Electrical drive systems with active magnetic bearings in industrial applications - possibilities and challenges

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Abstract—**This article describes the use of active magnetic bearings in an electrical drive system and how performance, reliability and availability can be increased significantly based on an application example. It is important to know about the strong interaction between the different system components to get the best technical results, as well as considering production related aspects.**

I. INTRODUCTION

The demands on machine tools regarding productivity, reliability and life cycle costs (TCO) are increasing permanently. Therefore, it is essential to constantly optimize and improve the entire machine, single components, the production processes, as well as machining parameters and a continuous monitoring of the machining processes is necessary. Machining spindles are key components in machine tools. They have major influence on productivity, output quality and availability. The following statements refer to spindles in grinding applications. Due to the increasing demands that spindles are facing, it is crucial to further examine alternative bearing techniques, in addition to ball- or rolling bearings. Special interest is put into active magnetic bearings, as they provide additional functionality. The past has seen various studies and investigations about the use and benefits of magnetic bearings in grinding spindles [1], [2], [3]. Beside the advantages like no friction and no wear, magnetic bearings i.a. are able to enhance the rotating speed, as well as bearing parameters can be adjusted and a continuous process monitoring and diagnosis is feasible. By using magnetic bearings in spindles, they become intelligent system components of a machine or an entire machining centre. The behavior of the magnetic bearing spindle "LeviSpin 700" has been investigated. Work results, additional functionalities and the value for the customer will be shown.

I. Design and Function of a Magnetic Bearing Spindle

A. Technical Data "LeviSpin 700"

One of the major guidelines to design a magnetic bearing spindle was to observe the size like a conventional spindle. The following table shows the data of the magnetic bearing spindle used in the example [4].

Nominal Power	15 kW
Nominal Speed	42.000 rpm
Nominal Current	32 Amp
Typ of Motor	Permanent magnet machine
Radial Force	800 N
Axial Force	800 N
Tool Taper	HSK 50E
Clamping state monitoring	Yes
Seals	Labyrinth seal with active sealing air
Cooling	Water, closed system

Table I: Technical Data LeviSpin 700

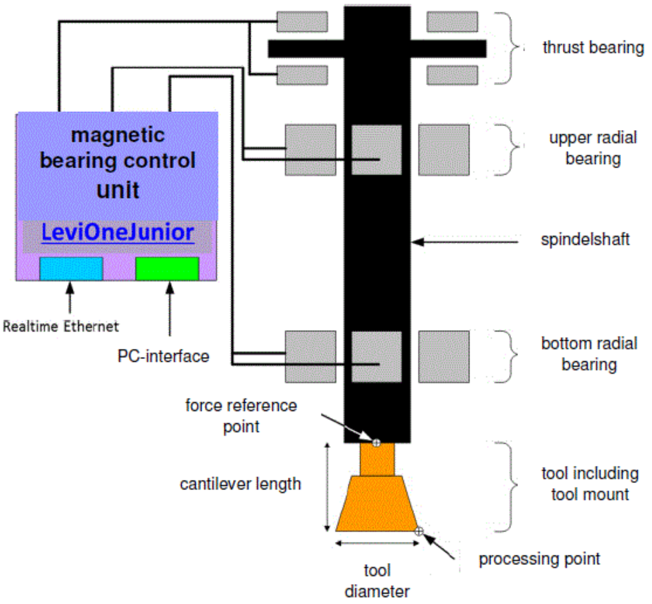

Figure 1. Magnetic bearing spindle basic configuration

In comparison to conventional spindles with ball-or rolling bearings, the shaft in a magnetic bearing spindle is levitated. Besides the rotation, there are additional degrees of freedom, which can be used but also need to be stabilized by the magnetic bearings. These degrees of freedom can be used by moving the shaft from its zero point or through oscillation in axial or radial direction.

Figure 2. Magnetic bearing spindle “LeviSpin 700” and magnetic bearing control unit “LeviOneJunior”

B. *Magnetic Bearings and Control Unit*

The control of the bearing is exclusively digital, using a high performance digital signal processor (Figure 2). The analogous position- and current signals are digitized and transferred to the processor. The digital control allows the user to access multiple bearing parameters and actual values which can be processed in a higher level control system, for instance in a CNC. The position of the rotor can be adjusted, as well as the stiffness of the bearings. Furthermore, it is possible to allow a force controlled machining, as well as continuous process monitoring [3], [5]. Therefore, a real time ethernet communication to the CNC of the machine is inevitable. It ensures the fast, real time data transfer between the electronic of the magnetic bearing and the CNC. As a consequence the five axis of the magnetic bearing system will be integrated in the CNC-program.

The force is proportional to the distance x between shaft and magnetic bearing stator and the needed current I, and can be calculated according to equation (1). kx and ki are absolute terms which are depending on the particular bearing.

$$F \sim kx * x + ki * I \qquad (1)$$

Position and current signals are reflecting an exact picture of the machining process. These signals, in combination with the cantilever length and the diameter of the tool (Figure 1) allow conclusions to the machining process, as well as operating with defined force like implemented in [3].

Due to the advantages for this application, the spindle in the example operates with unipolar bearings. Combining electromagnets with permanent magnets allows the use of much smaller electromagnets. This leads to a better dynamic, due to smaller inductivity, meeting increasing demands. This fact is used to oscillate the shaft or to fast line-out external disturbances. As already mentioned, using magnetic bearings allows minor adjustments of the rotating shaft. It can be moved several micrometers within the air gap. This fact can be used for tool compensation or superfinishing [10]. Besides, those bearings need less electrical power. They are short and compact, because of the high energy density of the permanent magnets. This has a positive impact on the rotor dynamics and the thermal situation.

C. *Motor and Drive*

The motor principle has been determined by refering to the induction machine as well as to the permanent magnet machine. The induction machine is commonly used in spindles. Reasons are the easy, solid and cost efficient rotor design and a wide field weakening range, which allows constant power over a wide speed range. On the other hand there are considerable advantages when using the permanent magnet machine. The following facts underline why the permanent magnet machine has been finally used for the above mentioned spindle:

- less rotor losses (rotor temperature)
- less volume / length (rotor dynamics)
- larger shaft diameter possible (rotor dynamics)
- large power efficiency over a wide speed range (energy efficiency)
- larger air gap possible (shaft displacement)
- shorter acceleration time (tool change time)

After setting the motor principle, defining the maximum size, torque and the rotational speed, the design of the motor can be done. Due to the compact construction, the high energy density and thermal utilization of the motor, a water cooling was installed to dissipate the heat loss effectively. For rotor dynamic reasons a four pole motor design was chosen to shorten the winding overhang. According to equation (2) a nominal speed of 42.000 rpm equals an electric frequency of 1.400 Hz. The used drive has to be capable to supply this frequency to this high speed permanent magnet machine.

$$f = \frac{n * p}{60} \qquad (2)$$

TABLE II: DATA OVERVIEW

	Parameter	Value
f	frequency	1.400 Hz
p	Number of pole pairs	2
n	Nominal speed	42.000 rpm

To minimize effects like dimensional deviation caused through thermal growth of the spindle shaft, it is inevitable to minimize losses in the spindle rotor. As shown in [7], the drive is mainly responsible. In order to reduce rotor losses of the motor, caused by current harmonics, the motor needs to supply by sinusoidal quantities. Therefore, the inverter is run with high PWM-frequency. If necessary a sine-wave filter or a choke is installed between the inverter and motor [6]. Figure 3 shows the direct impact of the PWM-frequency on the rotor temperature. The investigation has been executed by the PTW-Institute of the Technical University of Darmstadt. The temperature behavior of a 15 kW permanent magnet motor running at 27.600 rpm with different PWM-frequencies is shown in [8]. For the above mentioned reasons a drive Type “Sinus 4000” was chosen. This drive is a three level inverter with a PWM-frequency of maximum 64 kHz, designed to run high speed permanent magnet motors.

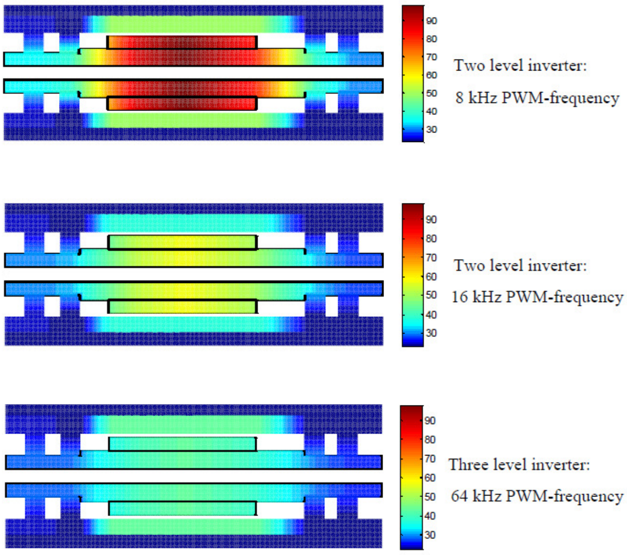

Figure 3. Impact of the PWM-frequency on the rotor temperature in °C

II. MACHINING RESULTS

The following examples refer to grinding tests with different materials at the Furtwangen University. Such as carbide metal, ceramic and steel. The tests were executed with a three-axis CNC-machine [2], [9]. The influence of axial oscillation and specific shaft displacement during the grinding operation on the machining results were of major interest. Additional investigations like measuring the grinding forces by the magnetic bearings, as well as monitoring the grinding process by current and position values were carried out. Figure 4 shows the test arrangement. FT is the tangential, FN the normal force in N, acting on the grinding tool.

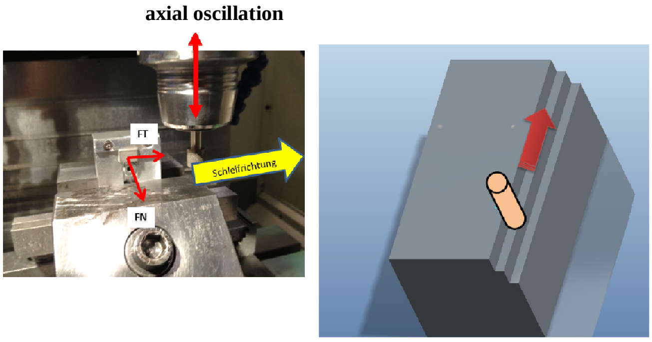

Figure 4. Test arrangement

As already mentioned the spindle shaft can be defined oscillated within the air gap of the touchdown bearings. In comparison to spindles with ultrasonic excitation, magnetic bearings spindles allow low frequency oscillation. Due to electrical and mechanical time constants of the system, the reachable amplitude is decreasing with increasing frequency. While the frequencies below 75 Hz amplitudes up to 120 µm are possible, using 700 Hz only allows 0.9 µm. Figure 5 shows the dependence of amplitude and frequency.

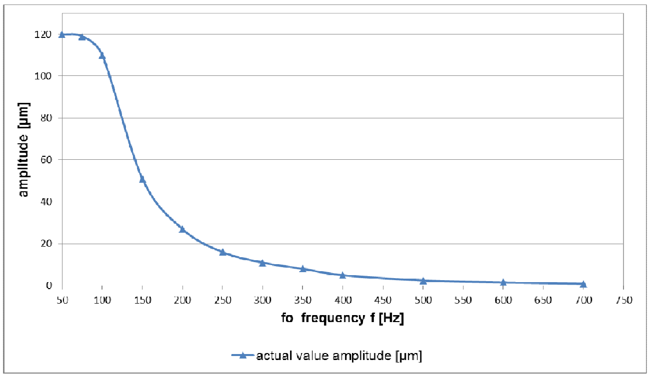

Figure 5. Dependence of amplitude and frequency

Magnetic bearings also permit to limit the amplitude even if larger amplitudes are possible by the system. Figure 6 shows the influence of the oscillation frequency on the grinding forces in tangential direction. The tangential force has been normalized, 100% equals no oscillation. The amplitude has been limited on various values. The optimum, regarding minimize the force, appeared at s~70/90 µm and 80 Hz.

TABLE III: CONSTRAINTS AND MACHINING PARAMETERS

	Parameter	Unit
Process	Peripheral grinding	
Material	Hard metal SMX/P25	
Tool	Grinding pin D91, Ø 10 mm	
v_c	Cutting speed	8,37 m/s
v_f	Feed speed	52 mm/min
a_e	Cutting depth	0,05 mm
FT	Tangential force	N
FN	Normal force	N
Rz	Average roughness	µm
s	Shaft deflection/Oscillation	µm

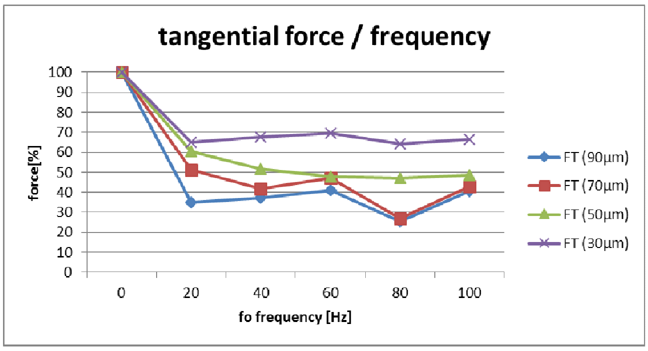

Figure 6. Dependence of amplitude and frequency

Similar results are shown in Figure 7, concerning the surface quality.

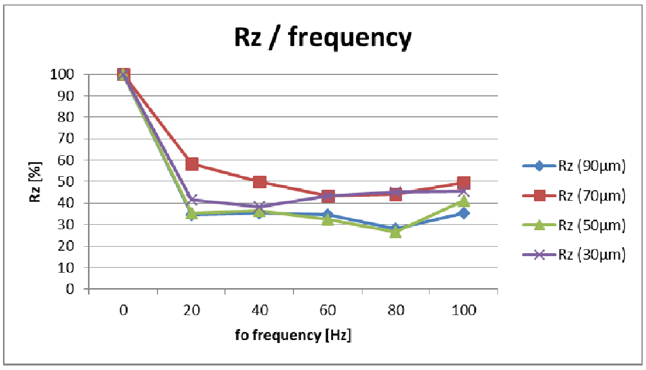

Figure 7. Dependence of average roughness and frequency

III. CUSTOMER VALUE

The use of magnetic bearings in grinding spindles leads to additional functionalities and features. As already shown, the axial oscillation helps to reduce forces during the grinding process. Besides, the surface of the material is of higher quality because of les roughness. By reducing grinding forces, overall productivity is increased through shorter machining time. With other words, this enables higher feed speed and therefore higher metal removal rate. Less forces on the tool extend the operating life. Combined with this energy efficient motor and the maintenance-free magnetic bearings, it will reduce the lifecycle costs significantly. By using the integrated sensors in the magnetic bearings, a continuous process monitoring and diagnosis is feasible. During the process generated data can be used directly and further processed. Abnormalities or faults can be detected early. This improves the availability of the machine.

IV. CONCLUSION

The behavior of a magnetic bearing spindle during grinding process has been investigated. Furthermore, additional functionality and usefulness were considered. Only if all system components are well aligned and interacting perfectly, the best performance and the highest costumer value can be achieved. In summary it can be said that:

- Magnetic bearings in grinding spindles enable performance increase and additional functionality
- Low-frequency axial oscillation reducing grinding forces and improving the surface quality, in other words increased productivity at higher quality
- conditional monitoring of the machining process is possible, as well as an improvement of the process reliability
- no further sensors needed to control and monitor grinding forces

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