LBs which utilize a reflective stainless steel tape with a gold graduation (currently 40 µm) as the measuring standard providing a one-piece measuring system with 5 µm /meter accuracy. A series of aluminum extrusions are used to house this tape providing protection from contamination and an accurate mounting surface. Two end caps secure the tape and provide a pre-determined tension factor. The beauty of stainless steel is that it has a similar coefficient of expansion as the machine itself and in many cases the workpiece thus mitigating thermally induced errors.

The LB system is available in standard version and mirror image version (for gantry applications), and with its distance-coded reference marks, a very short traverse will re-establish

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reference position. Gone are the days of moving long axes to one end of the machine to reestablish home position.

The aircraft industry has been the chief recipient of the benefits of this system in recent years in applications from wing spar manufacturing, to drilling/riveting, carbon fiber placement and waterjet cutting. With aircraft getting larger (A 340 and 787), the LB 382 scales system has gained in popularity and market share. HEIDENHAIN Corporation recently sold and installed two of these LB systems in Michigan, each with a travel of over 240' (look for a feature article on this application in a future issue of HeidenhaINFO).

HEIDENHAIN LB scale

In fact, in the last 20 years, HEIDENHAIN has sold over 130 miles of LB scale systems around the world, which is roughly equivalent to driving from Los Angeles to San Diego or Washington DC to Philadelphia.

So what does the future hold? Currently under development is the absolute version of this scale which will feature the purely serial EnDat 2.2 interface providing not only long measuring ranges but also no requirement to reference, as well as the ability to transmit not only position but also additional data between the measuring and control systems. Stay tuned.

HEIDENHAIN Increases CNC Accuracy with New KinematicsOpt

Committed to providing continuous advancements in the area of user-friendly CNCs, HEIDENHAIN Corporation now offers a new option to its already versatile iTNC 530 contouring control, making possible the automatic measurement and compensation of machine angular axes. Called KinematicsOpt, this new software option, coupled with a mounted HEIDENHAIN touch probe into the CNC machine spindle, increases the accuracy of this already high functioning control. The iTNC 530 can control up to 13 axes and a spindle.

The introduction of KinematicsOpt is the answer to CNC accuracy requirements becoming increasingly stringent, particularly in the area of 5-axis machining. With KinematicsOpt, it does not matter whether the individual axis being measured is a rotary table, tilting table or swivel head. The measurement process is the same.

KinematicsOpt-TS740

The procedure begins after having defined the measurement resolution and the area of each rotary axis that is to be measured. The operator then initiates probing of a calibration ball fixed at any position on the machine table. From the measured values, the iTNC 530 calculates the statistical tilting accuracy, with the KinematicsOpt software minimizing the spatial error arising from the tilting movements.

At the end of the measurement cycle, the machine geometry is saved in the respective machine constants of the kinematic table. A comprehensive log file is also saved, recording the actual measured cycles and the optimized dispersion (measure of the statistical tilting accuracy) as well as actual compensation values.

This software development follows other HEIDENHAIN productivity-enhancing control additions such as the following:

- Adaptive Feedrate Control (AFC)
- Dynamic Collision Monitoring (DCM)
- DXF Converter

Heavy Duty 800 Series Encoders from L&L Hold Tough in Rough Environments

With the introduction of the Leine & Linde 800 Series rotary encoders, parent company HEIDENHAIN Corporation now offers a line of encoders that are regarded among the most robust, maintenance-free and cost effective encoder solutions on the market today. In addition, this series can optionally be offered with ADSTM (Advanced Diagnostics System), a built-in system used for condition-based or preventative maintenance, guaranteeing the reliability of the intended application.

The Leine & Linde 800 Series encoders are widely used for motor feedback in the paper & pulp, steel and mining industries worldwide. They have also become the market's leading choice for generator feedback in wind turbines.

Leine & Linde model 862, a robust incremental encoder solution and a top choice for harsh environments

The 800 Series comes in shafted and hollow-shafted versions, with the ceramic bearing option maximizing encoder lifetime. The series is characterized by a dynamic and flexible range of pulse rates and electrical output combinations including a dual encoder solution. For hazardous applications, explosion-proof ATEX-certified encoder options are offered.

The 800 Series is one of the cornerstones in the Leine & Linde product portfolio where high quality flexible encoder solutions that make use of state-of-the-art technology are the essence of the business.

New HEIDENHAIN DRO Systems for Gauging Give More Options to Network

Answering the demand for a single-axis position display that could be more fully integrated into a machine data transfer network, HEIDENHAIN introduces the ND 200 Series Digital Readouts (DROs). This display series hosts multiple inputs, is flexible in its configuration, is suitable for future absolute length gauges and features comprehensive functions.

These newest single-axis ND 200 DROs come in two variants: the ND 280 featuring standard functions (with monochrome flat screen) to fulfill many measuring tasks and the ND 287 (with color flat screen) which is modular in design and allows up to four inputs. This feature allows toggling between multiple gauges, sensors and encoders to be done easily.

Within the HEIDENHAIN ND 287, three additional axis modules are incorporated. Two of them are analog, which permit the connection of analog sensors (such as temperature and pressure) and purely serial EnDat 2.2 units, which allows for the connection and full use of absolute encoders. Also, this DRO can be integrated into the Ethernet facilitating remote monitoring.

SPC (Statistical Process Control) is now also available on the HEIDENHAIN ND 287, allowing the ability to write up to 10,000 measured values to an internal memory and evaluate them statistically.

Single-Axis ND 200 DROs

Both the ND 200s come equipped with a card for gauge hookup (common use) and are an improvement over past HEIDENHAIN single-axis DROs as they sport new features. Among these are the ability to design functional equations to manage interconnected operations of multiple axes and soft keys, which provide many benefits with regard to operation and parameter setting. These units can display both linear and angle/rotary encoders, as well reading distance-coded reference marks. Encoders with EnDat 2.2 can be connected to both.

The height and width of the both units result from the requirement that they be suitable for installation in a 19-inch rack. This makes it possible to mount two position displays side by side in an electrical cabinet of this standard.

HEIDENHAIN's Revolutionary 2-Dimensional Encoder

Introducing an exciting new dimension to measurement, HEIDENHAIN Corporation presents the 1Dplus encoder. After much R&D, this uniquely innovative two-dimensional encoder was designed in order to allow measurement of linear guiding and thermal drift errors during movements of a stage or machine, allowing the processing and immediate compensation of these errors. This results in a system with very high accuracies with jobs done right the first time.

The most likely current applications for the 1Dplus include use in stacked stages, precise gantries, wafer processing, and in large flat panel display production and tests, though any motion stage user who wants to increase performance would benefit.

These truly revolutionary 1Dplus encoders are frictionless and have gratings in two dimensions, with models featuring two or three scanning units for simultaneous measurement of both the X and Y directions. Three scanning units allow the calculation of the angle of rotation of the bracket that houses the scanning units. These orthogonal encoder graduations provide an exciting new dimension in precision as the encoder system measures left and right (X axis), the up-and-down (Y axis) motion is measured (and compensated for by the control) as well.

HEIDENHAIN's early and current 1Dplus encoders are in use as the HEIDENHAIN interferential-type linear encoder, the LIF 400 with 1Dplus (see image). The measuring standard is DIADUR with a thermal expansion coefficient of 0 ppm/K. Current measuring length is 300 x 2 mm, with plans to increase that dramatically. The 1Dplus scale itself is 20 x 4.9 mm.

The X-axis measurement of the1Dplus has a current accuracy grade of ±1 µm and includes a reference mark. The grating period of the encoder is 8 µm; the signal period is 4 µm.

Technical Tidbit:

Torque in Servo Motors

When specifying servo motors for a new machine or CNC retrofit, there are many specifications regarding servo motor performance. One of the most confusing is the differing torque specifications of the motor. Torque can be specified in Newton meters (Nm) or more commonly foot pounds (lb-ft) or inch pounds (lbf-in).

1Nm = 0.74 lbf-ft = 8.85 lbf-in

Torque (also called moment of force) can be defined as: The mechanical work generated by the turning effect produced when force is applied to a rotational axis. Or the measure of how much a force acting on an object causes that object to rotate.

Rated Torque (MN) - The maximum continuous torque available at the rated speed that allows the motor to do the work without overheating (typically specified at a temperature). This is the working range of the motor.

Stall Torque (MO) - The torque, which is produced by a device when the output rotational speed is zero or the torque load that causes the output rotational speed of a device to become zero – i.e. to cause stalling.

Max. Torque (Mmax) - Also known as peak torque, the greatest amount of torque the motor can generate for a very short time period (typically specified in ms).

When specifying servo motors for a machine tool application, the commonly accepted specification is the Rated Torque.

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Dear Abbé...

Providing answers to questions of accuracy

Question: What is a PWM 9?

Answer: The PWM 9 is a complete universal measuring unit for inspecting and adjusting HEIDENHAIN incremental linear and angle encoders. Instead of offering just a series of LEDs on the encoder for installation which can lead to a green light that could just be marginally green and cause issues after the machine has shipped to the customer, HEIDENHAIN offers two devices that provide detailed information on the encoder signals and allows the user to install correctly, thereby increasing the safety margin and quality of the machine overall.

First, the small low cost handheld device that displays amplitude information to a resolution of 0.1V and the quality of the home pulse is called the PWT. There are various PWTs for the various electrical interfaces and are dedicated to that interface, such as 1Vpp or TTL. The other device, a PWM 9, however has this PWT mode as well as much more detail about the encoder signals, such as phase angle of sine and cos waves, encoder current consumption and encoder voltage and offsets. The PWM 9 has a slot where various electrical interface cards can be inserted, such as Endat (incremental analog signals only), TTL, and 1Vpp. PWM 9 is German for Phasen Winkel Messung which translates to Phase Angle Measurement, and it is the 9th iteration of this device.

PWM 9 shown in PWT mode.

The PWM 9 is also valuable for safe inline usage so that a user can look at the detailed encoder signal parameters while the machine axis is put to motion. This helps the users to determine if the encoder is installed correctly and with enough safety margin through the whole range of motion of that particular axis. Encoders with LEDs cannot compare as one does not know if certain areas of the motion axis are marginally “green” or not. Encoders using just a USB interface for setup also cannot be run inline with the machine axis in motion.

The PWM 9 has a monochrome backlit LCD screen that is easy to read from any angle. It also contains 3 BNC sockets for testing encoder outputs on an oscilloscope, which is probably the best way to install encoders as the lisajous pattern is very visible and easy to interpret with the proper training.

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For more information about HEIDENHAIN and any of the products or services mentioned here, please feel free to contact us.

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