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High-Precision positioning system with magnetic guidance

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Abstract
Positioning systems with magnetic guidance are of great interest for many modern applications, because of their absolutely non-contact operation with precisions up to the nm-range. This paper presents a positioning system with magnetic guidance, which is characterized by a very simple compact construction. Compared to other known systems with electromagnets or Halbach-Arrays, this concept allows decoupled levitation and propulsion forces as well as a freely accessibly mover from above in one structure. The results from the control of the magnetic guidance with stationary positioning are presented in this paper as well.

Keywords: Magnetic guidance, high-precision positioning system, magnetic levitation

1. Introduction

Modern positioning systems for many high technology areas should possess high-precision, high dynamic in multiple degrees-of-freedom as well as vacuum compatibility. One potential solution to achieve these requirements is the combination of an electrodynamic linear actuator with a magnetic guidance, which allows the realization of a high-precision linear positioning system. These systems are characterized by high dynamic, high-precision and an absolutely non-contact operation. By using at least three of such linear positioning systems (i.e. three linear actuators and three magnetic guidances), compact planar positioning systems with six degrees-of-freedom (6-DoF) can be realized [1]. These so-called 6-DoF magnetic levitation positioning systems have the potential to fulfil the requirements for numerous precision applications, such as microscopy or semiconductor industry, where a high degree of dynamics, precision and friction-free operation are desired. A literature review currently shows that attractive (with electromagnets [2]) or repulsive forces (with Halbach-Arrays [3]) are mainly used in high-precision magnetic levitation positioning systems to levitate the moving element (mover). Electromagnets, which generate reluctance forces, allow a simple realisation of the closed-loop control, due to the decoupled levitation and propulsion forces. However, a compact construction with a freely accessible mover from above cannot be realized. Compared to electromagnets, Halbach-Arrays, which generate Lorentz forces, enable the realization of a compact construction with a free accessible mover from above. But the main drawback of positioning systems with Halbach-Arrays is that these systems require the application of complex control algorithm because of the heavily coupled and position depended levitation and propulsion forces [3]. This makes the whole system very complex.

2. Magnetic guidance for high-precision positioning systems

As an alternative to existing solutions with Halbach-Arrays and electromagnets, another new guiding concept, which combines the advantages of both, is proposed. It uses the generated repulsive forces between a permanent magnet and an air-core coil to levitate the mover. The proposed concept allows the realization of a compact high-precision positioning system with a freely accessible mover from above and enables also the realization of simple controller design due to the decoupled levitation and propulsion forces. Figure 1 gives an overview of the novel proposed concept.

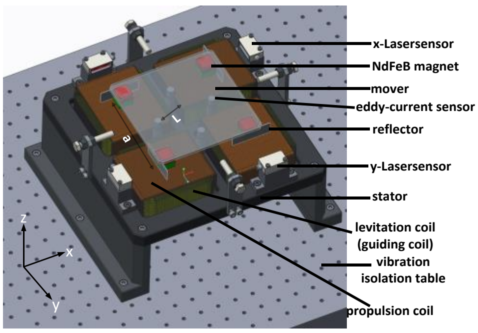

Figure 1. A 6-DoF positioning system with magnetic guidance.

The whole system is designed as an iron-free structure. This leads to a linear dependency between the currents and forces. Thus, there are no unwanted normal attractive forces between stator and mover nor eddy currents that normally have a negative effect on the dynamics of the system. In contrast to the electromagnets, with these air-core guiding coils, fast current changes and thereby highly dynamic controls are possible. Compared to the active construction (moving coils) of the mover, which is presented in [5], this passive construction (moving magnet) presents an advantage, namely, electrical cables that limit freedom of movement and also lead to wear are not needed. Another significant advantage of this positioning system is that only four permanent magnets are needed in the mover. This allows the realization of a simple and low cost implementation – compared to a mover with Halbach-Arrays (e.g. in [3]), a relatively expensive, complex mechanical construction is unnecessary. By not using ferromagnetic materials and Halbach-Arrays in the mover, a light and stiff construction is possible, that meets the highest dynamic standards. The prototype of this concept offers a travel range of 50x50x1 mm^3.

2.1. Force generation mechanism

The levitation and propulsion forces in this proposed positioning system are solely based on the electrodynamic force law (Lorentz force)

$$\mathbf{F} = \int_V \mathbf{J} \times \mathbf{B} dV \quad (1)$$

where $\mathbf{J}$ is the current density [A/m^2] in the coils, $\mathbf{B}$ the magnetic flux density [T] from the neodym-iron-boron (NdFeB) magnets and dV represents the small volume [m^3] in the coils. The propulsion system for the motion of the mover in the x- and y-axis consists of two pairs of propulsion coils, which are positioned at a 90° angle to each other. The magnetic guiding system to levitate the mover by repulsive Lorentz forces consists of four guiding coils. With a proper activation of these eight coils, a movement of the mover in 6-DoF can be realized.

2.2. Position measurement in 6-DoF

The high precision position measurement in magnetic levitation positioning systems is commonly achieved by capacitive or interferometric sensors for the suspension motion and propulsion motion, respectively [4]. To keep the development cost low, the metrology concept is made with four laser sensors and four eddy current sensors, which are fixed on the stator. Each laser sensors measures the translation in the x- or y-direction and each eddy current sensor measures the translation in the z-direction. These eight measured positions $\{z_1, z_2, z_3, z_4, x_1, x_2, y_1, y_2\}$ have to be transformed with a transformation matrix into six global coordinates $\{x, y, z, \varphi_x, \varphi_y, \varphi_z\}$ fixed on the mass centre of the mover [4].

3. Experimental results

Magnetic levitation positioning systems without a closed-loop control are unstable. Compared to a positioning system with Halbach-Arrays, a further big advantage of this proposed concept is that the levitation forces and the propulsion forces can also be independently controlled. Therefore, in the first trial run, a simple standard PID-Controller was used to demonstrate the feasibility of the developed demonstrator. The controller is designed for forces and torques acting on the mover in global coordinates. The total force of repulsion in z-direction F_z as well as the torque components T_x and T_y for rotation in the x- and y-axis respectively, are achieved by combinations of levitation forces by the guiding coils. This relation at the mover position $x = y = 0$ can be derived as

$$\begin{bmatrix} F_{z1} \\ F_{z2} \\ F_{z3} \\ F_{z4} \end{bmatrix} = \begin{bmatrix} 1/4 & -1/(2a) & 1/(2a) \\ 1/4 & -1/(2a) & -1/(2a) \\ 1/4 & 1/(2a) & -1/(2a) \\ 1/4 & 1/(2a) & 1/(2a) \end{bmatrix} \cdot \begin{bmatrix} F_z \\ T_x \\ T_y \end{bmatrix} \quad (2)$$

where a is the distance between the centre mass of two levitation coils (Figure 1) and F_{z1}, F_{z2}, F_{z3},F_{z4} are the levitation forces generated by the guiding coils.
The relation of the eddy-current sensor values and the movements of the mover in global coordinates z, φ_x, and φ_y is

$$\begin{bmatrix} z \\ \varphi_x \\ \varphi_y \end{bmatrix} = \begin{bmatrix} 1/4 & 1/4 & 1/4 & 1/4 \\ 1/(2L) & 0 & -1/(2L) & 0 \\ 0 & -1/(2L) & 0 & 1/(2L) \end{bmatrix} \cdot \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} \quad (3)$$

where z_1, z_2, z_3 and z_4 are the measured values from the sensors and L is defined as the distance between each sensor and the mass centre of the mover (Figure 1).
As mentioned, to prove the concept of stable levitation, the first goal of the closed-loop control is a stable stationary positioning of the mover in the three degrees of freedom z, φ_x, φ_y. A 400 µm step response is shown in Figure 2. As it can be seen, a stable levitation of the mover with a simple linear controller is possible without a control deviation. The settling time is 250 ms and the position error is about 40 µm.

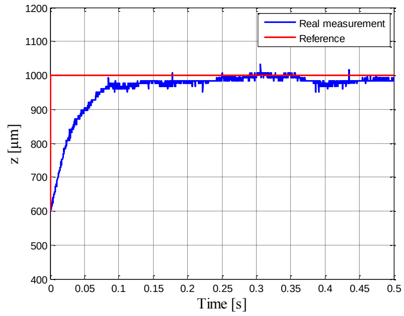

Figure 2. 400 µm step response.

Due to the applied magnetic guidances in this novel positioning system, there is neither friction nor backlash. Therefore dynamic and positioning accuracies of this system only depend on the employed non-contact position sensors and control algorithms. A high-precision positioning up to the nm-range can be achieved with low noise high-precision position sensors (e.g. laser interferometers or capacitance sensors) in combination with complex control algorithms (e.g. state space controllers) and low noise power amplifiers. Consequentially, to achieve nm-precision, these aspects must be considered in future work.

4. Conclusion

A new 6-DoF magnetic levitation positioning system, which combines the main advantages of existing solutions with electromagnets and Halbach-Arrays, such as decoupled levitation and propulsion forces as well as a freely accessible mover from above is presented in this paper. First experimental results obtained from the prototype show, that the magnetic guidance can independently controlled and a stable levitation of the mover is with a simple linear PID-Controller possible. Since the whole concept is an iron-free structure, the levitation and propulsion forces can be calculated semi-analytically. Therefore, ongoing work are currently focus on the semi-analytical calculation of forces as well as the realization of more complex controllers to improve static and dynamic characteristics of the magnetic guidance.

References

[1] Volkert R, Sattel T and Bertram T 2009 Reduction of disturbance effects and positioning noise for high-precision planar magnetic guidances EUSPEN (San Sebastian) pp 374-377

[2] Volkert R, Kireev V, Radler O, Ströhla T and Zöppig V 2006 Real-Time Hysteresis Compensation for Electromagnetic Actuators Applied in High-Precision Multi-Coordinate Drives EUSPEN (Baden) pp. 184-187

[3] Kim W.-J, Trumper D and Lang J 1998 Modeling and Vector Control of a Planar Magnetic Levitator, IEEE Transactions on Industry Applications 34(6), pp. 1254-1262

[4] Kim J.-J 2010 *Design and Control of a Magnetically Levitated Six Degrees-of-freedom Planar Motor using T-shape Halbach Magnet Array* PhD Thesis (Kaist)

[5] Compter Ir.J.C 2004 Electro-dynamic planar motor Precision Engineering 28(2), pp. 171-180