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CONTROL SYSTEM DESIGN OF A MAGNETICALLY SUSPENDED ROTARY TABLE

The paper deals with an axial magnetic bearing system for a rotary table. The table is supported by 16 current controlled magnets. Special emphasis is laid on control system design. Here, several control strategies are analyzed and experimentally investigated. High performance of cascade structure control systems is shown.

Присвячено осьовій магнітної системі, що підтримує поворотний стіл. Стіл підтримується на 16 керованих електромагнітах. Особлива увага приділяється розробці системи керування. Проаналізовано та експериментально досліджено кілька варіантів керування. Показано високу якість систем керування із каскадною структурою.

Посвящено осевой магнитной системе, поддерживающей поворотный стол. Стол поддерживается на 16 управлемых магнитах. Особое внимание уделяется разработке системы управления. Анализируются и экспериментально исследуются несколько вариантов управления. Показано высокое качество систем управления каскадной структуры.

Introduction

Active magnetic suspension systems are used in a wide range of technical applications. Their advantages are among others negligible friction, controllability and eco friendliness. The developed magnetic suspension system is meant to be utilised in a rotary table of machine tools. As known, magnetic bearing systems represent highly non-linear systems due to their variable inductance when the air gap is changing and the quadratic dependency between the current and the levitation force. The presented paper deals with simulation and practical investigations of a magnetic bearing system in traditional cascade structure where the inner velocity controller is designed using the inverse characteristics of the non-linear magnets. As known, theoretically exact linearization can be obtained when using feedback linearization. To this aim the first derivative of current is needed. However, when neglectin gdynamics of the current loop the inverse non-linear magnet characteristic can be applied in the feed forward path of the velocity loop. This approach has been still presented in a previous paper [4]. Here, a different construction will be considered where levitation and centering magnets are combined.

System Description and Governing equations

System description

The investigated magnetic suspension system of the rotary table consists of 16 hybrid magnets i. e. 8 support points. Their arrangement is shown in figure 1.

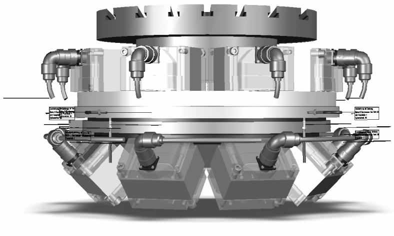

Fig.1. General view of the rotary table (CAD)

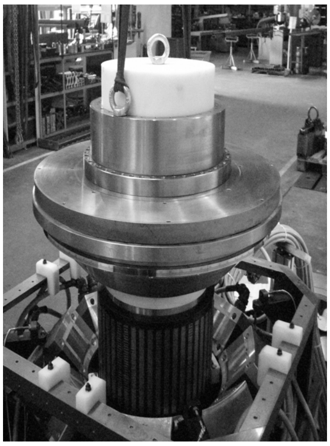

Fig.2. Assembling of the table

Here the upper and lower levitation magnets can bee seen. Centering and levitation functions are combined due to the inclined adjustment of the magnets. The upper magnets realize the rotor support in the coordinates (z, φ_x, φ_y). Here, z is the direction of levitation and (φ_x, φ_y) are the rotation angles around the x- and y-axis. The inclined lower mag-nets act as levitation and centering magnets. Rotation around the z-axis is carried out via an industrial synchronous motor with permanent magnets (torque motor) and will not be considered in detail in this paper. Neglecting rotation around the z -axis the whole magnet system possesses 16 actuators and 5 degrees of freedom (DOF) i.e. the system is mathematically over-determined. This fact has to be taken into consideration when designing the control system. Due to the differential arrange-ment of the magnet pairs both positive and negative forces can be obtained and the magnetic resistance of the overall air gap can be kept constant.

Figure 2 shows the assembling of the rotary table with the following parameters:

- diameter: 1,00 m,
- height: 0,5 m,
- Rotor mass: 270 kg,
- load capacity: 4000 kg,
- rotation speed: 250 min^{-1}.

Governing equations

The mechanical system consists of the magnetically supported rotor. Neglecting Coriolis forces, eccentricities, gyro effects and deviation moments the governing equation can written in generalized coordinates

$$Q = M\ddot{q} \tag{1}$$

The matrix of masses yieds

$$M = \begin{bmatrix} m & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 \\ 0 & 0 & 0 & J_{xx} & 0 \\ 0 & 0 & 0 & 0 & J_{yy} \end{bmatrix} \tag{2}$$

Coordinate transformations

As mentioned before the actuator system is mathematically over-determined and characterized by mechanical constraints. The parallel arrangement of the levitation magnets allows the repartition of forces and the table can be designed for higher forces. Moreover, similar to parallel robots the overall behavior features higher stiffness. However, the parallel construction of the actuator systems implicates the disadvantage of solving the problem of mechanical constraints. Figures 3 and 4 illustrate the chosen system of coordinates and the distribution of actuators. To eliminate the constraints a coordinate transformation has to be done. Due to the symmetric arrangement the actuator co-ordinate system (x, y, z, φ_x, φ_y) can be easily converted into the actor co-ordinates (δ_{M1}, δ_{M2}, …, δ_{M8}). Hence, for levitation via the upper magnets we obtain

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_{\varphi x} \\ M_{\varphi y} \end{bmatrix} = A_{LM}{}_8^5 \begin{bmatrix} F_{M1} \\ F_{M2} \\ . \\ . \\ . \\ . \\ . \\ F_{M8} \end{bmatrix} . \tag{3}$$

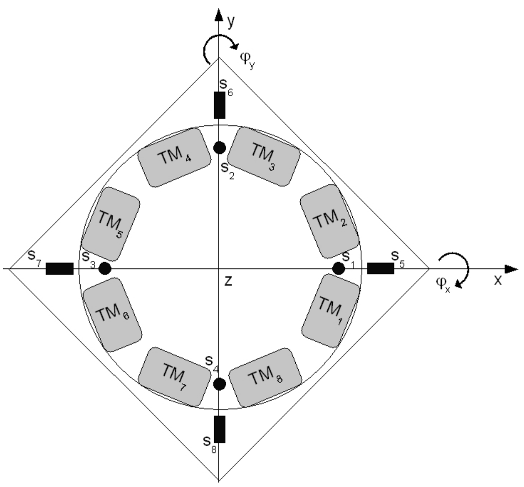

Fig.3. Top view of the magnetic levitation system

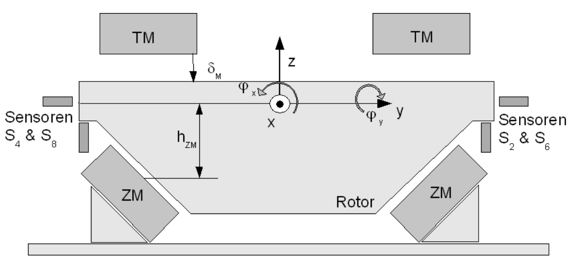

Fig.4. Side view of the magnetic levitation system

Here $A_{LM}{}_5^8$ stands for the transformation matrix from 5 DOF to 8 DOF and can be written as follows

$$\begin{bmatrix} \delta_{M1} \\ \delta_{M2} \\ \delta_{M3} \\ \delta_{M4} \\ \delta_{M5} \\ \delta_{M6} \\ \delta_{M7} \\ \delta_{M8} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -1 & r_{TM}\sin\frac{\pi}{8} & r_{TM}\cos\frac{\pi}{8} \\ 0 & 0 & -1 & r_{TM}\cos\frac{\pi}{8} & r_{TM}\cos\frac{\pi}{8} \\ 0 & 0 & -1 & -r_{TM}\cos\frac{\pi}{8} & r_{TM}\sin\frac{\pi}{8} \\ 0 & 0 & -1 & -r_{TM}\cos\frac{\pi}{8} & -r_{TM}\sin\frac{\pi}{8} \\ 0 & 0 & -1 & -r_{TM}\sin\frac{\pi}{8} & -r_{TM}\cos\frac{\pi}{8} \\ 0 & 0 & -1 & r_{TM}\sin\frac{\pi}{8} & -r_{TM}\cos\frac{\pi}{8} \\ 0 & 0 & -1 & r_{TM}\cos\frac{\pi}{8} & -r_{TM}\sin\frac{\pi}{8} \\ 0 & 0 & -1 & r_{TM}\cos\frac{\pi}{8} & r_{TM}\sin\frac{\pi}{8} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ \varphi_x \\ \varphi_y \end{bmatrix} . \tag{4}$$

Correspondingly the transformation of forces and couples from the 5 DOF co-ordinate system to the 8 DOF actuator system will be done by the inverse matrix $A_{LM}{}_8^5 = \left(A_{LM}{}_5^8\right)^{-1}$. As has been mentioned before, centering is carried out via the lower magnets inclined at 45^o. Consequently they apply both a centering and a levitation force and the transformation matrix has to be divided into two parts.

Non-linear System model and control structure

Non-linear system model

Magnetic actuators are characterized by non-linear behaviour due to their no-linear magnetic properties, changing air gape and quadratic force-flux characteristic i. e force-current-characteristic. Mathematical description of these dependencies with fixed parameters can only provide an approximate result in a given range of parameters. To cope with this drawback in a practical way the non-linear current-force-air gap characteristic $F = f(i,\delta)$ has been determined experimentally in a given range of significant values. After, a non-linear mathematical model has been trained to reproduce the measured characteristic. In previous works [4] an Adaptive Neural Fuzzy Inference System (ANFIS) was used. Present work has been carried out with a 4th order polynomial approximation. It can be stated that both approaches have given good results and can be utilized with equal success. Consequently, knowing the force to be applied on the levitation system we can determine the current necessary to produce this force. Figure 5 shows the modelled feed forward and inverse characteristic.

Control structure

When designing the drive structure we have to keep in mind that control actions have to be calculated in a mathematically determined 5 DOF co-ordinate system without constraints. However, force and couple inputs must be applied in the physically existing actuator based co-ordinate system. Hence, measured values must be first converted into the 5 DOF co-ordinate system, then the control algorithm determines the forces and couples to be applied in the 5 DOF co-ordinate system and finally these forces and couples have to be converted into the 8 DOF

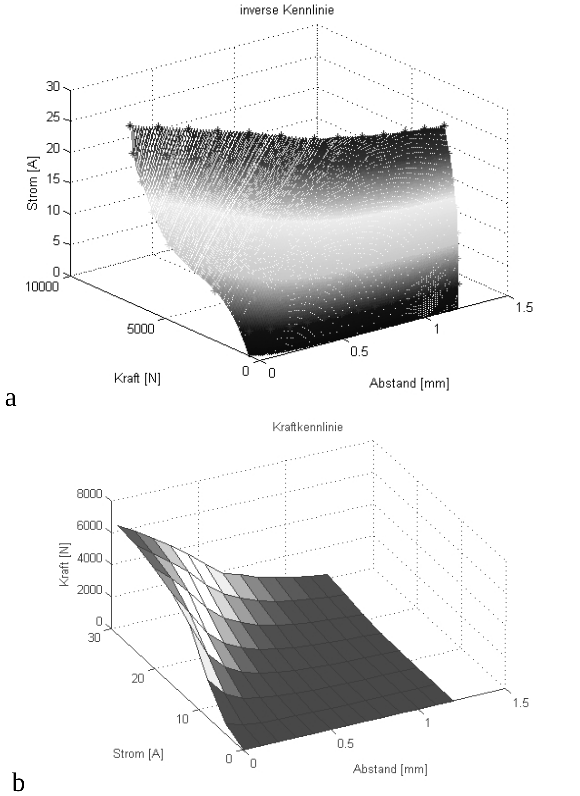

Fig.5. Direct (a) and inverse(b) current-air gap-force characteristic

coordinate system and distributed to the 16 actuators. For practical reasons cascade structure has been chosen (fig. 6). Experimental investigations prove that due to the feed forward compensation of the non-linear magnet characteristic invariable dynamics can be achieved in the whole range of operation. The current loop with a time

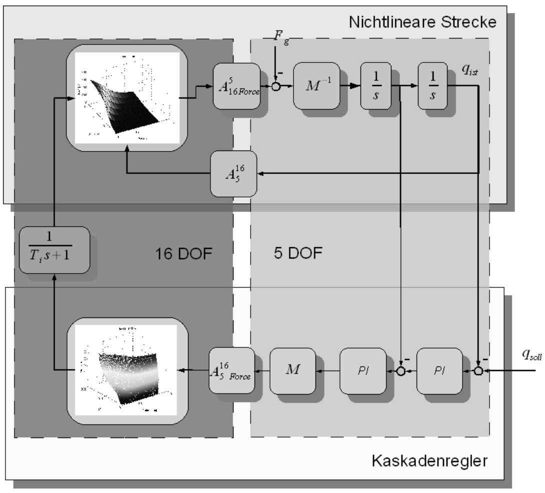

Fig.6. Step answer of the levitation system (z direction)

constant of 1μs does not affect the quality of feed forward compensation. So we can do without feedback linearization necessary from the theoretically point of view to transform the non-linearity at the system input. In fig.7 the step answer of the *z* position is given. Experiment and simulation show a good conformance. The position loop has been tuned according to the symmetrical optimum. This criterion was chosen because the table must possess both good disturbance performance and high-precision reference reaction at low frequencies when machining operations are required.

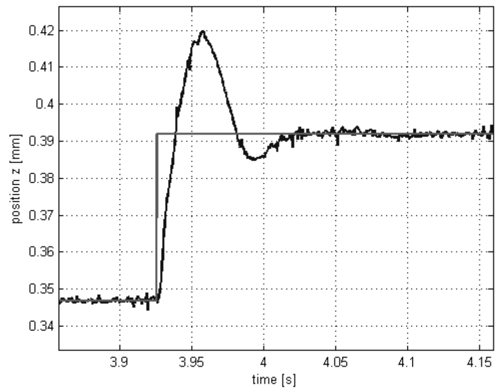

Fig.7. Step answer of the levitation system (z direction)

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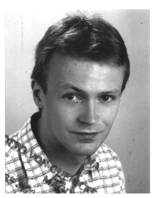

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