Nonlinear Control Design for the Magnetic Guidance of a Multi-Coordinate Positioning System

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Abstract — The multi-coordinate positioning system presented in this paper uses three identical electromagnets to guide a moving platform magnetically. Flux and force characteristics of the guidance actuators were computed by FEM simulations. For a single guidance electromagnet a dynamic model including the nonlinearities caused by magnetic saturation was developed together with an appropriate cascaded position control structure involving the Ljapunov function concept. Applicability was successfully proven by means of a hardware-in-the-loop test rig. Recent measurement results are shown.

I. INTRODUCTION

By combining electrodynamic planar actuators with magnetic guidance elements, reliable high-precision vacuum-compatible integrated multi-coordinate positioning systems can be designed, which are required for many modern applications, e.g., for the manufacture of integrated circuits. Compared to the well-known multi-coordinate drives with aerostatic bearings, no disturbance forces due to air supply pipes to the moving platform, no wear of these supply pipes as well as no guidance oscillations through variations of the supply pressure can occur in a magnetically guided system. Furthermore, active magnetic guidances allow an extended functionality: By means of a suitable control system as well as an appropriate configuration of the guidance actuators movements in six degrees of freedom with a single movable element can be realized. An operation of the drive in vacuum and in clean rooms is possible.

The goal of our research is to enable the utilization of magnetically guided and propelled multi-coordinate direct drives for positioning tasks in the nanometer range. Therefore, some configurations of such systems with attractive and repulsive guidance forces have been theoretically and practically investigated [1].

II. MULTI-COORDINATE POSITIONING SYSTEM

The multi-coordinate positioning system built up at the laboratory is shown in Fig. 1. It offers a 30 x 30 x 0.2 mm³ range of motion. Planar propulsion forces are generated according to the electrodynamic principle (Lorentz forces). Therefore the permanent magnets are fixed at the underside of the moving platform and flat propulsion coils are placed on the stator below the platform. The ferromagnetic platform is levitated by attraction forces of three electromagnets placed on the stator. A stable levitation, i.e., constant air gaps, can only be achieved with an appropriate control. Vertical position is measured by three eddy-current sensors placed in stator mounting holes below the moving platform. Horizontal position in the \( xy \)-plane is detected using an incremental optical \( xy \varphi z \)-measuring system with an interpolated resolution of 40 nm in \( x \)- and \( y \)-direction [2].

Fig. 1. Multi-coordinate positioning system built up at the laboratory

III. MODELING OF THE GUIDANCE ELECTROMAGNETS

The following system of differential equations describes the dynamic behavior of a single electromagnet [3]. With \( \delta = z_a - z \) follows:

\[
U = iR + \frac{d\psi(\delta, i)}{dt}, \quad (1)
\]

\[
-m\ddot{\delta} = F_w(\delta, i) + F_d, \quad (2)
\]

\[
F_w(\delta, i) = \frac{\partial}{\partial \delta} \int \psi(\delta, i) \, di, \quad (3)
\]

where \( U = U(t) \) denotes voltage, \( i = i(t) \) - electric current, \( R \) - coil resistance, \( \psi \) - magnetic flux linkage, \( z = z(t) \) - armature position, \( \delta = \delta(t) \) - air gap, \( m \) - mass, \( F_w \) - magnetic force, \( F_d \) - disturbance force.

For an adequate modeling the magnetic subsystem has to be described by nonlinear characteristics, considering the magnetic saturation of the guidance electromagnets. Static force and flux characteristics shown in Fig. 2 were calculated by FEM simulations using MAXWELL® and implemented as look-up tables in a Simulink® model (Fig. 3) to study the dynamic behavior of a single electromagnet [4].
IV. NONLINEAR CONTROL STRUCTURE

A. Control Structure

To stabilize the vertical position of the moving platform of the multi-coordinate positioning system, the air gap at each of the three electromagnets has to be controlled with respect to the feedback position sensor signal. Because of the nonlinear characteristics of an electromagnet simple control structures mostly fail, if a high dynamic stiffness is required for the guidance system. Thus the cascaded controller shown in Fig. 4 was developed [5].

This control structure is applied for each of the three electromagnets. The subordinate (inner) control loop refers to the electrical subsystem of the electromagnet and controls the current in the coils. Therefore a control Ljapunov function was derived, which is suitable for controlling the electrical subsystem taking into account its nonlinear character. The cascade’s superordinate (outer) loop controls the air gap of the electromagnet. The position controller’s output value equals the reference value for the current controller. The force of the electromagnet exerted on the moving platform depends on air gap \( \delta \) and electric current \( i \).

B. Computation of the control Ljapunov function for the current controller

The direct Ljapunov method provides sufficient information about idle state stability by means of a generalized energy function. An appropriate control law is proposed based on the construction of a control Ljapunov function (CLF). That way it is possible to design a closed control loop with the desired stability behavior.

The goal is to find a control law \( \alpha(s) \) for the control variable \( u \) of a time invariant system
\[
s = f(s,u), \quad s - state,
\]

such that the idle state \( s = 0 \) of the closed control loop
\[
s = f(s,\alpha(s))
\]
becomes globally asymptotically stable. For scalar systems
\[
V(s) = \frac{1}{2}s^2
\]
is always a possible Ljapunov function [6]. The control law \( \alpha(s) \) has to ensure, that for all \( s \in \mathbb{R} \)
\[
\frac{\partial V}{\partial s}(s) : f(s,\alpha(s)) \leq 0.
\]

For systems
\[
s = f(s)+g(s)\cdot \alpha(s), \quad f(0) = 0
\]
the CLF inequality becomes
\[
\frac{\partial V}{\partial s}(s) + \frac{\partial V}{\partial \alpha}(s) \cdot g(s) \cdot \alpha(s) \leq 0.
\]
The electric subsystem of the electromagnet is described with
\[
U = iR + \frac{d\psi(i,\delta)}{dt} = iR + \frac{1}{L} \frac{di}{dt} + \frac{1}{L} \frac{d\psi}{dt} \frac{d\delta}{dt}.
\]
The current controller has to provide the actual current \( i \) according to the reference current \( i_{ref} \). To fulfill the condition \( f(0) = 0 \), the control deviation \( \delta = i_{ref} - i \) is defined. With this state transformation the differential equation turns to
\[
\frac{d}{dt} \Delta i = \frac{R}{L} i_{ref} - \frac{1}{L} \frac{d\psi}{dt} \frac{d\delta}{dt} - \frac{1}{L} u.
\]

For this scalar system the Ljapunov function is \( V = \frac{1}{2} \Delta i^2 \).
The CLF inequality is therefore
\[ \Delta \left( \frac{R}{L} + \frac{d}{dt} \frac{d}{dt} + \frac{1}{L} \frac{d}{dt} \frac{d}{dt} \right) + \Delta \left( -\frac{1}{L} \right) u \leq 0. \] (11)

With the control law
\[ u = iR + L \frac{d}{dt} \frac{d}{dt} + \frac{d}{dt} \frac{d}{dt} \frac{d}{dt} \frac{d}{dt} + k \cdot L \cdot \Delta i \] (12)
the inequality \( \Delta^2 \cdot k \geq 0 \) is fulfilled. By using the nonlinear flux characteristic of the electromagnet shown in Fig. 2, \( L = L_i(i, \delta) = \frac{d}{dt} \frac{d}{dt} (i, \delta) \) and \( \frac{d}{dt} \frac{d}{dt} = \frac{d}{dt} \frac{d}{dt} (i, \delta) \) can be calculated, which both appear in the control law (Eq. 12).

C. Control of the air gap

A PI-controller coupled with a state controller is used in the outer loop of the cascade (Eq. 4) to control the air gap of the electromagnet. For the state part of the controller the velocity and acceleration values in \( z \)-direction are needed, which are calculated by differentiating the position signal once and twice, respectively. The following function is used to compute the controller’s set value:
\[ U(s) = k_p \cdot \left( W(s) - s Z(s) \right) + k_i \cdot \frac{W(s) - s Z(s)}{s} + \]
\[ + k_d \cdot s Z(s) + k_{d2} \cdot s^2 Z(s), \] (13)
where \( U(s) \) denotes the set value of the controller, \( W(s) \) - desired value, \( Z(s) \) - actual (measured) value.

Proportional and integral part with the weighting factors \( k_p \) and \( k_i \) are both calculated using the control deviation. Velocity and acceleration, multiplied by the weighting factors \( k_d \) and \( k_{d2} \), form the state part of the controller. The controller calculates the reference current, which is necessary for the adjustment of a certain air gap. The current control itself is performed by the control law found by the Ljapunov method (Eq. 12). To compensate the nonlinear dependency of the magnetic force on current and air gap, the inverse relation \( i(F, \delta) \) can be calculated from \( F(i, \delta) \) and added to the position controller as a look-up table. Thus a linear relation \( F_{mag} = c \cdot i \) is achieved.

V. HARDWARE-IN-THE-LOOP TEST RIG

The cascaded nonlinear controller presented above was applied to an electromagnet prototype within a hardware-in-the-loop test rig (Fig. 5). The main components of the test rig are the linear drive with the corresponding control electronics, the electromagnet and a powerful modular real-time capable DSP system manufactured by dSPACE®.

The electromagnet is attached to the linear drive, which allows the simulation of a load for the electromagnet. Force and damping can be adjusted via a PC with LabView®. The linear drive’s slider is guided by magnetically preloaded aerostatic bearings and driven by a moving coil actuator. Control is carried out via an analog power amplifier, whose current is set by the real-time data processing system ADwin GOLD® with an implemented state controller. The interpolated resolution of the incremental position measurement system is 25 nm.

The nonlinear controller for the electromagnet is implemented in the dSPACE® system. This system consists of several hardware and software components, which allow operating the test rig, measuring and processing sensor signals in real-time as well as visualizing measured values. Matlab / Simulink® runs on the host PC, where the nonlinear controller is modeled. The model can be translated into program code suitable for the processor card without any further programming effort by means of a real-time-interface (RTI). A real-time control of the electromagnet is possible at once. The set value (control voltage) is generated by the D/A converter card DS 2103 and passed on from an analog power amplifier to the magnet coil. Sensor signals for position and current are transmitted to the processor card via the A/D converter card DS 2003. The software ControlDesk® offers a graphical user interface and allows constant monitoring of all system states and real-time tuning of control parameters.

VI. MEASUREMENT RESULTS

To evaluate the performance of the nonlinear cascaded controller running on the dSPACE® system, a constant load for the electromagnet of 15 N without damping was set by means of the linear drive. Thus the weight of the moving platform of the multi-coordinate positioning system (Fig 1) is simulated, which each of the three electromagnets has to carry. For A/D signal conversion and for the subordinate current controller a sampling rate of 10 kHz was chosen, for the superordinate air gap controller a sampling rate of 1 kHz has been used. Based on simulation results the control parameters were tuned manually at the test rig, whereas a
short settling time was aimed. With $k_p = 3750$, $k_d = -50$, $k_{d2} = -0.09$, $c = 43$ and $k = 700$ the step response sequence shown in Fig. 6 was obtained. Overshoot is about 20% of the step height; a reduction is expected by means of future parameter optimizations. Fig. 7 shows a 50 µm step response in detail. Settling time is 150 ms and a 3 µm position error is achieved. Currently the control performance is deteriorated by the noise of the analog power amplifier, which supplies the current for the magnet coil. The noise visible in the current signal (Fig. 8) possesses an amplitude of 0.06 A and must be reduced strongly by using better power amplifiers, e.g. with a digital input.

**Fig. 6.** Step response sequence for a variation of the air gap.

**Fig. 7.** 50 µm step response in detail.

**Fig. 8.** Electric current conducted by the coil of the electromagnet.

**VII. CONCLUSIONS**

Starting from a nonlinear model for the electromagnetic guidance actuators of a high-precision multi-coordinate positioning system, a cascaded control structure for controlling the air gap of a single electromagnet has been presented. The control law for the subordinate current controller has been derived according to the direct Liapunov method. The function of the nonlinear controller was proven through measurements of several step responses with a hardware-in-the-loop test rig. Based on simulation results, the control parameters were manually adjusted at the test rig. Measurement results were shown. An improvement of the controller behavior and a reduction of overshoot are expected from parameter optimizations in simulations or directly at the test rig. Furthermore, the influence of sensor noise has to be reduced. For a high-precision positioning the sensor noise must be kept low, as the position cannot be controlled more accurately than it is measured. Thus low noise sensors, e.g. laser interferometers or capacitance measuring systems, as well as better power amplifiers have to be used and the measurement signals have to be filtered.

During the forthcoming research phase, a program module for compensation of the electromagnet’s force-current hysteresis by means of an inverse Jiles-Atherton model will be used to improve the controller. The Jiles-Atherton model allows an effective and highly accurate description of hysteresis effects. As it is described with a relatively simple differential equation, it can easily be implemented in a hardware-in-the-loop system. Recent simulations show promising results, which will soon be reported.

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**REFERENCES**


