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Improving the sensory capabilities of an electromagnetic guided rotary table for the use in machine tools

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Abstract

Difficult-to-machine materials are still challenging the production industry. Examples are highly complex components of aircraft engines. Alongside innovative processes, also improved machine tool components are helping to comply with the demands of this task.
This paper presents a swivel rotary table with an active magnetic bearing (AMB). Opportunities in machining through employing a workpiece-sided AMB are presented. The inherent capabilities to work as a sensor and actor as well as its stiffness and damping depend on the precise knowledge of the magnets characteristics. Therefore, a methodology to automatically identify the characteristic curve is presented.

Peer-review under responsibility of the NAMRI Scientific Committee

Keywords: active magnetic bearing; AMB; swivel rotary table; machine tool

1. Introduction

Active magnetic bearings (AMB) are a growing technology for coping with high demands in industrial challenges. Due to the fact that magnetic bearings neither have any mechanical friction nor need lubrication, they can be used in high speed and hazardous environments. There are no risks of inflammation. Furthermore, damping and stiffness can be adjusted to the needs. An impressive example for the use of this technology are modern gas turbines made by the company Siemens [1]. Rotors of multiple tones are magnetically guided in 5 degrees of freedom (DOF) during their use. The safe properties reduce the risk of inflaming the gas and raise the turbines efficiency.

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Moreover, AMBs can be used in a variety of applications such as the well-known magnetically levitating train "Transrapid" or in production environments e.g. machine tools. Examples for linear magnetic guides in machine tools are the machine prototypes "Schnelle Maschine" and "Neximo" ([2], [3]). Both guides are implemented in the z-axis. A stand-alone rotary table is presented in [4] and a swivel rotary table for machine tools is presented in [5]. The last mentioned prototype of a swivel rotary table is further presented in this paper.

Nomenclature

δ_A	levitating rotor displacement at the magnets (vector)
δ_S	measured rotor displacement at the sensors (vector)
F_A	magnet force vector
J_A	Jacobian matrix to transform the generalized pose to δ_A
J_S	Jacobian matrix to transform the generalized pose to δ_S
M	mass matrix of levitating rotor
q	generalized pose
Q	generalized forces

2. The magnetic guided swivel rotary table

To machine complex parts with high demands on form and accuracy 5-axis machine tools are used. Beside the three standard linear axis (x, y and z) a rotary motion for turning and a swivel motion for tilting are used. These two motions are implemented into swivel rotary tables. Common swivel rotary tables rely on YRT roller bearings. By interchanging them with an AMB the performance and usability can be extended. Especially, higher rotating speeds and adjustable damping and stiffness are beneficial. Complex vibration prone machining parts, for example aircraft components, can achieve a higher precision due to the controlled damping. In [6] the shifting stability lobes due to the changing eigenfrequency are shown for a milling process while re-contouring a blisk.

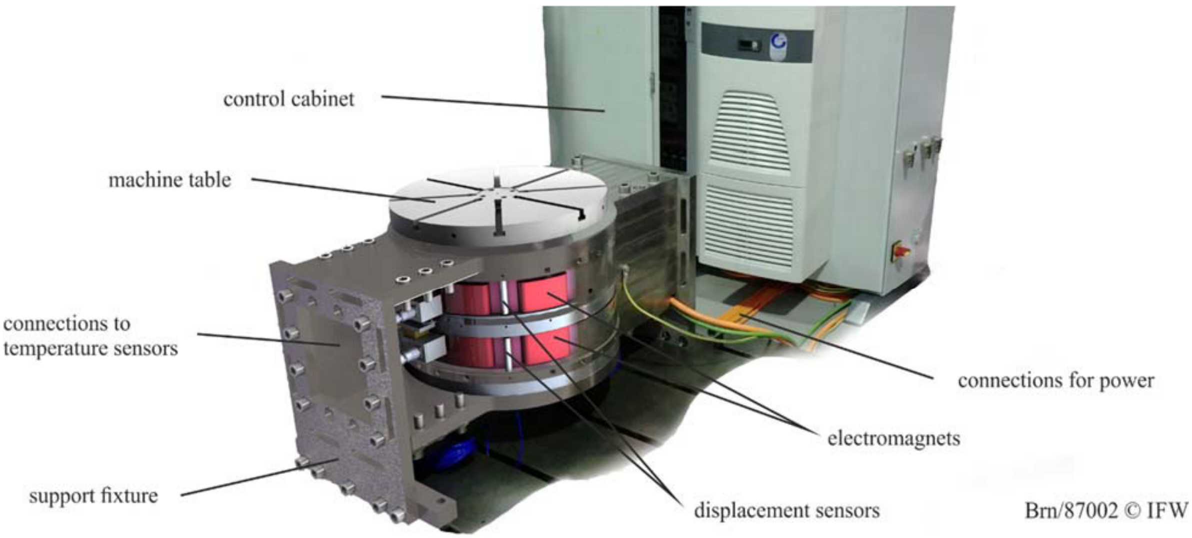

Fig. 1. Picture of the magnetic guided swivel rotary table with CAD overlay.

To design a magnetically guided swivel rotary table a methodology was given in [5]. In Figure 1 a picture with overlaid CAD of the assembled prototype can be seen. The overall proportions are according to a standard machine table with a diameter of 500 mm. The conceived mounting to the swivel motors is on the left and right side of the prototype. Therefore, all connections for sensors and power are lead to the sides. A support fixture is attached to analyze the AMB characteristics outside of the machine tool. In the background of Figure 1 the control cabinet containing the standard Siemens drive technology and sensor evaluation units is shown. Eddy current sensor are used to measure the levitating object's displacement.

Similar to AMBs in gas turbines, 5 DOF have to be controlled. This task is performed by four radial electromagnets and eight axial electromagnets. Maxwell's pulling force formula can be used to roughly calculate the force of an individual magnet. In summary, the electromagnet force $\mathbf{F_{Em}}$ is proportional to the square of the electric current $\mathbf{i}$ and the distance $\boldsymbol{\delta_A}$ to the attracted object.

$$F_{Em} \sim \frac{i^2}{\delta_A^2} \tag{1}$$

By pairing two opposing magnets it is possible to circumvent the nonlinear characteristic. For this purpose, both magnets receive a bias current $\mathbf{I_0}$ besides a control current $\mathbf{I_C}$ which is added to the upper and subtracted from the lower magnet, as seen in Figure 2. Therefore, all 12 magnets are designed to work in pairs and thus each magnet has a counterpart on the opposing side with reversed force direction. Each pair combines the two nonlinear current to force characteristics to one linearized characteristic.

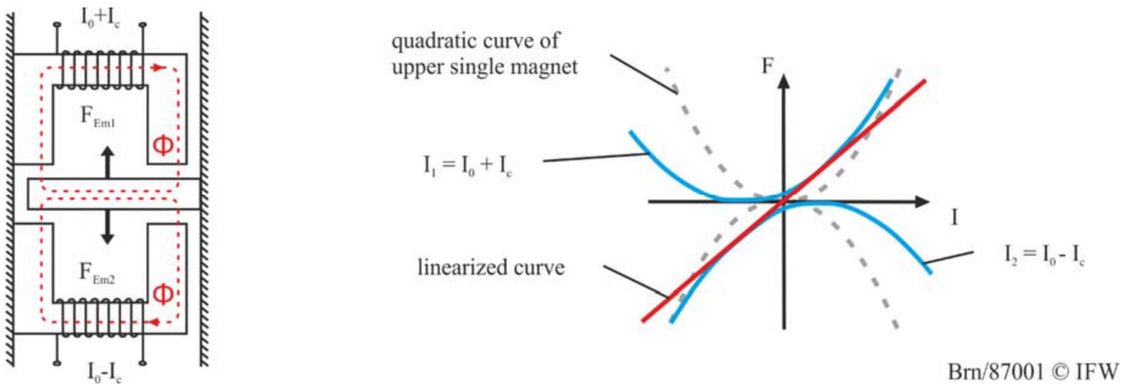

Fig. 2. Opposing magnets and the resulting linearization.

It is possible to reduce the number of needed inverters by half by using standard 3-phase Siemens inverter technology. Details can be seen in [7]. Figure 3 shows the magnet arrangement as well as the levitating (and rotating) disk of the rotor which is connected to the shaft in the center. On top of the shaft the machine table is mounted (not displayed; see Figure 1). The radial magnets are designed as an E-core with a bended magnet surface. In contrast, the axial magnets are designed as a double E-core with two coils and an even magnet surface. A direct drive is attached below the disk to enable rotation (not displayed).

3. Identification of the characteristic magnet curve

For stable levitation in AMBs a closed loop controller is needed. Basic closed loop controllers are for example "PID" or "state space" controllers. Both controllers are linear controllers and therefore need a linearized controlled system at a defined operating point. Hence, the precise knowledge of the magnets nonlinear current-distance-force characteristic curve is key to the performance. The controller can be enhanced by adding a state observer which estimates non measurable variables. Hereby, the control accuracy often can be improved and the additional information can be further used. One example is the force observer. It can be utilized for additional functions to obtain cutting forces, calculate the tool deflection, measure the decreasing workpiece weight and its eccentricity or the metal removal rate.

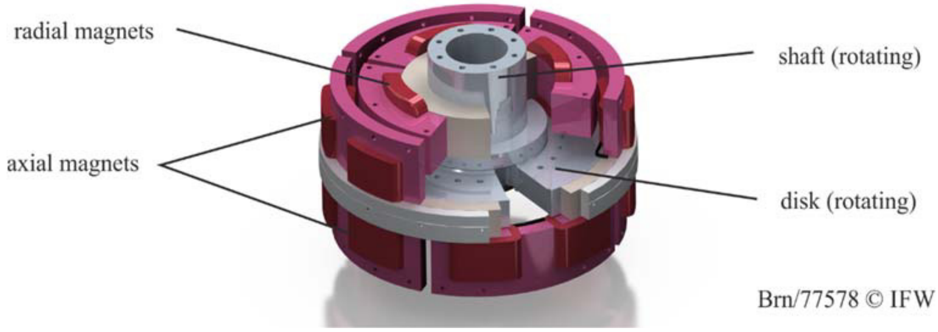

Fig. 3. The magnet arrangement of the swivel rotary table.

A stored current-distance-force characteristic curve is used by the observer to calculate the magnet forces. Obviously, the accuracy of the functions depends on the accuracy of the curve! This curve can be roughly estimated by using equivalent magnetic networks or FEM. Further precision can be gained by measuring the "true" characteristic within a test stand. Although the characteristic may be measured, after mounting the magnet during assembly the precise distance to the levitating object is unknown. This is due to mounting and machining tolerances within the whole assembly.

Thus, a more precise characteristic curve has to be identified after assembly for each magnet pair separately. To circumvent a mechanical test-stand with a force sensor, an automatic identification using an accelerometer is presented in the following.

3.1. Position signal used for identification

The identification algorithm is applied while levitation. Hence, a stable closed loop controller as well as an acceleration sensor are needed. Using a sinusoidal position setpoint instead of a steady position an acceleration proportional to the magnet force can be measured. A variation of the sinus frequency enables different acceleration measurements at the same position. The three dimensional characteristic curve of the magnet (force-current-position) can be gained by repetition at different positions.

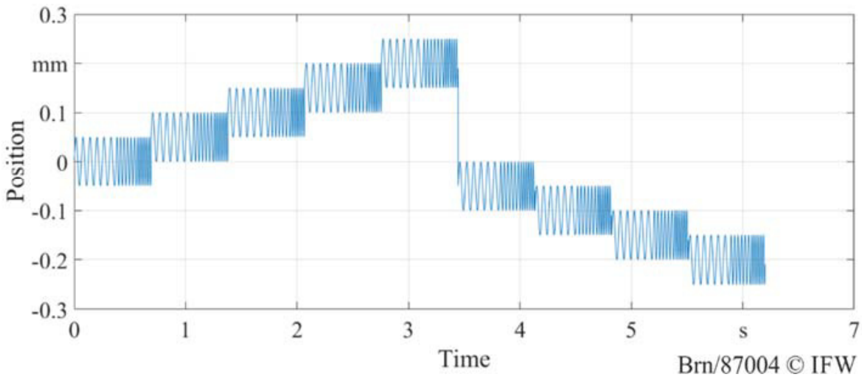

Fig. 4. Sinusoidal position signal used for identification.

The following assumptions are taken as a basis:

- Low sinus frequencies lead to a near stationary characteristic curve
- The position changes are to slow to cause controller instability
- Measured signals can be separated from disturbances using a low pass filter

In the subsequent example the total distance between magnet and levitating rotor is 1 mm. The usable air gap for positioning is reduced to ± 0,3 mm by the safety bearings to prevent damage to the magnets by an emergency stop. Another 50 µm are used as a minimum positioning distance to the safety bearings to avoid contact and controller instability. Figure 4 shows the position signal for an identification applying three frequencies (100 Hz, 200 Hz, 300 Hz) at nine different positions. The radial x-axis was identified.

3.2. Reconstructing the characteristic curve

In Figure 4 above the position signal is shown for one translational motion. The signal has to be repeated for each translational direction of motion. The Jacobian matrix **Js** is used to relate the generalized pose **q** to the displacement sensors **δs**.

$$\delta_s = J_s\, q \tag{2}$$

To obtain the generalized pose from the sensors measurement the Moore-Penrose-Pseudoinverse is applied.

$$q = J_s^+\, \delta_s \tag{3}$$

The generalized pose **q** is related to the rotor displacement at the magnet by the matrix $\mathbf{J_A}$.

$$\delta_A = J_A\, q \tag{4}$$

If the levitating rotor is regarded as a rigid body and generalized coordinates are used, the equation of motion assembles as:

$$Q = M\,\ddot{q} + M\,g \tag{5}$$

Where **Q** are the generalized forces, **M** is the mass matrix, **q** is the pose and **g** is the gravitational vector. The stiffness matrix and the damping matrix become zero because the rotor acts as a single mass. Additionally, disturbance forces due to permanent magnets of the direct drive have not been regarded.

Two magnets are combined as one actor. Therefore, the combined force $\mathbf{F_A}$ can be determined by

$$F_A = J_A^{T+}(M\,\ddot{q} + M\,g) \tag{6}$$

The magnets current can be read from the inverter. The second derivative of **q** is measured by the acceleration sensor. Hereby, the three axes of the magnet's characteristic curve are determined. Obviously, the levitating mass has to be known in advance. This is achieved either by measuring the mass matrix or reading it directly from CAD. The latter is the easiest way but implies correct assigned materials and a precise fabrication.

Figure 5 shows the obtained data points in black using the above identification signal.

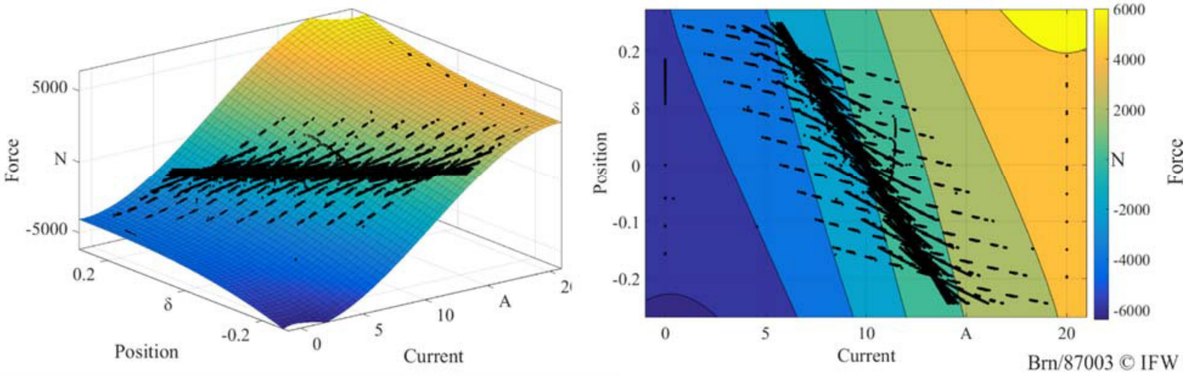

Fig. 5. (a) Obtained data points (black) on fitted characteristic curve; (b) Top view.

It can be seen that the majority of data points accumulate around 10 A. This is plausible considering it is the mean operating current $\mathbf{I_0}$ for stable levitation. By fitting for example a third degree polynomial the characteristic curve is reconstructed (Figure 5). The shown data is determined by a closed loop controlled Matlab/Simulink model of the AMB. In a following study the effects of sensor noise on the data accuracy are examined using the prototype.

4. Summary

Complex machining parts demand innovative machine tools. Electromagnetic guides can enhance the machine tool performance by adaptive damping and stiffness. Further benefits are the friction and lubricant free levitation as well as the inherent capabilities to work as sensor and actor. A prototypical electromagnetic guided swivel rotary table is presented. Details regarding the overall set-up and the magnet arrangement are shown. To achieve precise force measurements using the prototype, the magnet's characteristic curve considering mounting tolerances has to be known. Hence, a method to identify the characteristic curve is presented. It utilizes an acceleration sensor as well as sinusoidal oscillations at different levitation positions. Finally, the identified curve is shown.

Acknowledgements

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