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Analysis of the vibration characteristics of an air bearing spindle to identify and control the magnitude of the radial run-out with an active magnetic bearing

Felix Zell[1], Andreas Lange[1], Benjamin Kirsch[1], Jan C. Aurich[1]

[1]*RPTU Kaiserslautern, Institute for Manufacturing Technology and Production Systems*

felix.zell@rptu.de

Abstract

One way to improve surface quality and tool life in micro machining is to constantly adapt the spindle speed to the current feed rate, i.e., maintaining a constant feed per tooth. Air bearing spindles, which are commonly used in micro machining, are not suitable for this cutting mode. Their passive control behaviour combined with a low damping leads to increased error motions during the required changes in spindle speed. The increased error motions then impair geometric accuracy during milling. An additional active magnetic bearing could provide active control capabilities to reduce radial error motions during speed changes. This could enable the application of constant feed per tooth without the ramifications (e.g., high complexity) of a fully magnetic bearing spindle.
This paper presents a concept to introduce active control capabilities to an air bearing spindle by adding a single active magnetic bearing acting directly on the micro end mill. Hence, a hybrid spindle system with closed-loop feed-forward (radial) run-out control is created without redesigning the air bearing spindle itself.

A detailed explanation of the hybrid spindle concept and the construction of a fully functional prototype will be provided, highlighting the necessary steps for development. Additionally, initial results of the analysis of the vibration characteristics of the air bearing spindle will be presented and discussed. The magnitude of the radial error motions of the analysed air bearing spindle is found to be 1.5 µm at a spindle speed of 95 000 min^{-1} with dominant frequency components up to 6 400 Hz.

Micromachining, Actuator, Magnetic bearing, Control

1. Introduction

As the trend towards the miniaturisation of components continues, the demand for more efficient manufacturing processes to produce micro structured components is also increasing [1]. Micro machining is a promising alternative to other commonly used micro manufacturing processes, like lithography-based manufacturing, with high geometrical freedom, a wide range of machinable materials and short production times [2]. To enable production of those small geometrical features, the milling tool diameter must be small (D < 100 µm) as well. In turn, spindle speed and concentricity requirements for the tool spindle are high to achieve sufficient cutting speeds and geometric accuracy. [3]

The required speeds are generally achieved using either air bearing spindles or spindles with active bearings [1, 4]. Air bearing spindles impress with their simple and robust design, but their passive system behaviour limits their possible applications. Any concentricity deviations that occur only subside slow and lead to geometric deviations in the workpiece. As changing spindle speeds result in additional radial error motions, milling with constant feed per tooth, generally a viable option to improve surface quality in micro machining, is not possible when using air bearing spindles [5].

Spindles with active bearings, such as magnetic bearing spindles, generally allow the rotor position to be controlled and dynamic damping behaviour to be achieved. However, they are rarely used in micro machining due to their complex and expensive design. [6]

Another approach are hybrid spindles in which active bearings enhance the capabilities of air bearing spindles. For example, [7] added a magnetic bearing to an air bearing spindle and was thus able to dampen natural vibrations and increase the maximum spindle speed. However, the focus was on specific resonance frequencies rather than a wide range of spindle speeds. The approach pursued here for controlling the rotor position with the specific application goal of micro-machining has already been described by [8], but with the focus set on theoretical feasibility.

A detailed explanation of the hybrid spindle concept and the construction of a fully functional prototype will be provided, highlighting the necessary steps for development. Additionally, initial results of the analysis of the vibration characteristics of the air bearing spindle will be presented and discussed.

2. Hybrid spindle concept

The hybrid spindle concept aims to enhance the geometric precision of micro milling operations by adding a single magnetic actuator to an air-bearing spindle. Its purpose is to control the rotor position during operation, particularly during speed changes, to allow for constant feed per tooth milling operations with improved geometric accuracy.

The combination of the two components and the division of tasks between the air-bearing spindle, which ensures the necessary load capacity, rigidity and emergency running properties, and the magnetic actuator, which only has to compensate for the radial error motions, minimises the complexity of the system.

The procedure for developing the hybrid spindle is as follows.

First, the spindle has to be characterised to determine the design requirements for the control loop dynamics and the magnetic actuator, as well as the forces of the magnetic actuator. The main objective is to identify the maximum radial error motions and the highest relevant vibration frequency. While the amplitude of the radial error motions will set design requirements for the magnetic actuator, the maximum disturbance frequency will also affect the control loop design. This is done by integrating a displacement measurement system (section 3.1) and measuring the radial run-out over the full speed range of the air bearing spindle. The model-based design of the control loop and the magnetic actuator is based on these results. Due to the high complexity, the non-linear relationships in the calculation of the magnetic bearing forces and the mutual interactions between the controller and the magnetic force development, a model-based approach is chosen here. To account for non-linear relationships in the magnetic bearing forces calculation (e.g., eddy current losses, non-linear material behaviour, fringing effects) a numerical magnetostatic simulation will be utilised [6]. The results of the numerical simulation are implemented in the control loop model in form of 4D look-up tables to reduce the computation time needed for each time step and hence the overall simulation time. Figure 1 illustrates the difference between the open-loop control of an air bearing spindle and the closed-loop control of the proposed hybrid spindle. The displacement measurement system creates the feedback path to close the control-loop in conjunction with the PID-controller and the magnetic actuator. For the optimisation of the control parameters model-based automatic tuning methods within the control system environment (MATLAB Simulink[1]) will be used. To improve response time and control accuracy of the control loop, a feed-forward approach will be investigated (see figure 1 c)). The rotor speed is used to predict the spindle error motion response. For the prediction model, information about recurring periodic error motions (also known as synchronous error motions) is essential. The spindle characterisation therefore focuses on these synchronous error motions. After the successful design and optimisation of the magnetic actuator and control parameters over several iteration loops, a functional model of the magnetic actuator is produced and integrated into the air-bearing spindle. Finally, the hybrid spindle system is validated via milling tests. Comparing cutting forces, tool wear and processing results of milling operations with and without activated closed-loop control will allow for an assessment of the influence of the hybrid spindle system.

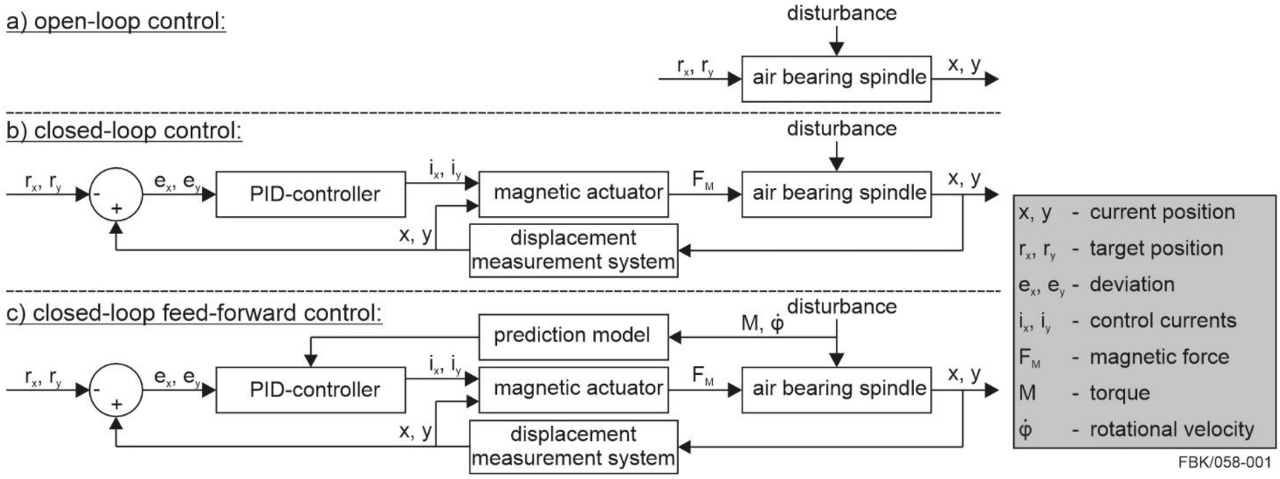

Figure 1. Schematic control loop configurations: a) open-loop air bearing spindle, b) closed-loop hybrid-spindle, c) closed-loop feed-forward control hybrid spindle

3. Methods

As outlined, the first step in developing the hybrid spindle is to characterize the radial error motion behaviour of the air bearing spindle (ABL[1] 160 MM). Therefore, a series of test runs at differing spindle speeds is performed. The displacement of the spindle rotor, i.e., a 3 mm diameter artefact with high concentricity, is measured during each test run individually. Starting at the minimum spindle speed (25 000 min^{-1}), the spindle speed is increased by increments of 5 000 min^{-1} until 120 000 min^{-1} is reached. See section 3.1 for details on the measurement system.

The artefact is assumed to be perfectly round and centred along the axis of rotation. Thus, the measured radial run-out of the artefact surface is equated to the radial error motion of the spindle axis of rotation. To analyse the measurements in detail, the spindle error motion is broken down into its individual components using a frequency classification method. This enables the identification and characterisation of regularly occurring vibration components. Detailed information on the frequency classification method is given in section 3.2.

3.1. Measurement system for radial error motions

A capacitive displacement measurement system was used to measure the radial error motions for its high resolution and bandwidth, small measurement spots and it being not affected by adjacent magnetic fields. Two sensors measured the rotor displacement along the x and y axis respectively (see figure 2). An additional third sensor was used to provide accurate instantaneous spindle speeds and angular position information, as there is no encoder built into the air bearing spindle itself. By measuring against a triangular section at the end of the artefact and evaluating the peaks in the sensor signal, it was possible to reliably assign the x and y displacements to their individual revolutions. The three analogue sensor signals were simultaneously digitised by a DAQ at a sampling rate of 50 000 samples/s and recorded via a MATLAB[1] script. Refer to table 1 for additional data on the sensor system and the DAQ.

Table 1. Specifications of the measurement system

Micro-Epsilon[1] capaNCDT 6222/DL 6222	
Measuring range	0.2 mm
Resolution @20 kHz	0.05 % FSO
Bandwidth	20 kHz (-3dB)
Analogue output	-5 V – +5 V
Axial position x-sensor / y sensor	13.5 mm / 8 mm
National Instruments[1] NI-USB DAQ 6210	
Nominal range - Full scale	-1 V – +1 V
ADC resolution	16 bit
Absolute accuracy at full scale	310 µV
Sensitivity	10.4 µV
Sample rate	50 000 samples/s
Sample time	3 s

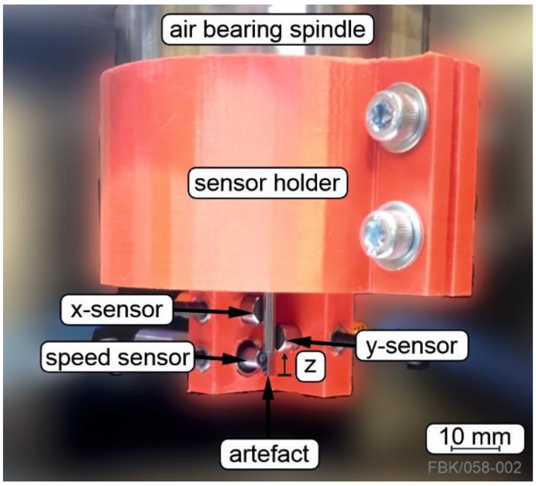

Figure 2. Placement of the capacitive sensors for x-, y-run-out and speed measurements

3.2. Spindle metrology

The total spindle error motion can be decomposed based on its frequency components i.e., synchronous and asynchronous [9]. It is useful to normalise the frequency contents using the rotational frequency, also known as fundamental frequency. As a result, the frequency spectrum is given in units of undulations per revolution. Multiples of the fundamental frequency are referred to as order.

There are two ways of calculating the different frequency components, either in the time or frequency domain. In the time-based domain, the synchronous error motion is calculated by averaging the total spindle error motion over all sampled revolutions at each individual angular rotor position. The asynchronous error motion is calculated as difference between total and synchronous error motion. In the frequency domain synchronous and asynchronous error motions are separated by first transforming the raw data with a fast Fourier transformation (FFT), then separating integer and non-integer Fourier components, respectively, and finally retransforming the frequency information with the inverse FFT. The Fundamental error motion can be easily identified as the once per revolution component.

The synchronous and asynchronous error motions describe periodic error motions that occur at integer and non-integer multiples of the fundamental frequency respectively.

Apart from the frequency classification the spindle error motions can also be separated with respect to the sensitive direction, which describes the direction perpendicular to the workpiece/artefact surface at the point of machining/measurement [9]. Based on whether the point of machining/measurement is fixed and the workpiece is rotating or vice versa, fixed sensitive and rotating sensitive directions can be distinguished respectively. The spindle error motion is measured in the fixed sensitive direction, but in milling operations with a single point tool, as is the case in micro milling, the errors affect the workpiece according to the rotating sensitive direction. Therefore, the spindle error motion measured in the fixed sensitive direction (*X* and *Y*) has to be converted to the rotating sensitive direction error motion *R* according to equation 1 as a function of the spindle rotation angle θ.[9]

$$R = X \cdot \cos(\theta) + Y \cdot \sin(\theta) \quad (1)$$

Finally, the spindle error motion can also be classified based on directional information. In case of the hybrid spindle control, only the radial error motion at the tool tip is relevant. The radial error motion (R_{new}) at any location (a_{new}) along the rotation axis can be computed according to equation 2 once the pure radial error motion (R) at a given axial location (a) and the tilt error motion (α) are known [9].

$$R_{new} = R + \alpha \cdot (a_{new} - a) \quad (2)$$

To compute the tilt error motion with the chosen measurement setup, two measurements of the radial error (R_1 and R_2) at a known axial spacing l are required [9].

$$\alpha = (R_2 - R_1)/l \quad (3)$$

4. Results

The fundamental and residual synchronous error motion values are shown in figure 3 a) and b) respectively.

Generally, the fundamental error motion values rise moderately with increasing spindle speed up to 80 000 min^{-1}. Beyond this point, the fundamental error motion values in the fixed x (fixed y) sensitive direction drop significantly from 1.7 µm (2.0 µm) to 0.4 µm (0.75 µm). This may be due to a shift in the axis of rotation of the spindle, caused by the rising imbalance forces, which are proportional to the square of the rotational speed.

The residual synchronous error motions are almost constant over a wide span of spindle speeds with one exception. At a spindle speed of 95 000 min^{-1} the maximum error occurs with values as high as 1.5 µm, probably due to resonance with a natural oscillation frequency of the spindle. Increasing spindle speeds further led to a rise in the fixed sensitive direction synchronous error in the y-direction, but not in the x-direction. This implies that either some components of the spindle may exhibit structural asymmetry or there is additional tilt error motion at play.

To identify the shape and highest relevant orders of the radial error motion at this spindle speed, the polar plot and the frequency spectra of the residual synchronous error motion are plotted in figure 4. Although the polar plots of the fixed x- and y-sensitive direction reveal a three lobed shape of the error motion, the rotating sensitive direction, which correlates to the resulting form errors of a milling operation with this spindle, display a predominantly two and four lobed shape. Hence, the control loop and the magnetic actuator must be designed to compensate spindle error motions of 1.5 µm occurring at frequencies of up to 6 400 Hz, because of dominant error motion components at four times the fundamental frequency of approximately 1 600 Hz.

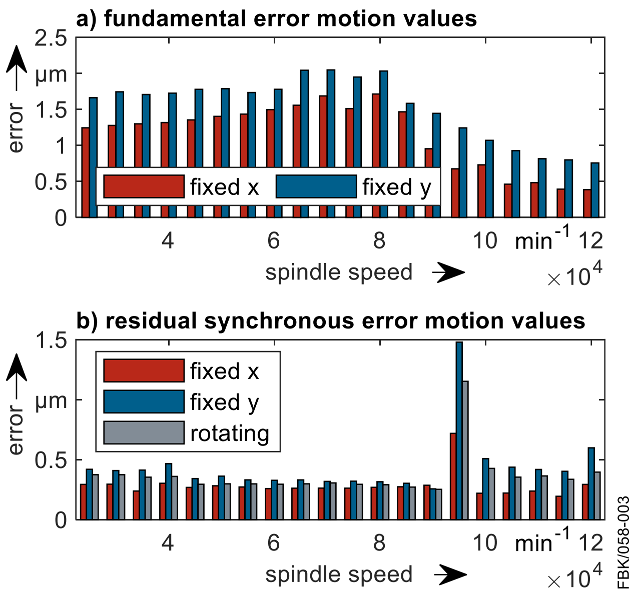

Figure 3. a) fundamental and b) residual synchronous error motion values for the entire spindle speed range

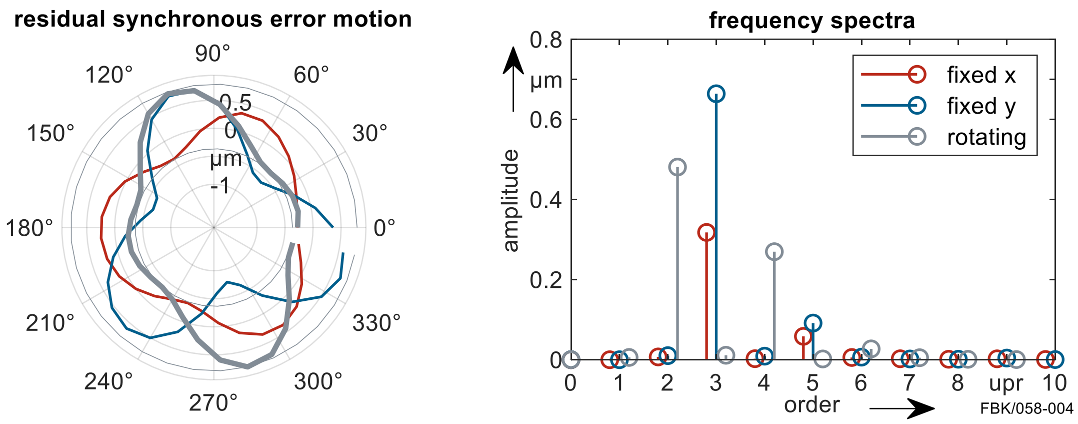

Figure 4. Polar plots and frequency spectra of the residual synchronous error motions at a spindle speed of 95 000 min^{-1}

5. Conclusion and outlook

In this paper, we introduced a concept for controlling the radial error motions of air bearing spindles in micro machining with an additional active magnetic bearing. Enabling speed changes required for micro milling with constant feed per tooth without compromising manufacturing accuracy due to additional radial error motions is the main objective of this hybrid spindle concept under development.

Essentially, there are four major steps involved in the development of the hybrid spindle according to the proposed concept. 1. Characterisation of the air bearing spindle i.e., measuring and analysing the spindle error motion. 2. Model-based design of the magnetic actuator and the control loop. 3. Design and integration of the magnetic actuator. 4. Validation of the hybrid spindle performance through milling tests.

The first step was described in detail. A capacitive displacement sensor system alongside a precision ground artefact was utilised to measure the radial error motions near the tool tip in x- and y-direction simultaneously. Error motion data was gathered for the entire spindle speed range in 5 000 min^{-1} increments. For the in-depth analysis of this raw displacement data a frequency classification method was used.

The fundamental error motion values slowly rose with increasing spindle speed to a maximum of 2.0 µm for the y-direction at 80 000 min^{-1}. Increasing spindle speed further led to a significant drop in the fundamental error motion values. The residual synchronous error motion values showed a sharp exception at a spindle speed of 95 000 min^{-1} with a three to fourfold amplification of the fixed sensitive direction value to approximately 1.15 µm. A detailed investigation of the polar plot and the frequency spectrum of the residual synchronous error motion in the rotating sensitive direction at 95 000 min^{-1} revealed the predominant influence of the second and fourth harmonic order elements.

The following conclusions can be drawn from these results:

- Radial error motions of the air bearing spindle can be measured with the implemented capacitive displacement measurement system. By attaching the probes to the spindle body, the system is also suitable to measure the radial error motions and provide the feedback path for the closed control-loop during milling operations.
- Differences between the measurements in x- and y-direction suggest either the presence of structural asymmetries or an influence of tilt error motion. This needs further investigations in future works.
- As the exception in the residual synchronous error motion values may be due to resonance with a natural oscillation frequency of the spindle, smaller speed increments are required in this range. In order to find the exact resonance frequency, a more detailed characterisation of the spindle will be carried out in the range of 90 000 min^{-1} to 100 000 min^{-1}.
- The magnetic actuator and the control loop are required to at least compensate for a radial rotor error motions of up to 1.5 µm at a frequency of approximately 6 400 Hz (i.e., four times the rotational frequency of 1 600 Hz).

With these initial results for the vibration characteristics of the air bearing spindle and the derived requirements for the control loop and the magnetic actuator, the second step of the hybrid spindle concept will be conducted next. Any findings of the additional investigations into structural asymmetry of the spindle, rotor tilt error motion and the exact resonance frequency will also be considered in the model-based design of the magnetic actuator and the control loop.

Acknowledgement

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[1]Naming of specific manufacturers is done solely for the sake of completeness and does not necessarily imply an endorsement of the named companies nor that the products are necessarily the best for the purpose.

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