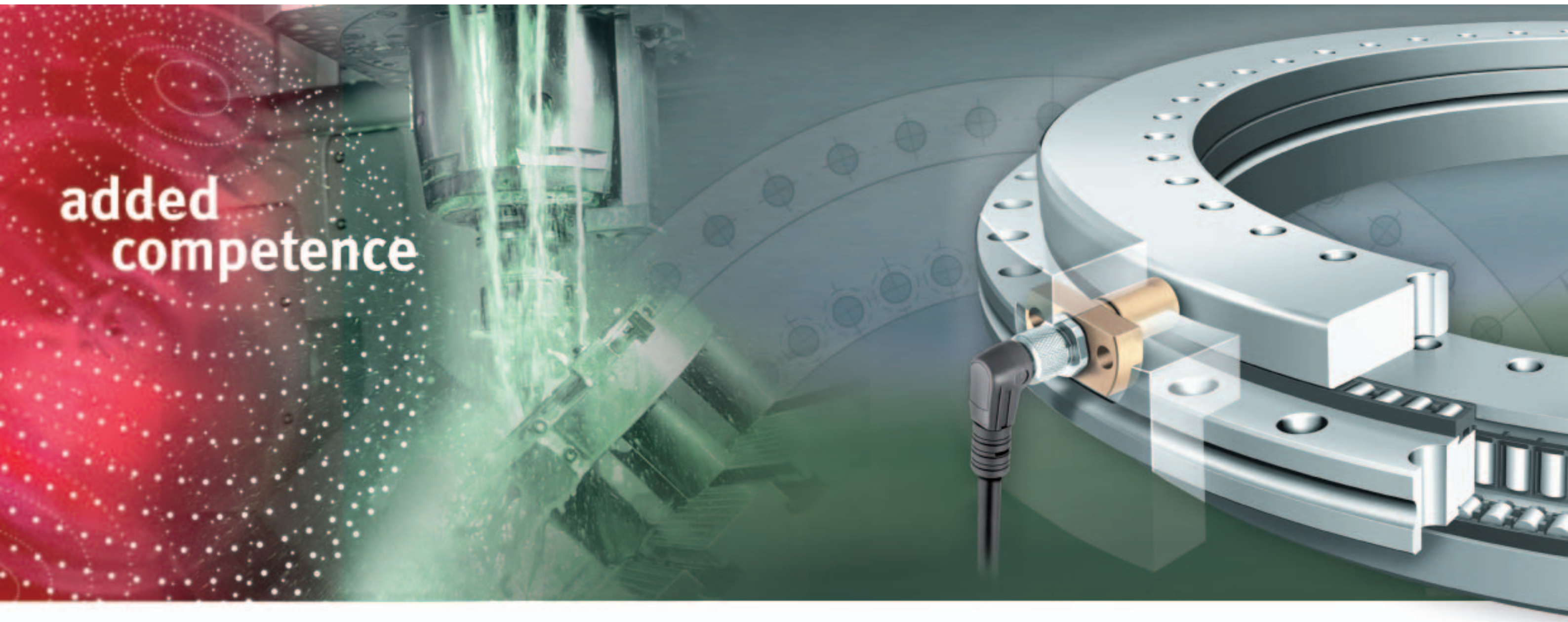

Magnetic versus Optical

A comparison of angular measuring systems for rotary axes

SCHAEFFLER GROUP
INDUSTRIAL

Magnetic versus optical

A comparison of angular measuring systems for direct drive high precision rotary axes

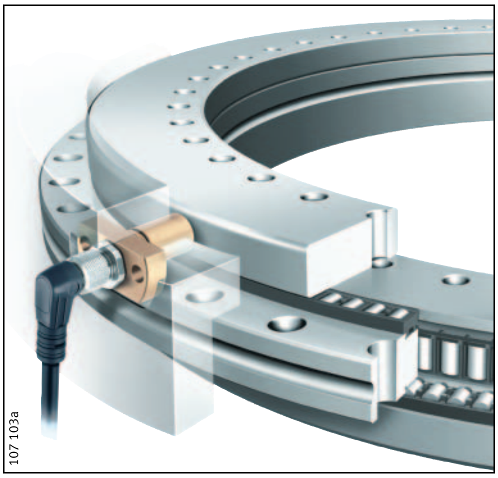

Figure 1 · HIGH-SPEED rotary axis bearing with magnetic angular measuring system, YRTSM

In the search for the optimum measuring system for highly dynamic direct drives in machine tools, preference is generally given to optical systems. For use in rotary table axes, however, magnetic measurement principles have proved to be a reliable alternative, *Figure 1*.

The characteristics of the two types of measuring systems and their effects are compared in a rotary table with a torque motor drive.

Introduction

For rotary tables used for milling and turning operations, a wide range of high performance drive components is available. In particular, this covers torque motors and the associated converters and controllers as well as rotary table bearing arrangements matched to these. When selecting the angular measuring system for highly dynamic, direct drive rotary table axes intended for use in combined milling and turning, optical measuring systems with very high accuracy and angular resolution are generally given preference. Due to the optical measurement principle, however, no special precautions are taken in relation to contamination by, for example, cooling lubricants or rolling bearing greases. The optical transducers are generally available in the form of mounted rotary encoders that must be fitted centrally in the rotary table and have their own compensation coupling with mechanical flexibility. This means that the axial central passage is not available for supply lines and that particular attention must be paid to mechanical rigidity when connecting the measuring system to the direct drive rotary table, in order to achieve high control rigidity.

The following paper gives a comparison of an optical rotary encoder with the magnetoresistive, incremental angular measuring system YRTSM from Schaeffler KG and integrated in the bearing. This offers advantages in relation to robust resistance to cooling lubricants and rolling bearing greases, can be fitted to give space savings and, due to its design principle, leaves the central passage free. The comparison was carried out in a joint development project between Schaeffler KG and the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen on a rotary table representative of practical use that was fitted for this purpose with both measuring systems in parallel, *Figure 2*.

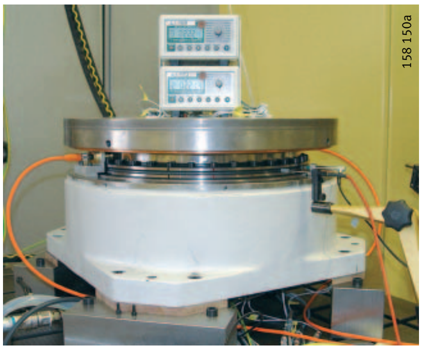

Figure 2 · Direct drive rotary table, fitted with one optical and one magnetoresistive angular measuring system

Key data

The reference measuring system was a high resolution mounted optical rotary encoder with 36 000 lines per revolution, fitted to the lower side of the rotary table axis at the height of the torque motor. The incremental, magnetoresistive measuring system YRTSM, *Figure 1*, is matched to the bearing series YRTS, which is available in a wide range of bore diameters and can achieve high limiting speeds. In this case, a bearing of type YRTSM325 with an inside diameter of 325 mm and a limiting speed of 760 min^{-1} was used.

The magnetic angular pitch is fitted flush to the rotating shaft washer of the bearing and is scanned by means of two sensor heads that are arranged at an angle of 180° to each other and flange mounted directly on the rotary table base component, *Figure 3*.

Scanning by means of two heads ensures that any centre displacement occurring as a result of machining forces is compensated internally in the system and that absolute measurement accuracies of less than ±3″ are achieved.

In addition, this type of scanning gives a doubling of the angular resolution, such that a signal derived from a total of 5184 lines per revolution is transmitted to the controller. The signals from the two heads are combined in an electronic evaluation system that is connected to the NC controller. In the development of the electronic evaluation system, the focus was on the shortest possible computing cycle times, which make it possible to achieve short idle times and thus the maximum control quality.

The rotary table is driven by a torque motor of type RE11-3P-410×50 from the manufacturer IDAM with a non-cooled moment rating of 307 Nm, while the controller was a Sinumerik 840D/611D with performance control.

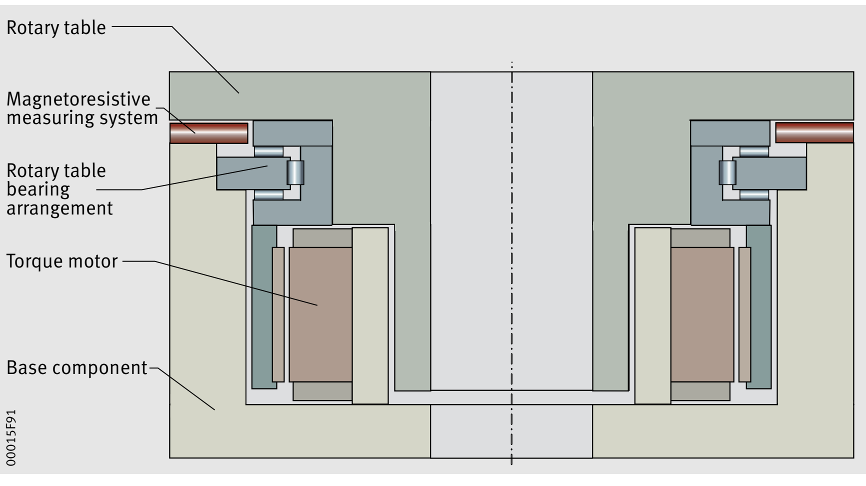

Figure 3 · Design arrangement of rotary table with both angular measuring systems

Results of comparative investigations

The rotary table completely ready for operation, *Figure 3*, was optimised in terms of controller and filter settings as a first stage in the investigations. The set current value filters were restricted to a low pass filter that was reduced for both measuring systems from 2 kHz (standard setting) to 1 kHz, while additional correcting variable limiters and other influencing factors (e.g. override functions, set speed value filters) remained completely switched off. For each measuring system, two sets were determined each with controller settings with different requirements, using the same optimisation principles for determining the parameters for both measuring systems in order to give better comparability. “Moderate” indicates the settings for production operation, where an amplitude increase in the frequency response for set input of the speed controller of max. +3 dB was permitted, while a positive amplitude was not permitted in an frequency range in the positional control loop.

In this way, a situation is avoided where the excitation of disruptive vibrations can lead to ringing and thereby to damaged profiles of the workpiece.

The “maximum” settings brought the system as far as possible to the stability boundary in order to determine the dynamic potential of the rotary table.

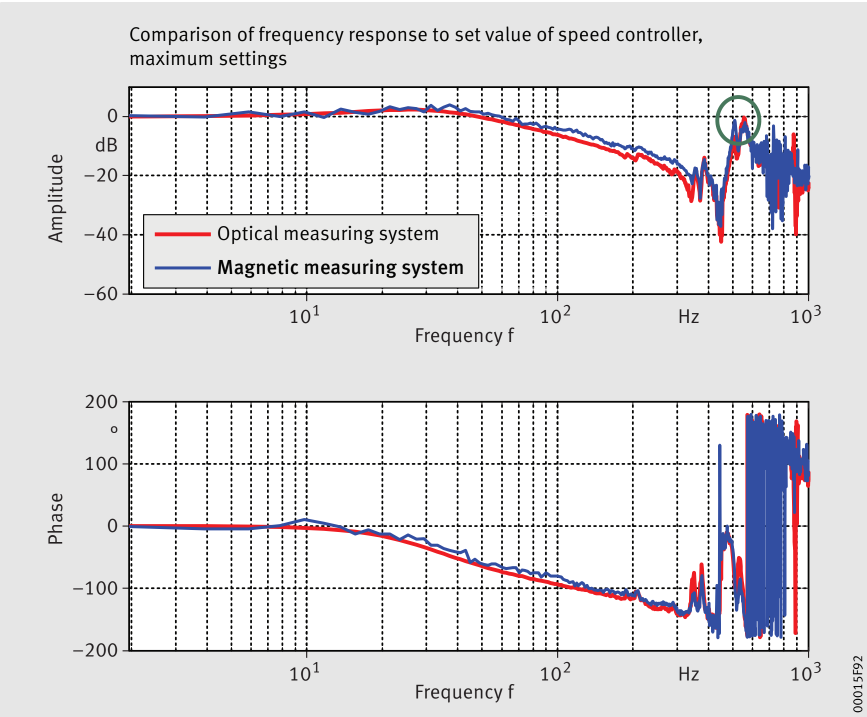

Figure 4 · Comparison of frequency response to set value of speed control loop of both systems

The relevant settings can be found in the table. Due to the modified filter settings, the proportional share in the speed controller (K_p) could be significantly increased for both measuring systems, strongly benefiting the dynamic characteristics of the rotary table. After optimisation of control, higher controller settings in direct comparison were possible with the magnetic measuring system YRTSM. In the frequency response to set value of the speed controller, it was found that the optical measuring system was restricted by a vibration of approx. 550 Hz, while the magnetic measuring system only reached the stability limit at a higher K_p due to a vibration of approx. 500 Hz, *Figure 4*, marked in green.
The step responses of the control loops were still stable at these settings with both measuring systems and showed no unacceptable ringing.
With the aid of modal analysis of the table structure in the range from 150 Hz to 2 000 Hz, it was shown that a tumbling vibration occurs between the housing of the optical measuring system and the housing of the rotary table at 550 Hz that the coupling in the optical measuring system may not have been able to completely compensate and thus led to measurement errors.
The magnetic measuring system benefited on the other hand from the rigid mechanical connection directly to the bearing in the rotary table.

The effects of mounting the measuring system in direct drives on the controller settings have already been demonstrated [1]. In addition to this dominant natural form, modal analysis identified other natural frequencies that are apparent to a limited extent in the frequency response to set value or lie beyond the relevant controller bandwidths.

Both measuring systems allowed stable synchronous running. The quality of the speed signal was dependent on the resolution of the measuring signal used and could be improved by using the actual speed value filter.
A considerable influence is exerted by the Dynamic Servo Control (DSC) in the Siemens controller, which displaced the internal calculation of the positional controller into the drive and thus eliminated the internal system idle time of the set speed value interface [2].
The activation of this additional function gave a very significant improvement in the low frequency disruption behaviour of control using a magnetoresistive measuring system.

In the final result, the dynamic behaviour of the rotary table with the two measuring systems on the Siemens controller 840D/611D was comparable.
It was found that the magnetic system was not inferior to the optical measuring system in terms of controller settings and dynamic behaviour. In contrast, it was even possible to achieve higher controller settings with the magnetic measuring system, which is apparent from the minimal differences between the curves in *Figure 5* and *Figure 6*.
Compared to the moderate settings that fulfilled the aforementioned setting rules, the maximum parameters gave an additional reduction in the build-up time of the step responses (to 95% of the set value) by 20% to 25% in both control loops and for both measuring systems. The build-up time in the positional control loop for a step of 0,5° was a minimum of 67 ms, while a set step of 1 min^{-1} in the speed control loop required approx. 8 ms.
In addition, the ringing in the step responses of the speed control loop was reduced by between 5% and 10%.

The speed signals had different noise severity levels corresponding to the difference in resolution between the two systems and, for presentation in *Figure 6*, required low pass filtering at 1 kHz again.

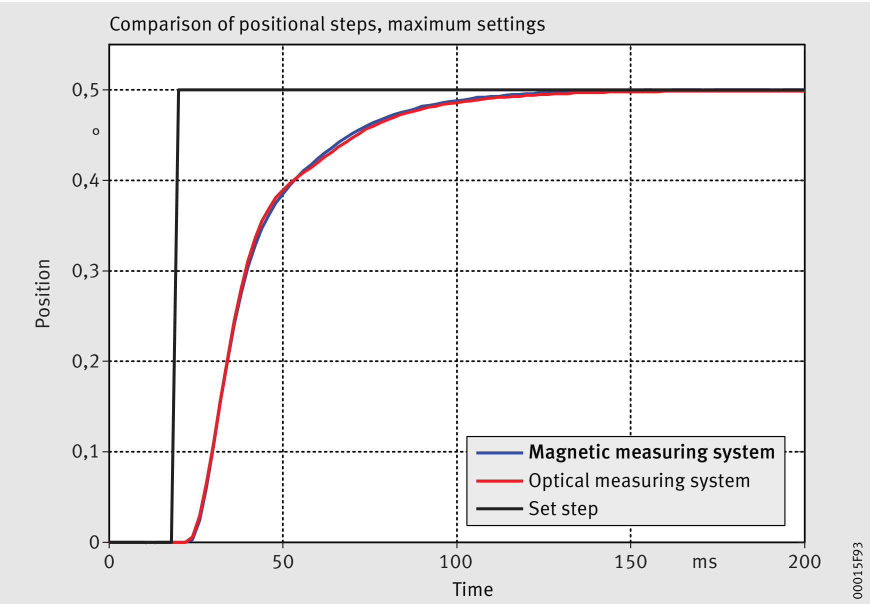

Figure 5 · Comparison of step response of positional control loop of both systems

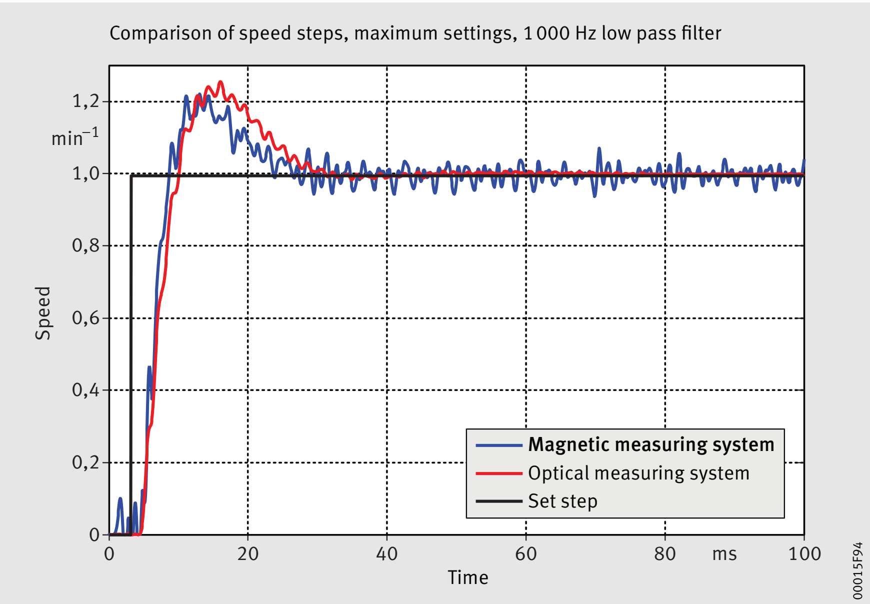

Figure 6 · Comparison of step response of speed control loop of both systems

The increased noise of the magnetic measuring system was found in the moment-forming current but was not converted into additional heating of the motor. Appropriate temperature measurements during intermittent long term operation were carried out without water cooling on the torque motor windings, based on a travel cycle corresponding to practice.
The temperatures determined in the equilibrium condition differ between the two angular measuring systems at the various measurement points by less than 0,5 K, *Figure 7*.

In parallel with the measurement investigations, a simulation model of the rotary table was developed using Matlab/Simulink that reflected the characteristics of the mechanical system and its control. The complete representation of the cascade control with the various filters, the different scanning times as well as the characteristics of the motor and the associated inertia of masses allowed modelling of the dynamic behaviour of the rotary table.
In addition, the simulation results could be further improved by the integration of excerpts of actual measured noise in the simulated measuring systems.

The model demonstrated clearly, by variation of measuring system characteristics and the control parameters, how the system dynamics are dependent on the achievable controller settings and the characteristics of the measuring system.
Furthermore, the modelling of the rotary table showed that the power loss of the moment-forming current in the motor as a function of the load moment is a multiple of the contribution of the power loss due to current noise. Motor cooling should in actual operation lead to an additional reduction in heating of the motor windings that is caused by the current noise.

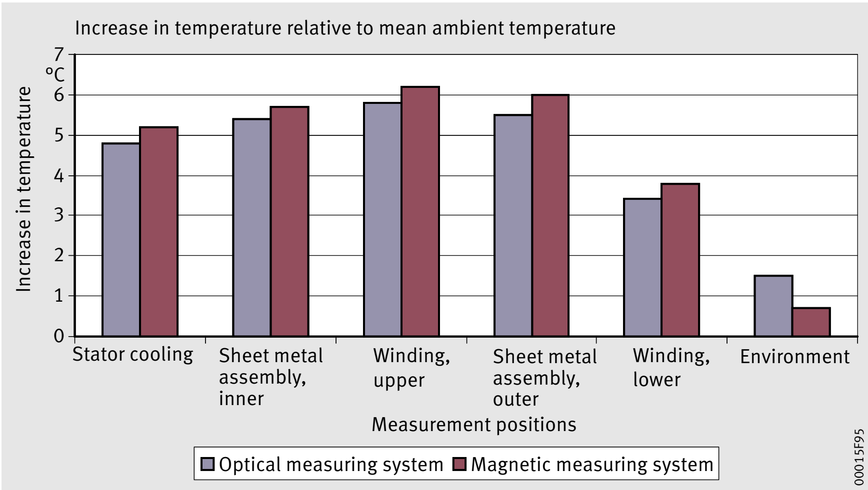

Figure 7 · Comparison of heating of the motor windings with both measuring systems

Compilation of the controller settings determined for both measuring systems			
Magnetic measuring system		Optical measuring system	
Moderate setting	Maximum setting	Moderate setting	Maximum setting
K_v = 2,0	K_v = 2,5	K_v = 1,9	K_v = 2,5
K_p = 1 200	K_p = 2 300	K_p = 1 000	K_p = 1 700
T_p = 7,5 ms	T_p = 7,5 ms	T_p = 7,5 ms	T_p = 7,5 ms
K_i = 10 V/A	K_i = 10,4 V/A	K_i = 10 V/A	K_i = 10,4 V/A
T_i = 2 000 µs	T_i = 2 000 µs	T_i = 2 000 µ	T_i = 2 000 µ
Set current value filter: Low pass at 1 kHz No band rejection filters		**Explanations:** K_v corresponds to the P factor of the positional controller K_p corresponds to the P factor of the speed controller T_p corresponds to the time constant I proportion of the speed controller K_i corresponds to the P factor of the current controller T_i corresponds to the time constant I proportion of the current controller	

Summary

For direct comparison, a rotary table axis from Schaeffler KG fitted with an optical rotary encoder was also equipped with the magnetoresistive angular measuring system YRTSM. Optimisation of controllers and filters, investigation of the dynamic behaviour as well as modal analysis of the table structure and the heating behaviour in long term operation in partnership with the WZL showed that the behaviour of the rotary table with both measuring systems was comparable on the whole. For many applications, the angular measuring system YRTSM completely integrated in the bearing design envelope and operating on the magnetoresistive basis offers a cost-effective solution with design advantages, without the need to take account of losses relating to the dynamics of the rotary axis system or measurably higher power losses in the torque motor. For very high synchronous running requirements such as those in ultra-precision applications, however, it may be necessary to use high resolution optical mounted rotary encoders in direct drive rotary table axes in machine tools in certain circumstances.

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High load carrying capacity at very high precision

Angular measuring systems for direct drive high precision rotary axes

The company AXA Entwicklungs- und Maschinenbau GmbH is relying on the bearing series with the integrated angular measuring system from Schaeffler Group Industrial for its new turning/milling centre VHC50-D in order to achieve high speeds, high load carrying capacity at very high precision, rigidity and dynamic properties.

High speed capacity and high load carrying capacity at very high precision, rigidity and dynamic properties:
these are the challenging objectives set by AXA Maschinenbau GmbH in Schöppingen in the development of a new multi-axis machining system, *Figure 8*. The central task was the new development of a rotary table, *Figure 9*, that can be used not only for drilling and 5 axis milling but also for turning.
As a result, vertical turning and facing as well as milling and drilling are possible in a single clamping operation.
In the selection of drive components for this rotary table, AXA Maschinenbau allowed no compromises.
In addition to a torque motor, the high speed axial/radial cylindrical roller bearing YRTSM460 from Schaeffler Group Industrial was selected. The new bearing series with the integrated angular measuring system has been specially developed for direct drive,
highly dynamic and precise rotary axes.

The advantages are very high precision in machining and extremely cost-effective production of complex components.

Rotary table bearing with integrated, magnetoresistive angular measuring system

The bearing is equipped with a magnetoresistive angular measuring system integrated in the bearing design envelope and is specifically matched to direct drive rotary tables for machine tools. The magnetic angular pitch is applied flush and without joints to the rotating shaft washer of the bearing. It is scanned by two sensor heads that are arranged at an angle of 180° to each other and flange mounted directly on the rotary table base component.
Scanning by means of two heads ensures that any centre displacements occurring as a result of machining forces are compensated internally in the system.
Absolute measurement accuracies of less than ±3″ are thus achieved.
In addition, this type of scanning gives a doubling of the angular resolution and transmits analogue signals derived from 7 008 lines per revolution are transmitted to the controller. The signals from the two heads are combined in an electronic evaluation system that is connected to the NC controller.

Electronic evaluation system with the shortest possible computing cycle time

In order to achieve the maximum control quality, development of the electronic evaluation system focussed on the shortest possible computing cycle time. This extremely fast electronic evaluation system and the special bearing design allow a limiting speed of 560 revolutions per minute for the selected bearing size. Both sensor heads are flange mounted using screws in a mechanically rigid arrangement to the rotary table base component. Due to the rigid linkage of the angular pitch to the rotating rotary table and the robust, vibration-resistant connection of the sensor heads to the base component, very high amplification factors are achieved in the control loop and the best possible control quality, control rigidity and dynamics can be achieved.
Furthermore, this design can be integrated in the bearing design envelope giving space savings, such that the centre of the rotary table is available for the passage of supply lines.
This results in more compact machine subassemblies and cost savings in design, purchasing and assembly work.

Resistant to rolling bearing greases, oils and cooling lubricants

The sensor heads and the electronic evaluation system are protected against chemical, mechanical and electronic

Figure 8 · Turning/milling centre, type VHC50-D from AXA Maschinenbau GmbH

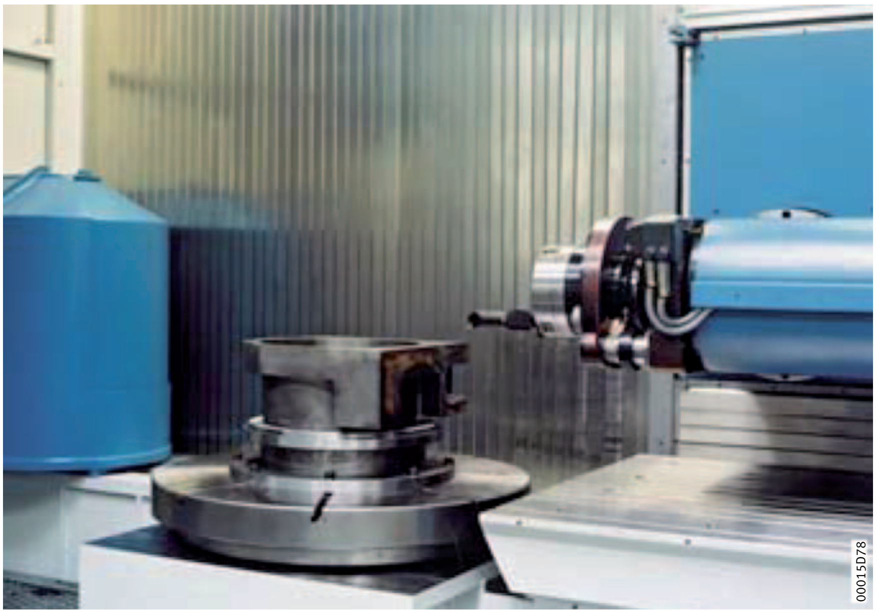

Figure 9 · Rotary table for turning/milling in a single clamping operation

influences from the environment, as demonstrated in comprehensive environmental simulations. In particular, the magnetoresistive measurement principle proved itself resistant to rolling bearing greases and oils as well as to cooling lubricants. The use of the angular measuring system in machine tools under production conditions demonstrated its suitability for practical application. In cutting tests, profile deviations of less than 2″ were found.

For extremely rigid and dynamic controller settings

With the new bearing series YRTSM, Schaeffler Group Industrial has developed an angular measuring system that is optimally matched to the requirements of direct drive rotary axes for machine tools. It is available for bearing inside diameters from 200 mm to 460 mm and, depending on the size, allows limiting speeds of up to 1 160 revolutions per minute.
The measuring system combines very high measurement speed and limiting speed with high measurement accuracy and also allows extremely rigid controller settings for the torque motor drive.
This corresponds fully to the trend for high speed rotary tables for cost-effective complete machining using milling and turning.

First publication

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