Modelling of an adaptive main spindle equipped with an electro-magnetic damping actuator

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Kurzfassung

Eine Frässpindel wurde um einen aktiven Dämpfer in Form eines Magnetlagers erweitert, um damit ihr dynamisches Verhalten positiv zu beeinflussen. Es wird gezeigt, wie SimulationX zur Modellierung des Gesamtsystems aus Spindel, Magnetlager und Fräsprozess genutzt wurde. Die gewonnenen Modelle dienen dazu, eine geeignete Dämpfungsregelung in MATLAB zu entwerfen und mit LabVIEW auf eine FPGA-basierte Echtzeit-Plattform zu implementieren.

Abstract

A milling spindle was equipped with a damping actuator. This actuator works as an active magnetic bearing (AMB) to improve the dynamic behaviour of the spindle. It is shown in this paper how SimulationX has been used to model the overall system with the spindle, the AMB and the milling process. The achieved models are aimed to design the damping control within MATLAB and to implement it into a FPGA-based realtime platform using LabVIEW.

Introduction

In modern milling machines, motor spindles are frequently used to drive the tool. Normally, these spindles are built up of an electric motor, whose rotor shaft is supported by roller or journal bearings. On one shaft side, a manual or automatic clamping system holds the tool to be driven. A motor spindle is a complex mechatronic system, which can get into vibrations by process or imbalance forces. These unwanted vibrations may decrease the machining quality and, in worst case, cause spindle damage. To increase the dynamic behavior of the spindle, the radial damping of the spindle shaft can be usefull [1].

Figure 1 shows the sectional view of the examined adaptive main spindle, which is comprised of the standard components and an additional radial active magnetic bearing (AMB) in its housing. This AMB will be controlled to act as an damping actuator to decrease unwanted rotor shaft bending vibrations.

Comprehensive knowledge of the dynamic spindle behavior, the AMB characteristics and the process loads is essential to design the damping control. In the following, SimulationX is used to model this all as the basis for the subsequent MATLAB control design.

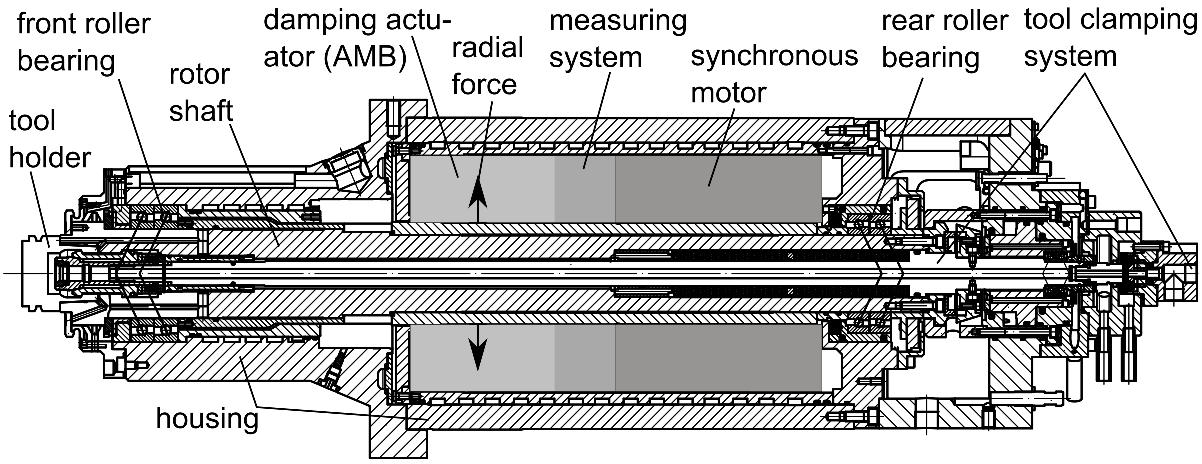

Figure 1: Sectional view of the adaptive main spindle with the electro-magnetic damping actuator

Modelling of the adaptive main spindle

Figure 2 illustrates the active principle of the adaptive main spindle.

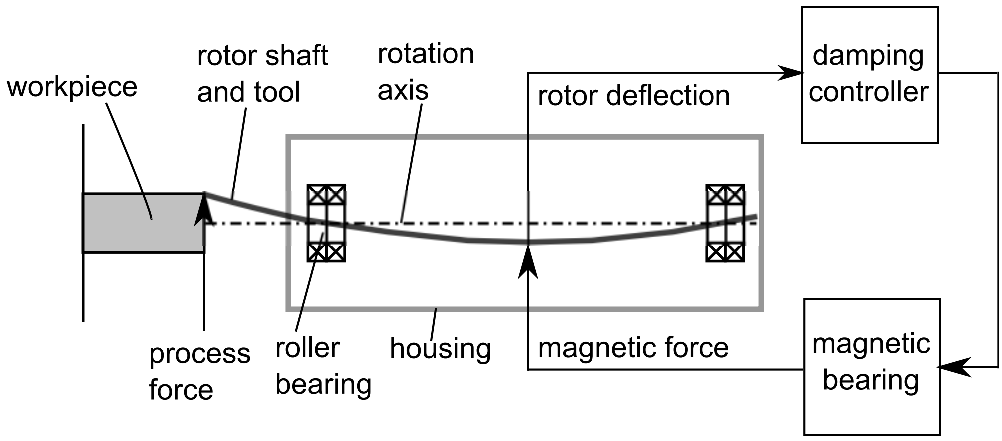

Figure 2: Active principle of the adaptive main spindle

It is expected that the process force and residual imbalances cause a small rotor shaft displacement and bending. A submicron optical displacement sensor captures the resulting rotor deflection. The damping controller computes an optimal correcting magnetic force, which is generated by the AMB to the spindle shaft. In the following, the rotor, AMB and milling modelling will be presented briefly.

Rotor dynamics The rotating parts of the adaptive main spindle are the rotor shaft, the motor and AMB armatures, the ball bearing inner rings, the tool clamping system and the tool. It is neither reasonable nor feasible to describe this multitude of parts, which are force and shrink fittet, completely quantitative. Instead, the rotor is described as one elastic continuum in elastic bearings. In fact, the numerous areas of contact increase the internal damping, which is taken into account by a model parameter in summary. Figure 3 shows on the left the rotor contour with roller bearings and deflection and load points.

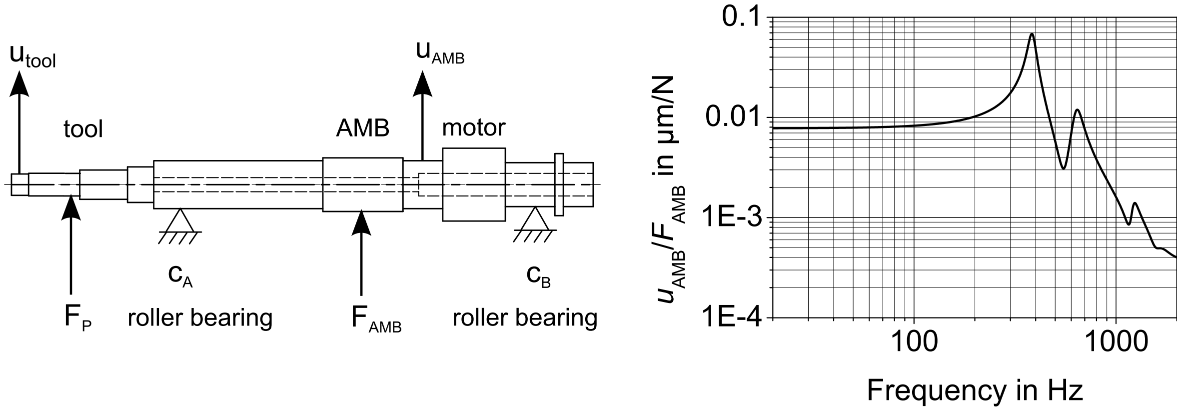

Figure 3: Simplified rotor geometry with the roller bearing stiffness c_A and c_B, the deflection measuring points u_{tool} and u_{AMB} and the process and AMB forces F_P and F_{AMB} (left), calculated frequency response (right)

The developed rotor model in SimulationX uses eight elastic beam elements from the multi body simulation (MBS) toolbox, which are based on Timoshenko's beam theory. Figure 3 shows on the right-hand side an example of the frequency response from AMB force to the rotor shaft deflection with three eigenfrequencies in the range to 2 kHz.

AMB modeling Figure 4 shows on the left schematical the AMB design for the F_x force direction.

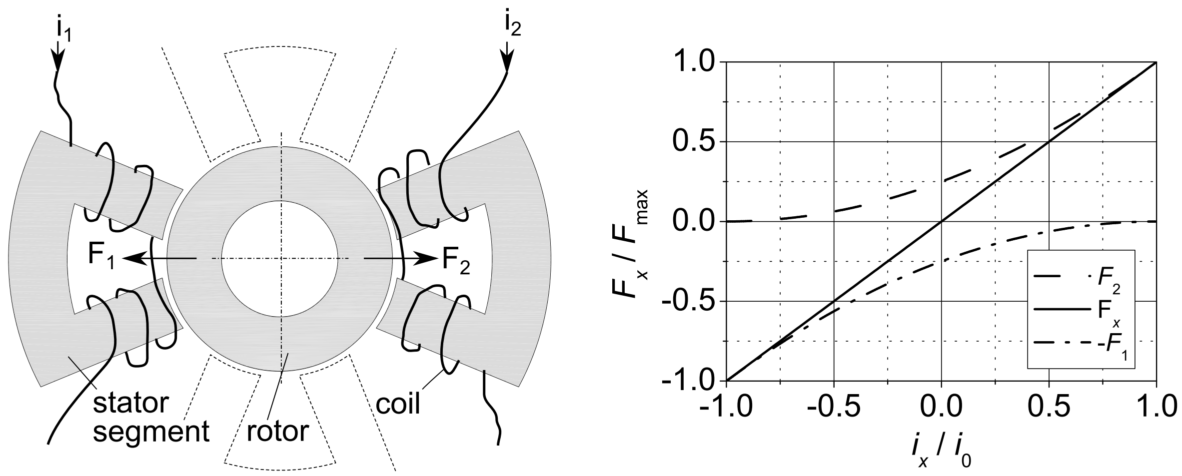

Figure 4: AMB active principle (left) and characteristics in case of bias current premagnetization (right)

Two electrical horseshoe magnets are arranged oppositely in a stator. The coil currents cause a magnetic field, which generates pulling Maxwell forces in the air gap between AMB stator and armature. Most of the AMBs of this kind use a bias current i_0 to get a linear force-current characteristics. With $i_1 = i_0 + i_x$ and $i_2 = i_0 - i_x$

you get $F_x = F_{max} \cdot i_x / i_0$ [2]. Figure 4 shows on the right-hand side an example simulation result. The *y*-axis behaves in the same way in vertical direction.

The AMB behavior was described within the SimulationX type designer directly in the Modelica language. Different model complexities were used for AMB and control design.

Milling process The milling process is characterized by the process force and torqe between workpiece and tool. Figure 5 shows on the left the dynamic model of milling with two degrees of freedom [3].

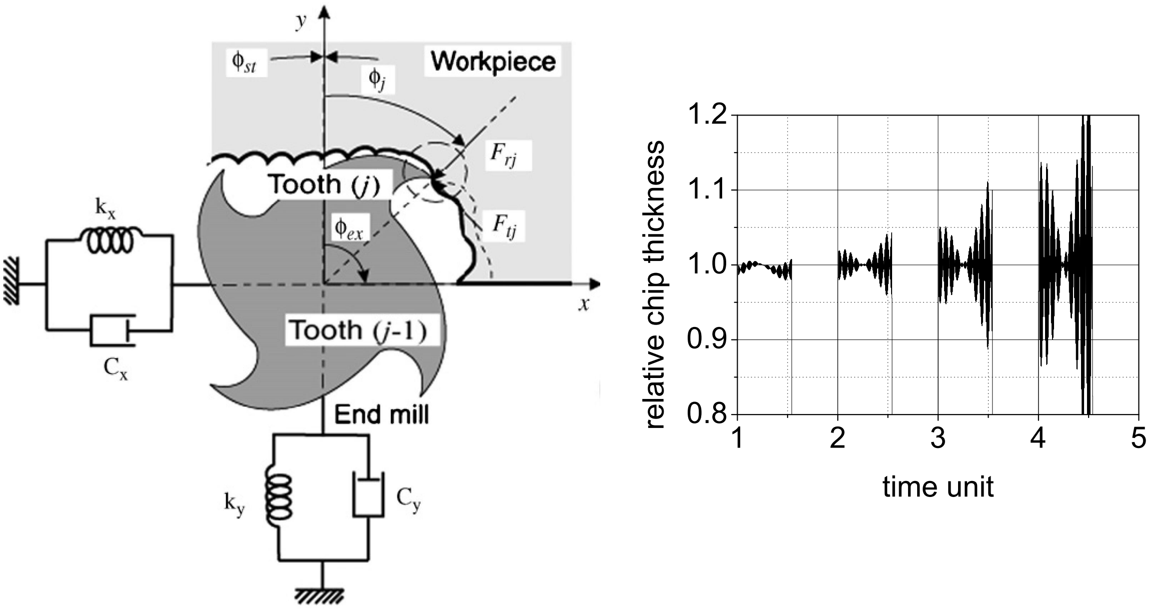

Figure 5: Dynamic model of milling with two degrees of freedom [3] (left), regenerative chattering (right)

A linear, two dimensional milling force model according [3] was implemented to SimulationX via the Modelica description. It simulates the process forces in the interaction between workpiece and tool and takes into account the major tool dimensions and cutting conditions.The process force is proportional to a dynamic chip thickness, which is varying due to spindle, workpiece and tool vibrations. Figure 5 shows on the rigth example results for the dynamic chip thickness. The tool gets into vibrations and the process gets instabilin this case!

Damping control

The damping control aims, in general, to damp the first two eigenfrequencies of the rotorshaft cp. Figure 3 by the AMB. For the reliably and productive spindle usage, a robust controller is needed according to the technological scope of machining, e. g.:

- maximum static stiffness at the tool centre point for maximum accuracy
- maximum dynamic stiffness in case of known excitation frequencies
- avoiding chattering for maximum productivity
- maximum damping for the machining of compliant workpieces

Control design in MATLAB The control design is performed in MATLAB. Therefore, the SimulationX plant model is transfered to MATLAB in state-space form. Model inputs are the AMB currents i_x and i_y; model outputs are the measured rotor shaft deflections x_{AMB} and y_{AMB} near to the AMB. The plant model can be assumed to be linear for one constant rotor speed, because there are only small rotor deflections compared to the AMB air gap.

Figure 6 shows on the left side the closed control loop with a LQG optimal controller. On the right side, an example step response for the damped and undamped system is given.

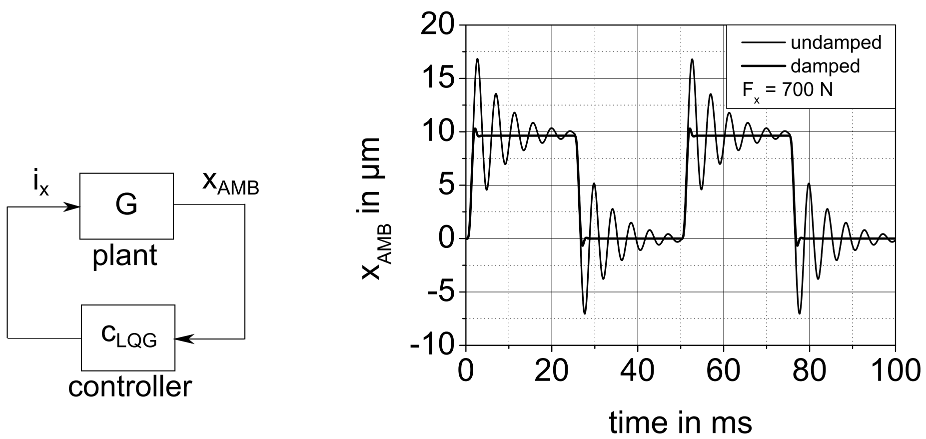

Figure 6: Optimal feedback control (left), rotor deflection step response of the controlled and uncontrolled system (right)

Overall system model The developed overall system cp. Figure 7 couples the

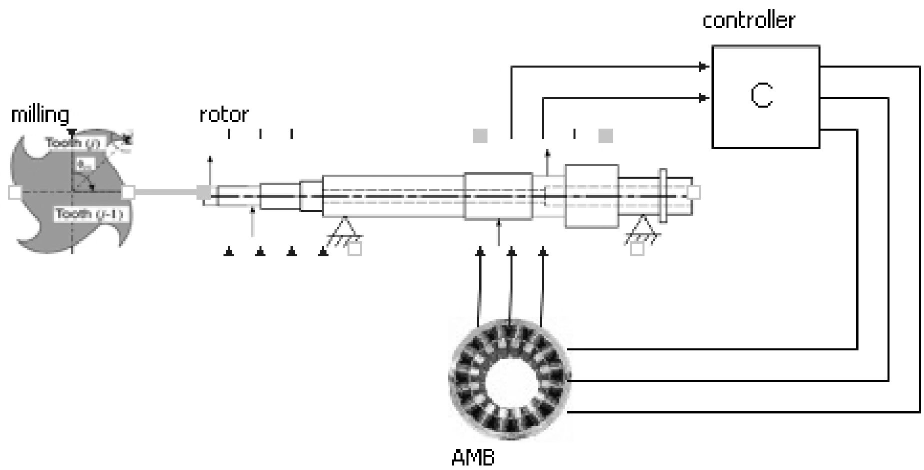

Figure 7: Adaptive main spindle system model

described models of the rotor, the AMB, the milling process and the controller. MBS and signal connectors can be used alternatively. Several open MBS connectors allow it to integrate the adaptive main spindle into a virtual machine tool. So, machine and workpiece compliancies can be taken into account easily. The controller from MATLAB generates the AMB set currents and can be tested within SimulationX. The overall model can be expanded easily, e. g. by more detailed inverter models for the AMB or a speed depended bearing stiffness.

Conclusion

This work gives a short overview of the modelling of an adaptive main spindle equipped with an electro-magnetic damping actuator. The modeled system consists of the spindle rotor, an active magnetic bearing, the milling process and a damping controller. Due to its multi-domain potential and its Modelica support, SimulationX is practical to handle this problem in a very demonstrative and flexible way.

The spindle uses a controller, which was designed in MATLAB, tested in SimulationX and implemented in LabVIEW. This did work very well but, maybe, with less tools it could be easier in some cases.

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References

[1] P. E. Allaire, M. E. F. Kasarda, R. R. Humphris, and R. D. Lewis: Vibration Reduction in a Multimass Flexible Rotor Using a Midspan Magnetic Damper. In *Proceedings of the 1st International Symposium on Magnetic Bearings*, pages 149–158. ETH Zürich, 1988.

[2] Alfons Traxler: *Eigenschaften und Auslegung von berührungsfreien elektromagnetischen Lagern.* Dissertation, Eidgenössische Technische Hochschule Zürich, 1985.

[3] Y. Altintas and E. Budak. Analytical Prediction of Stability Lobes in Milling. *CIRP Annals - Manufacturing Technology*, 44(1):357–362, 1995.