DESIGN AND REALIZATION OF A MINIATURE MILLING SPINDLE WITH ACTIVE MAGNETIC BEARINGS

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ABSTRACT
This paper describes the design of two active magnetic bearing spindle systems. A miniature active magnetic bearing spindle, with two radial bearings, one axial bearing and a permanent magnet synchronous motor has been built. The spindle is controlled by five, decentralized PID controllers. The closed loop bandwidth of the system is 380 Hz. The static positioning error was measured to be below 45 nm (1σ). This spindle has been tested with rotational speeds up to 120.000 rpm.

To reach higher rotational speeds a second miniature active magnetic bearing spindle has been designed. The rotor dimensions are smaller than in the first generation in both length and diameter. The basic design concept is a small disk shaped rotor, which eliminates the passing of one rigid mode and several flexible body modes during startup. The gyroscopic coupling in a disk shaped rotor is larger when a relatively short rotor is applied. In this research, the aim is to use resistance of a gyroscope against tilting to an advantage.

INTRODUCTION
The miniaturization of product design requires additional processing techniques for the three-dimensional structuring of micro features in different types of materials. For example, silicon micro machining technologies find limited applicability as it is used to machine silicon in 2.5 dimensions. A machining tool for micro-milling is commercially available, spindle and stages are in these systems equipped with stiff air bearings.

In this research the applicability of Active Magnetic Bearings for micro-machining is investigated. The proper combination of micro milling with other micro machining technologies such as Electro Discharge Machining (EDM), and Electro Chemical machining (ECM) to achieve higher accuracies is investigated.

A high speed, precisely controlled spindle is required for the development of a bench top micro milling machine. Micro milling is typically classified as machining with tool diameters smaller than 0.5 mm. For a high surface quality, a high cutting speed and high positioning accuracy are required. The target spindle speed for this research is higher than 300.000 rpm, with a positioning uncertainty of 0.1 μm.

In this paper, the designs of two Active Magnetic Bearing (AMB) spindles are presented. AMBs are suitable very high rotational speeds, due to their lack of mechanical friction. The AMBs potentially enable very high machining accuracies. The high machining accuracy and high surface quality can be achieved when the position and the rotational motion are properly measured and controlled with the AMBs. In example, with AMBs the rotational axis can be chosen arbitrarily. To improve the quality of the cutting process even more, the active nature of the bearings will be used to control chatter and to investigate model based cutting force estimation for online process monitoring and control [1].

In a previous paper, the mechatronic concepts were presented [2]. In this paper, the realization and the first results are presented, where rotational speeds over 120.000 rpm.

TWO TEST SETUPS
In this research, two different active magnetic bearing designs have been considered. First, the miniaturization of a more classical active magnetic bearing setup was investigated. This setup will be referred to as the “long rotor setup”.

Second, a novel disk shaped rotor concept, suspended by combined active magnetic bearings, has been designed [2], and is referred to as the "short rotor setup". The two concepts are illustrated in Figure 1.

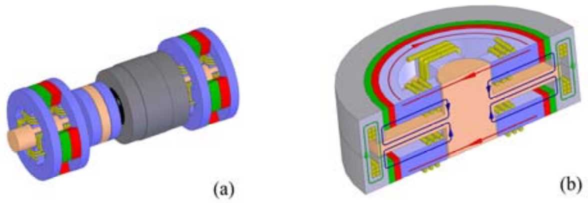

FIGURE 1: The active magnetic bearing setups. The long rotor setup (a), and the short rotor setup (b).

LONG ROTOR SETUP

The design and realization of the long rotor setup will be presented. This setup allows for the investigation into the design of homo polar active magnetic bearing systems, and provides a test platform.

With the testing platform, components of the AMB setup, like the homo polar radial bearings and the sensing principle, can be evaluated. In addition advanced control strategies, like LPV control, can be developed. Milling experiments with sub-millimeter sized tools can be done at high rotational speeds. The online cutting process monitoring techniques can be developed using the information from the magnetic bearings, like the gap measurements and currents in the coils [1].

Setup Design

This prototype consists of two radial bearings and one axial bearing constraining a small sized spindle in five degrees of freedom. This spindle will be driven by a commercially available permanent magnet synchronous motor. The spindle is designed for speeds up to 200 000 rpm.

Conventional AMB spindles employ laminated rotors to keep the eddy current and hysteresis losses to a minimum. The application of laminations on a rotor for high speed applications is critical, due to high centrifugal stresses [3]. In the long rotor setup, employing a laminated rotor is impossible, because of loss of contact between the lamination stack and the rotor, therefore a solid rotor has been used. To reduce the eddy current losses, the rotor material has a relatively high resistivity, 600 nΩm.

To keep the rotating losses as low as possible, a homo polar radial bearing concept is used, as illustrated in Figure 2. Permanent magnets provide a bias flux, which axially passes the rotor in the radial bearings. The flux in the gaps is controlled in the radial plane, as illustrated in Figure 2. The properties of both the radial and axial bearings are listed in Table 1. The position sensors are integrated between the legs of one radial bearing unit. This makes the radial bearings co-located, which has several advantages in the radial bearing control. The backup bearings consist of ceramic rings, which are also integrated within the radial bearing units. The integration of the position sensors and backup bearings reduces the size of the radial bearings. With this compact radial bearing design the shaft length is kept as short as possible. By reducing the shaft length, the critical speeds corresponding to flexible modes, are increased.

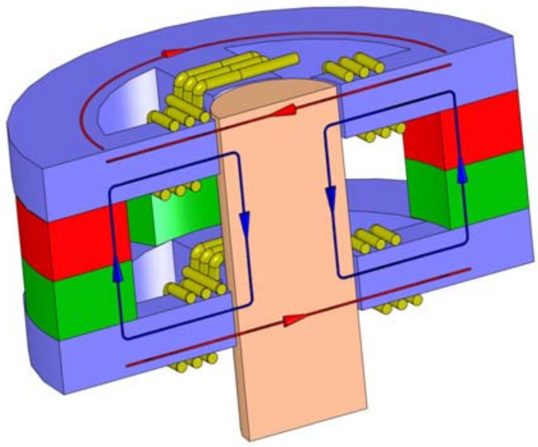

FIGURE 2: Radial homo polar bearing concept (Two subsystems in the long rotor setup). The bias fluxes are generated by the permanent magnets and illustrated in blue. The controlled fluxes are generated in the radial plane and shown in red.

TABLE 1: Properties of the long rotor miniature AMB setup.

Rotor Mass	0.18	*kg*
Rotor Length	$130 \cdot 10^{-3}$	*m*
Rotor Diameter	$12 \cdot 10^{-3}$	*m*
Thrust disk diameter	$30 \cdot 10^{-3}$	*m*
Max. Bearing force (radial)	17	*N*
Negative Bearing stiffness (radial)	$5 \cdot 10^{4}$	*N/m*
Force Current constant (radial)	4	*N/A*
Airgap (radial)	$4 \cdot 10^{-4}$	*m*
Max. Bearing force (axial)	17	*A*
Negative Bearing stiffness (axial)	$5 \cdot 10^{4}$	*N/m*
Force Current constant (axial)	4	*N/A*
Airgap (axial)	$3 \cdot 10^{-4}$	*m*

The axial bearing is a conventional concept using two reluctance type actuators acting on each side of a thrust disk. The reluctance type actuators are supplied with a bias current for linearization purposes. The disk on the rotor is the part of the rotor with the largest diameter, 30 mm. The stresses in thrust disk are the limitation for the maximum rotational speed this rotor can achieve. The properties of the axial bearing are listed in Table 1.
To drive the spindle shaft, a commercially available motor (E+A, Switzerland, enca, mSpW 4/1.5 - 2) is used. This is a sensor less permanent magnet synchronous motor; synchronization information is obtained from the coil currents. Theoretically, the motor and motor driver maximum speed is 250 000 rpm.

To ensure an accurate spindle assembly, the separate radial bearings, motor and axial bearing are aligned using a v-groove concept. The v-groove base has been made by wire EDM. The spindle components, the radial bearings, the axial bearing and the motor are ground cylinders. By placing the cylindrical components in the v-groove, the cylinders are supported along two datums, which ensures alignment within the tolerance. This is a modular design, and enables rapid and accurate replacement of all the components in the AMB system, if necessary. The finished setup is shown in Figure 3.

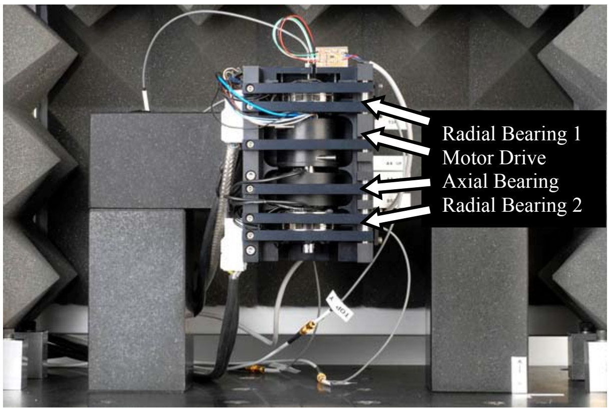

FIGURE 3: Realized miniature AMB milling spindle, the long rotor setup.

Experimental Results

Using the modeled force current (Ki) and force position (Ks) constants, the plant transfer function of the radial bearings has been predicted. Using this transfer function, a stabilizing PD controller was designed.

Once the rotor was successfully levitated, the actual plant transfer function could be measured. This plant transfer function gives an indication of the quality of the prediction of the force current (Ki) and force position (Ks) constants. The predicted and the measured plant transfer functions are shown in Figure 4. From this measurement it can be seen that considerable phase lag is present in the system. Possible causes for this phase lag are: eddy current effects, strengthened by the use of a non laminated rotor, and the use of eddy current sensors.

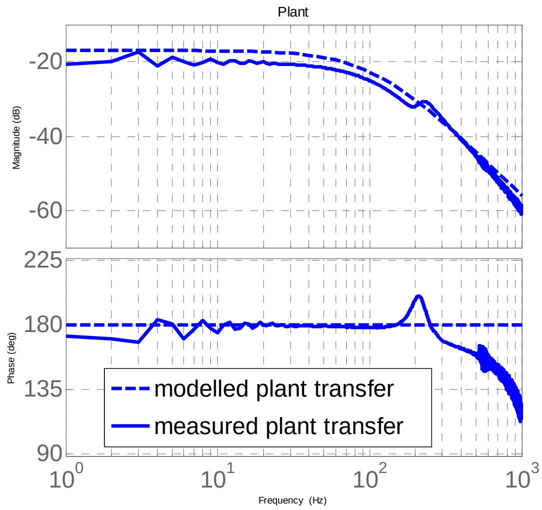

FIGURE 4: The plant transfer function of the radial bearings. The modeled plant transfer function(dashed) is shown as well as the measured plant transfer(solid line).

The plant transfer function is used to design and tune a PID controller. The closed loop transfer function one of the radial bearings is shown in Figure 5, exhibitin a bandwidth of 380 Hz. The transfer function was obtained by calculating the Empirical Transfer Function Estimate (ETFE) from the displacements of the shaft and the refence input, as described in Ref. [1]. Presently the miniature AMB spindle is controlled by 5 decentralized PID controllers. Two rigid modes can be recognized, as well as the first flexible mode.

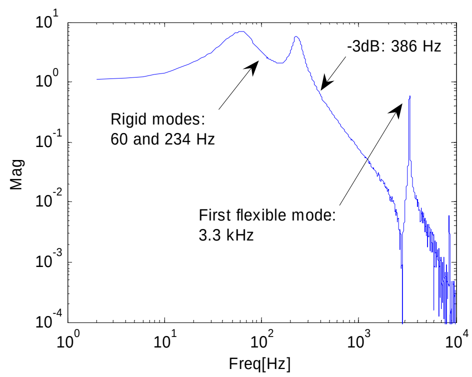

FIGURE 5: The closed loop transfer function of one of the radial bearings. A 380 Hz bandwidth is achieved.

In Figure 6 the Cumulative Amplitude Spectrum (CAS) of the error signals at zero rotational speed is shown. The CAS of the error signal shows how the error is built up over the frequency range. This gives an indication of the source of the disturbances entering the system. From the CAS we can conclude that the one sigma (1σ) static error is below 45 nm.

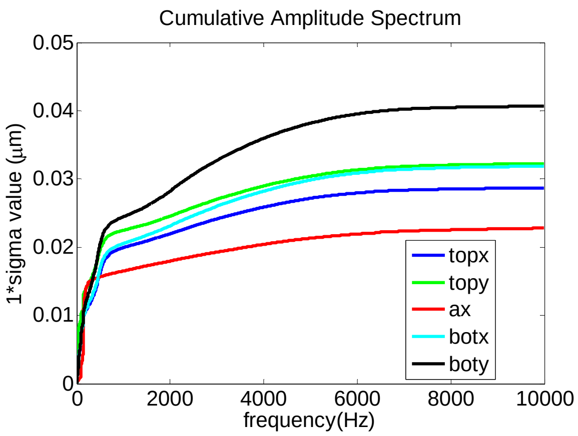

FIGURE 6: The Cumulative Amplitude Spectrum of the error signals from the 5 Active Magnetic Bearings in the miniature spindle.

The miniature AMB milling spindle has successfully operated with speeds up to 120.000 rpm. To achieve this rotational speed, the critical speeds corresponding to the rigid, controlled, modes had to be overcome. A critical speed is the point where the rotational speed equals a resonance frequency. The critical speeds are overcome by changing the controller parameters when the rotational speed approaches a resonance. The closed loop resonance frequency of the system is shifted to a considerably lower frequency than the rotational speed, this way the critical speed is passed while avoiding the point where the rotational speed actually equals the resonance.

Before increasing the rotational speed above 120 000 rpm, a more centralized controller must be implemented. The first step towards this centralized controller is to add cross-feedback to the current PID controllers. The technique that will be implemented is based on a state feedback controller by Ahrens [4].

Sensor Performance in the Long Rotor Setup

This section covers the selection and characterization of the position sensors the miniature AMB milling spindle. Three sensing principles have been considered for the spindle: eddy current sensors, capacitive sensors and optical reflective sensors. For the first prototype, eddy current sensors were selected.

Eddy current sensors were used because they do not require target grounding as capacitive sensors do, which is undesirable in a high speed application. Optical reflective sensors were not used in the initial design because of their limited resolution and because of their sensitivity to surface reflectivity changes during operation.

Two key drawbacks of eddy current sensors are the sensitivity to inhomogeneities in the moving target material, and they introduce significant phase lag into the system. The performance of the eddy current sensors was tested in comparison with an extra optical reflective sensor in the spindle. The optical sensor has a lower resolution than the eddy current sensor, however, the transfer function measurement with the optical reflective sensor shows less noise in the higher frequency region than the eddy current sensors.

From this observation interference between the magnetic field and the eddy current sensor readings was suspected. To verify this assumption, the rotor was mechanically fixed in the magnetic bearings, and a transfer function measurement was done from the applied current to the eddy current sensor reading. The result of this experiment is shown in Figure 7. In Figure 7, at frequencies above 100 Hz, the transfer function shows a +1 slope, indicating a coupling between the magnetic actuators and the eddy current sensor.

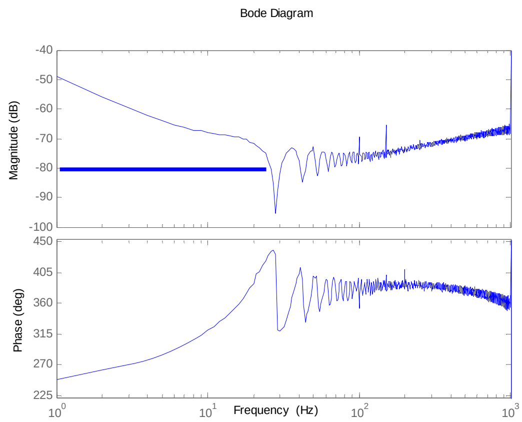

FIGURE 7: Transfer function from an excitation of the bearings (A) to the reading of the displacement sensor (mm), with an immovable rotor.

A second verification experiment was performed by measuring the rotor position at various rotational speeds and comparing the eddy current sensor signal with the optical reflective sensor signal. The results of this experiment with the rotor running at 496 Hz are shown in Figure 8. For this experiment the gains of the two sensor outputs are matched at very low frequencies. The results of this experiment show a loss of gain and phase in the eddy current sensor.

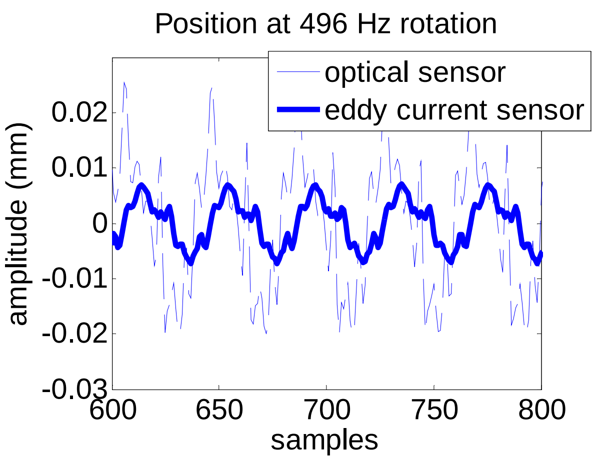

FIGURE 8: Rotor position reading from the eddy current sensor, solid line, and the optical reflective sensor, dashed line. The rotor speed was 496 Hz.

The quality of the rotor position measurement is essential for the successful estimation of the cutting forces using the active magnetic bearings. One key upgrade to the long rotor system will be replacing the eddy current sensors with optical reflective sensors. The drawback of the optical reflective sensors is a lower resolution. With less phase loss in the sensors however, a higher control bandwidth can be achieved.

SHORT ROTOR

This section describes the design of the second high speed AMB concept, the short rotor setup, illustrated in Figure 1. The goal of this setup is to enable higher rotational speeds. Several conceptual designs of high speed spindles were modeled to determine their rotordynamic behavior. It was concluded that a short, disk shaped rotor has several benefits over a relatively long rotor, as often applied in conventional magnetic bearing systems [2].

By reducing the length of the rotor, the gyroscopic coupling is increased. When the inertias, $I_z/I_x, I_y \geq 1$, the critical speed belonging to one conical rigid resonance mode can be avoided [2]. Critical speeds belonging to flexible rotor modes can be avoided by using a short rotor.

In this research, the aim is to use the larger gyroscopic coupling to reduce the error response to tilting disturbances. The larger gyroscopic coupling creates however a greater control challenge.

Setup Design

In order to match the criterion: $I_z/I_x, I_y \geq 1$, the rotor must have a disk shape. The rotational speed is limited by the diameter of the disk, therefore a very compact design is required. To reach 300 000 rpm, the diameter of a solid steel disk must not exceed 20 mm. Magnetically suspending a compact disk shaped rotor in five degrees or freedom requires an unconventional AMB design.

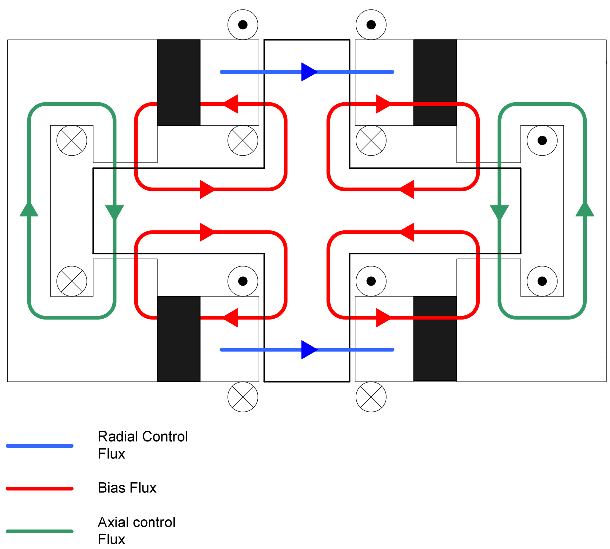

FIGURE 9: Disk shaped rotor concept, suspended by combined Active Magnetic Bearings.

The AMB concept for suspending the disk shaped rotor is illustrated in Figure 9. The concept is based on a combined axial-radial bearing concept presented by Lee [5]. For the short rotor setup design two extra degrees of freedom are added to the original concept. This allows the disk shaped rotor to be supported in five degrees of freedom by AMBs.

In this concept a radially magnetized ring magnet provides the bias flux, illustrated in black in Figure 9. The permanent magnet ring provides the bias flux for the radial bearing as well as for the axial bearing. The generation of the bias flux for three actuators with one permanent magnet enables a very compact magnetic bearing design. The flux in the radial air gap is controlled in the radial plane by the coils around the stator legs, see Figure 9. The control flux in the axial direction is generated by a circular coil, also illustrated in Figure 9. The gap measurement is done with optical reflective sensors. Integrating the optical sensors in the short rotor setup required sensors with a small diameter tip, 0.9 mm.

Currently the design of the short rotor setup has been finalized. Analytical as well as FEM analysis has been completed on the magnetic actuators of the short rotor setup. A section view of the short rotor setup design is shown in Figure 10. A motor is currently designed to be integrated into the short rotor setup.

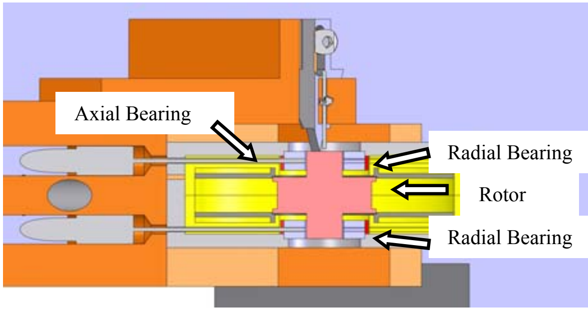

FIGURE 10: Section view of the designed short rotor setup. One can recognize the rotor, the radial bearing stators, the axial bearing stator and the optical reflective sensors.

CONCLUSIONS AND FUTURE RESEARCH

The design of two magnetic bearing spindles is presented, one with a relatively long rotor, and one with a disk shaped rotor. The long rotor spindle has been built and successfully been tested with speeds up to 120.000 rpm. This spindle is controlled with 5 decentralized PID controllers. With the PID controllers, a closed loop bandwidth of 380 Hz. has been realized. With this spindle a static error below 45 nm has been achieved.

The position of the shaft is measured with eddy current sensors. The suitability of eddy current sensors for this high speed application has been described. The eddy current sensors show significant gain and phase loss at high rotational speed, as well as a coupling between the magnetic field applied and sensor reading.

The future work consists of the design of a centralized controller, as well as implementing optical reflective sensors.

The design of the compact active magnetic bearing setup with a relatively short rotor has also been presented. The use of a disk shaped rotor has several advantages. A critical speed corresponding to a conical mode shape, as well as flexible resonances can be avoided. A disk shaped rotor is more subject to gyroscopic effects, but aim to use this to our advantage.

The support of a small disk shaped rotor demands a very compact design. A permanent magnet is used to provide a bias flux in the axial direction as well as in the radial direction. Currently the design is finalized, as well as the FEM analysis and fabrication will start shortly.

ACKNOWLEDGEMENT

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