Design of a Novel Miniature Spindle Concept with Active Magnetic Bearings using the Gyroscopic Stiffening Effect

Maarten Kimman, Hans Langen and Jan van Eijk
Faculty of Mechanical Engineering
Dept. of PME/Advanced Mechatronics
Delft University of Technology
Mekelweg 2, 2628 CD, Delft
m.h.kimman@tudelft.nl

Henk Polinder
Faculty of Electrical Engineering
Dept. of Electrical Power Processing
Delft University of Technology
Mekelweg 4, 2628 CD, Delft
h.polinder@tudelft.nl

***Abstract*— A high speed spindle will be designed for micro fabrication applications. The aim is to reach 0.1 μm accuracy with a rotational speed of at least 300.000 rpm. A study is done into the behavior of different rotor shapes. A short rotor and a long rotor are modeled by solving the non linear Newton and Euler equations numerically. The short rotor tilts much less under the influence of the cutting forces than a long rotor. The short rotor is thus much stiffer around the rotational axis than a long rotor.**

Short rotors are easier to bring up to speed. The gyroscopic coupling between the two vertical planes is much stronger in case of a short rotor. This can cause instability and must be taken into account in the design of a control system. The possibility to use this gyroscopic stiffening to our advantage will investigated.

Two active magnetic bearing systems will be built. The performance of a long rotor and the performance of a short rotor, both magnetically levitated, will be compared. The design of a magnetic bearing system for a prototype with a long rotor is described in this paper. This prototype is built to gain experience in the design of small magnetic bearings, with permanent magnets for bias. The setup will be used to test the performance of a long rotor

***Index Terms*— High Speed, Gyroscopic Stiffening, Active Magnetic Bearing Design**

I. Introduction

Miniaturization of product design requires more freedom in the three-dimensional structuring of micro features in different types of materials. Current fabrication techniques of micro structures, like photo lithography, are limited to two dimensional structuring of silicon like materials. In the Microfactory project we investigate the downscaling of micro part fabrication using techniques such as micro milling, electronic discharge machining and electro chemical machining, aiming at 0.1 μm accuracy.

In the development of a desktop machine integrating these micro structuring technologies, the design of an active magnetic bearing spindle is required. Micro milling is done with a mill diameter of 0.1 mm. For a high surface quality, a high cutting speed is required. This means that a spindle will be designed with high operating speeds of 300.000 rpm and higher. Active magnetic bearings are applied for their possibility to operate with very high accuracy. Contact less bearings are preferable due to their lack of mechanical friction at very high operating speeds. With active magnetic bearings, the modularity of the spindle system can possibly be increased. During the different machining steps, the process can be changed by replacing the spindle/tool setup. These machining steps can be micro milling, electronic discharge machining(EDM) and electro chemical machining(ECM). The active magnetic bearings will be used to position the micro tool at the correct reference. Active magnetic bearings also offer the possibility of super positioning an orbital motion on top of the rotational motion of the tool. By doing this, the surface finish of the workpiece can be improved. The applicability of active magnetic bearings is researched looking for an optimal configuration making use of gyroscopic stiffening. Other projects in the Microfactory project involve the design of the high speed motor and the design of a dual positioning stage to position the workpiece under the spindle described in this paper.

In this paper, a review on high speed rotation is given. The three dimensional modeling of different rotor types is described. Two concepts considering the modeling results are introduced. Finally the design of the prototype spindle is presented.

II. Background

When designing a rotor for high speed rotation several difficulties have to be overcome. One is the limitation in rotor diameter due to centrifugal forces. For a solid steel rotor at 300.000 rpm this is 22 mm. The high centrifugal stresses in the rotor are critical when the rotor material is non uniform, for example when laminating the rotor to reduce eddy currents. The high stresses must not cause loss of contact between the lamination and the rotor. Larsonneur[1] has addressed these difficulties when building an active magnetic bearing system for high speed rotation.

The eccentricity is the difference between the geometrical axes, and the inertial axes of the rotor. These eccentricity causes high centrifugal forces when the rotor is rotating around its geometrical axis, given by:

$$F = m\omega^2\epsilon \tag{1}$$

Therefore, at high speed the rotor will rotate around its inertia axis.

Most rotors have two rigid body critical speeds to overcome. The first critical speed is related to the cylindrical mode and the second critical speed is related to the conical mode shape. Whitley[2] reviewed the principles of high speed rotation for gas-centrifuges already in 1962. and he stated that short rotors have no critical speeds related to rigid conical modes. Flexible modes due to the shaft length are exited at a much higher frequency when using a short rotor.

The resistance against tilting of a gyroscope can be used to our advantage, because the gyroscopic effect can be used to stabilize a rotating body, as is shown with the gyroscopic stabilization of the Levitron™, as described by Genta[3].

For a miniature spindle especially, the design of a radial bearing for a disc-shaped rotor is an extra challenge. W. Lee[4] described the design of a combined axial-radial bearing for shorter shafts. This paper presents a bearing setup based on this concept to suspend a disc shaped rotor in 5 degrees of freedom. The gyroscopic effect will be used to stiffen the rotor at high speed. To the authors knowledge no disc-shaped motor is available for such high rotational speeds. Within the Microfactory project another research project will deal with the design of the motor drive and power electronics.

Before building the magnetically suspended disk shaped rotor, a prototype will be build using a long rotor in combination with two homo polar radial magnetic bearings and one axial magnetic bearing. This setup will provide insight in the design and miniaturization of homo polar magnetic bearing systems, where the bias flux is provided by permanent magnets. For spinning up the long rotor, a commercially available motor can go up to 250 krpm. With this setup the limitations of long rotors will be tested. For higher speeds a new motor should be designed. The performance of the long rotor will be compared to the performance of the short rotor.

III. Modeling

The Newton and Euler equations are used to study the behavior of a rotor and the stabilizing effect at high speeds. The goal is to determine the optimal dimensions of the rotor and to determine the control effort necessary for stable and accurate rotation. It is expected that the tilting of the rotor does not have to be controlled at high speed. The nonlinear equations of motion are solved using a MATLAB ODE solver.

$$\begin{array}{lcllcl} m\ddot{x} & & & = & \sum F_x \\ m\ddot{y} & & & = & \sum F_y \\ m\ddot{z} & & & = & \sum F_z \\ I_x\dot{\omega}_x & + & \omega_y\omega_z(I_z - I_y) & = & \sum T_x \\ I_y\dot{\omega}_y & + & \omega_z\omega_x(I_x - I_z) & = & \sum T_y \\ I_z\dot{\omega}_z & + & \omega_x\omega_y(I_y - I_x) & = & \sum T_z \end{array} \quad (2)$$

In these equations the angular velocity around the spin axis, ω_z, will be very large, causing a large coupling between the rotor axes. This term has a stiffening effect on the rotor. The equations of motion are observed in the local rotating frame of the rotor. In this simulation, the effect of the cutting forces on the translation of the rotor, as well as the angle of rotation in the vertical plane. The tilting of a short rotor is compared with the tilting of a long rotor.

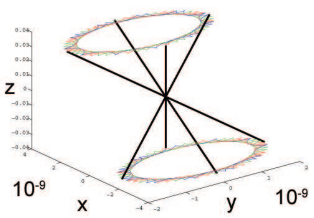

Fig. 1. The tilting of a long rotor at 300.000 rpm.

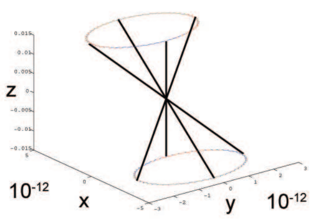

Fig. 2. The tilting of a short rotor at 300.000 rpm.

The modeling results are shown in figures 1 and 2. In these figures the rotor is illustrated by the black bar. The orbit described by the tips of the bar is illustrated. From the results, shown in figures 1 and 2, it is concluded that the influence of the cutting forces on the tilting of the fast rotating rotor is small, for both long and short rotors. However, the tilting of a long rotor is clearly much larger than the tilting of a short rotor at the same speed, confirming the advantages of the use of a short rotor.

IV. Gyroscopic Stiffening

From the modeling results it can be concluded that a short rotor performs better than a long rotor. The gyroscopic coupling stiffens the axis of rotation. Due to this stiffening, the rotor tilts much less under influence of the simulated cutting force. The gyroscopic coupling becomes stronger when reducing the length of a rotor, thus with increasing ratio of moments of inertia around the z-axis and the x-y axis, thus $I_z/I_x, I_y \lll 1$.

Magnetically suspended rotors can become unstable with increasing speed due to this gyroscopic coupling, when there is no coupling between the controllers in the x and y direction. This cause of instability is described by Ahrens [5]. This instability can occur when digital control systems are used, when sensor actuator collocation is not fulfilled or when certain nonlinearities are considered. The gyroscopic coupling must therefore be well considered in the control system design. For example by using a centralized controller[5].

V. Concepts

Two magnetically levitated rotors will be built. The first rotor to be built is suspended by a classical bearing setup. It consists of two radial bearings and one axial bearing, as shown in figures 3 and 4. The radial bearings are homo polar active magnetic bearings. The bias flux in the radial bearings is provided by permanent magnets. With the design and fabrication of this setup, the miniaturization of a conventional magnetic bearing system is investigated. Also, experience will be gained in the design of homo polar bearings with permanent magnets for bias. With this setup, the limitations of a long rotor will be tested.

The second concept is a disc shaped short rotor, suspended by a compact magnetic bearing, as shown in figure 5. This concept is based on a combined radial and axial bearing[4]. By changing the coil setup, the concept shown in figure 5 is used to suspend a disk shaped rotor in five degrees of freedom. The bias flux for all of the five actuators is provided by one pair of permanent magnets. The four coils in the top of the bearing constrain two degrees of freedom. The coils in the center of the bearing prevent axial motion. The lower coils constrain the two remaining degrees of freedom. The rotor can be stabilized at low speeds constraining all degrees of freedom. At high speeds the gyroscopic stiffening and the possibility of actuating fewer degrees of freedom will be tested.

The possibilities of reducing the eddy currents in a rotor at high speeds will be investigated as well as the performance of both systems is to be compared.

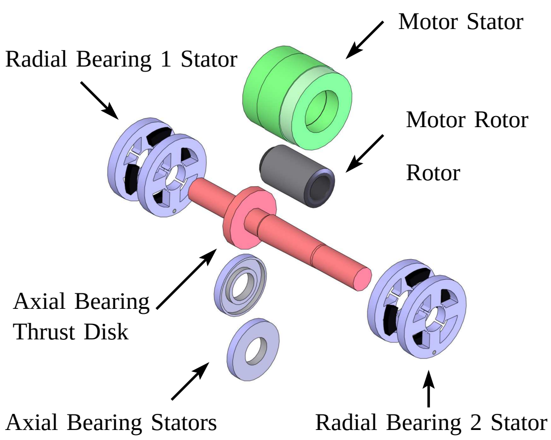

Fig. 3. Exploded view of the suspension of the long rotor with two radial bearings and one axial bearing. In this figure one can recognize the two radial bearings and the axial bearing stators. Also the permanent magnet synchronous motor, consisting of rotor element and stator element, is illustrated.

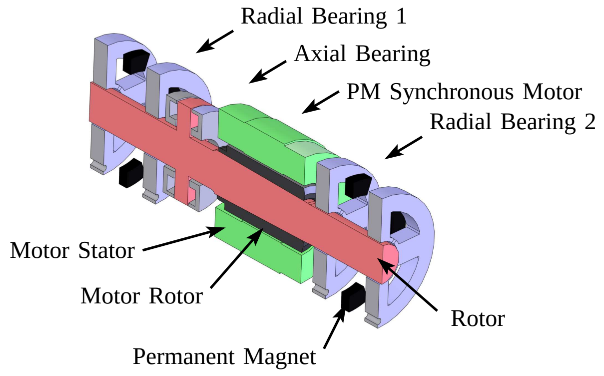

Fig. 4. Section view of the magnetically levitated rotor with two radial bearings and one axial bearing. The rotor is radially suspended by homo polar stators with a permanent magnet induced bias flux.

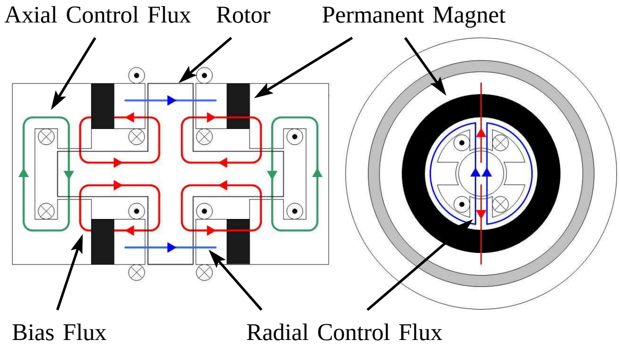

Fig. 5. A disk shaped rotor, suspended by a compact combined axial radial active magnetic bearing setup. The bias flux is provided by permanent magnet rings. These permanent magnets create a bias flux for the axial direction, as well as for the radial direction.

VI. Prototype Design

In this section, the design of the first prototype is described. Before designing the prototype, a literature study into the application, micro milling, has been done. Dow et.al.[6] have created a model to predict the cutting forces during micro milling. The simulated cutting forces were a good approximation of the experimental cutting forces. To design the magnetic bearings for a milling spindle, it is necessary to know the disturbance forces entering the spindle due to cutting. The model from Dow[6] is used to predict the cutting forces during micro milling. The predicted cutting forces are shown in figure 6.

From this simulation it is concluded that the cutting forces stay below 0.2 N in the horizontal plane, and that the cutting forces are smaller than 0.6 N in the axial direction of the spindle. These disturbance forces are very small and have a very high frequency. Compensating for the cutting forces with the active magnetic bearings will be impossible due to their high frequency. The inertia of the spindle must be large enough to avoid translation and rotation of the rotor larger then the specifications.

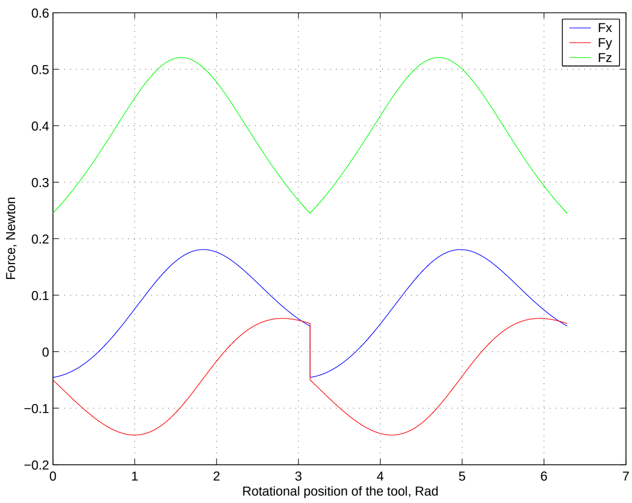

Fig. 6. Predicted cutting forces.

The prototype active magnetic bearing setup consists of a long rotor. The prototype rotor is suspended by two radial bearings and one axial bearing, as shown in figures 3 and 4. In this section, the components of the prototype setup will be discussed.

For the airgap measurement, high resolution, high bandwidth inductive sensors will be used. Five sensors will be used in the first prototype. The sensors for the radial airgap measurement are integrated in the radial bearing units. The axial displacement measurement is done at one end of the rotor. The resolution of the inductive sensors is 25 nm at 20 kHz.

Furthermore, the resistivity of Sandvik 1802 steel against eddy-currents is to be investigated. It will be investigated if a control bandwidth of 400 Hz can be reached using homo polar active magnetic bearings in combination with a rotor of Sandvik steel.

The prototype setup is illustrated in figures 3 and 4.

A. The Rotor

It is mentioned that the rotor will not be laminated due to the high centrifugal stresses. The rotor is made of Sandvik 1802 stainless steel. The Sandvik 1802 steel has a high resistivity with respect to normal steel. By applying Sandvik 1802 steel, it is expected that the phase loss due to the eddy currents can be kept to a minimum.

The rotor is equipped with a thrust disk as a body for the axial magnetic bearing. To minimize the number of flexible critical speeds to overcome, the magnetic bearing setup is designed to keep the length of the rotor as small as possible. For the press fit connection with the motor, a conical section is integrated in the spindle. The rotor is illustrated in figure 3. The properties of the rotor are listed in table I.

B. The Radial Bearings

The radial bearings are homo polar active magnetic bearings. The bias flux in the radial bearings is provided

TABLE I
ROTOR PROPERTIES

Length	$120 \cdot 10^{-3}$	m
Diameter	$12 \cdot 10^{-3}$	m
Thrust Disk Diameter	$30 \cdot 10^{-3}$	m
Mass	0.13	kg

by permanent magnets. The bias flux crosses the rotor in longitudinal direction. The control flux crosses the rotor in radial direction. The concept of the radial bearings is illustrated in figure 7. By using a homo polar bearing, the rotor does not have to change polarity during each revolution. By using a homo polar bearing setup, the hysteresis and eddy current losses will be kept low. The use of permanent magnets reduces the power consumption and the heat development in the bearings. The properties of the radial bearings are listed in table II

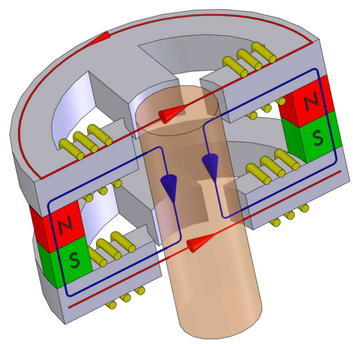

Fig. 7. Homo polar bearing concept, illustrating the rotor and the stator with permanent magnets for bias flux and the control coils. The bias flux in the axial direction of the rotor is illustrated, as well as the control flux in the radial plane.

TABLE II
RADIAL BEARING PROPERTIES

Max. Bearing Force	17	N
Negative Bearing Stiffness	$5 \cdot 10^{4}$	N/m
Force Current Dependency	15	N/A
Airgap	$4 \cdot 10^{-4}$	m
Pole Shoe Area	$4.5 \cdot 10^{-5}$	m^2
Bias Flux in Airgap	0.6	T
Max. Control Flux in Airgap	0.2	T
Number of Poles	8	[-]
Number of Coil Turns (1 direction)	60	[-]

C. The Axial Bearing

To constrain the axial movement, a conventional axial bearing principle is applied. The axial bearing consists of two reluctance type actuators in a circular shape. The actuators are mounted in differential driving mode on each side of the thrust disk. A bias current will be supplied through the coils to linearize the bearing force. The properties of the axial bearing are listed in table III

TABLE III
AXIAL BEARING PROPERTIES

Max. Bearing Force	22	N
Negative Bearing Stiffness	$1 \cdot 10^5$	N/m
Force Current Dependency	22	N/A
Bias Current	1	A
Maximum Current	2	A
Airgap	$4 \cdot 10^{-4}$	m
Pole Shoe Area	$2.7 \cdot 10^{-4}$	m^2
Number of Coil Turns	25	[-]

D. The Motor

The motor will be a commercially available permanent magnet synchronous motor. This motor is rated for speeds up to 250.000 rpm. The motor is supplied as a rotor unit and a stator unit. The rotor unit is mounted to the spindle shaft by a press fit. The negative stiffness caused by the permanent magnets in the motor is in the same oder of magnitude as the negative stiffness in the radial magnetic bearings. The controlled stiffness of the bearings will be 10 times higher.

The motor is controlled by a commercially available power inverter. This inverter is able to drive permanent magnet synchronous motors with speeds up to 320.000 rpm. The power inverter drives the motor sensor less. A separate encoder will be mounted to the spindle for the speed measurement.

VII. CONCLUSION AND FURTHER RESEARCH

The modeling presented in this paper shows that a short rotor is more suitable for high speed rotation than a long rotor. Two active magnetic bearing setups are presented, one with a long rotor and one using a short rotor. The design of the miniature spindle with a long rotor is presented. With this setup the performance of a solid rotor in combination with homo polar, permanent magnet biased, magnetic bearings will be tested. In the near future a second active magnetic bearing setup will be built. In the second setup the homo polar bearings are integrated into one compact bearing design, levitating a disk shaped rotor. The performance of both systems will be investigated.

ACKNOWLEDGMENT

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REFERENCES

[1] Larsonneur R. Design and Control of Active Magnetic Bearing systems for High Speed Rotation. Ph.D. thesis. Swiss Federal Institute of Technology. Zürich, Switzerland; 1990.
[2] Whitley S. Review of the gas centrifuge until 1962. Part II: Principles of high-speed rotation. Reviews of Modern Physics, Vol 56, No 1 1984;p. 67–97.
[3] Genta G, Delprete C, Rondano D. Gyroscopic Stabilization of Passive Magnetic Levitation. Meccanica 34 1999;p. 411–424.
[4] Lee WeiLung. Aufbau un Regelung homopolarer Magnetlagersysteme. Ph.D. thesis. Technical University of Braunschweig. Baunschweig, Germany; 2002.
[5] Ahrens M, Kucera L, Larsonneur R. Performance of a Magnetically Suspended Flywheel Energy Storage Device. IEEE Transactions on Control Systems Technology 1996;4(5):494–502.
[6] Dow TA, Miller EL, Garrard K. Tool force and deflection compensation for small milling tools. Precision Engineering 28 2004;p. 31–45.