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Ironless magnetically levitated planar actuator

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This paper describes a magnetically levitated planar actuator with moving magnets. This ironless actuator has a stationary coil array above which a translator with a permanent-magnet array is levitated and propelled in the xy plane. During the movements in the xy plane, the set of active coils is switched, as a result of which the stroke in the xy plane can be made, in principle, infinitely long. Measurements on the realized planar actuator show the feasibility of this concept. © 2008 American Institute of Physics. [DOI: 10.1063/1.2832310]

INTRODUCTION

Magnetically levitated planar actuators are of increasing interest to, among others, the semiconductor industry as they combine and integrate motion in the xy plane and an active magnetic bearing and can operate under vacuum conditions. Although the translator of these actuators can move over relatively long distances in the xy plane only, it has to be controlled in six degrees of freedom (DOFs) because of the active magnetic bearing. The force and torque in these actuators can be calculated with the Lorentz force law.

Two planar actuator concepts can be distinguished. They have either stationary magnets and moving coils¹ or stationary coils and moving magnets.^{2–5} The advantage of the latter concept is that it is truly contactless as a cable to the translator or mover is not necessary. Whereas other moving-magnet planar actuators^{2,4} require a redesign of the actuator, the stroke of the investigated planar actuator can be increased by simply adding extra stator coils and switching between different sets of active coils.

TOPOLOGY

Figure 1 shows a schematic overview and the key dimensions of the investigated ironless planar actuator.⁶ The translator contains a permanent-magnet array with a quasi-Halbach magnetization. The translator has a (horizontal) size of $300 \times 300 \text{ mm}^2$ and a total mass of 8.2 kg. The actuator has 84 stator coils with concentrated windings which are arranged in a herringbone pattern. Each coil is connected to a single-phase power amplifier. The rectangular stator coils have two different orientations in the xy plane. Because the coils are rotated 45 mechanical degrees with respect to the permanent magnets, the coils can be designed in such a way that the force production in the xy plane is physically decoupled. This is demonstrated in Figs. 2 and 3, which show the emf of the dark gray coil in Fig. 1, measured while moving the magnet array with a speed of 1.0 m/s over the indicated dashed lines (airgap of 0.5 mm). Neglecting the peaks due to the end effects of the magnet array, the cross coupling between the emf waveforms in the two directions and, there-

fore, the force components produced in these directions is 1%. Except for the force production in the xy plane, the other degrees of freedom are not physically decoupled, but they are decoupled and linearized by feedback linearization.⁷

LONG-STROKE MOTION IN THE XY PLANE

Although the planar actuator has 84 coils, only 24 coils are simultaneously used for the levitation and propulsion of the translator. During the movements in the xy plane the set of active coils is switched, as only the coils below the magnet array can exert significant force and torque. Figure 4 shows a detail of the coil array, the edges of the magnet array and its mass center point. In the coil array four numbered regions are indicated. Each region has a different set of active coils. In region 2, the dark gray set of coils is active. When the mass center point moves in the y direction, the bottom four coils are smoothly switched off using position dependent weighting functions in the decoupling algorithm. At the horizontal boundary A, 20 coils are active. When the magnet array moves further in the y direction (into region 1), the adjacent top four coils are smoothly switched on. Similarly, when moving in the x direction, the left column of

FIG. 1. Schematic top view of the moving-magnet planar actuator.

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FIG. 2. emf measurement on line $a-a'$, which is defined in Fig. 1 (speed, 1.0 m/s; airgap, 0.5 mm).

active coils is smoothly switched off when the translator moves toward boundary B. At boundary B, 18 coils are active. At the crossing of boundaries A and B, i.e., at point C, only 15 coils are active. The result of the switching is that the electromechanical structure of the actuator changes with the position.

Despite of the sinusoidal emf-waveforms, the currents in the coils are nonsinusoidal because not only the force but also the torque has to be controlled. The planar actuator is clearly overactuated and, therefore, there is an infinite set of solutions to the inverse problem. In order to arrive at a unique solution, the coil currents are calculated by inverting a mapping of the force and torque acting in the planar actuator as function of the position and orientation of the translator using a minimal energy constraint. Due to the repeating distribution of the coils in the xy plane, each of the four individual regions in Fig. 4 can be considered identical. As the inverse mapping is nonsingular in one region and on its boundaries, it is also nonsingular in all other regions. Therefore, an infinite stroke in the xy plane can be created by extension of the coil array. The planar actuator in Fig. 1 has 28 regions.

EXPERIMENTS

The influence of the switching between different coil sets on the accuracy of the planar actuator has been investi-

FIG. 3. emf measurement on line $b-b'$, which is defined in Fig. 1 (speed, 1.0 m/s; airgap, 0.5 mm).

FIG. 4. Switching boundaries between different sets of active coils. The dashed line indicates a detail of the trajectory used in the experiment.

gated by experiments on a prototype. A detail of the prototype is shown in Fig. 5. It shows the stator coils, the translator, and the measurement frame. The measurement frame is mounted on an external xy -positioning system. This system moves along with the translator of the planar actuator and follows the same trajectory in the xy plane. During normal operation, there is no contact between the translator and the measurement frame. However, when the planar actuator becomes unstable, the stroke of the translator is limited by the measurement frame and damage to the planar actuator is prevented. The position of the translator with respect to the measurement frame is measured with eight eddy current sensors (2 mm range, $0.16 \mu\text{m}$ rms resolution) of which five are indicated in Fig. 5. Four of these sensors are oriented in the z direction, two in the x direction, and two in the y direction. The external xy -positioning system itself is equipped with optical encoders ($1 \mu\text{m}$ resolution). The position and orientation of the translator of the planar actuator with respect to the stator coils are reconstructed from the information of both the optical encoders and the eddy-current sensors.

The position error of the planar actuator has been measured on a trajectory of its mass center point which was chosen in such a way that it passes through the points at which only 15 coils are active, as indicated by the dashed line in Fig. 4. The planar actuator is controlled by six SISO feedback controllers with a bandwidth of 35 Hz. The acceleration profile, power dissipation (i.e., the total Ohmic losses in the coils), and the position and angle errors of the trans-

FIG. 5. Overview of the planar actuator and its measurement frame.

FIG. 6. Acceleration profile, power dissipation (Ohmic losses), and the position and angle errors of the translator of the planar actuator (airgap, 1.0 mm).

lator of the planar actuator are shown in Fig. 6. The maximum speed and acceleration of the translator during the experiment were equal to 1.15 m/s and 11.5 m/s², respectively. The translator was levitated 1.0 mm above the coil array. The vertical lines in Fig. 6 indicate the moments in time at which the set of active coils changes. During the movement, the position error is less than 25 μm , and the angle error is less than 80 μrad . No significant change of the error could be measured due to the switching between the coil sets and the variation of the number of active coils. Both during acceleration and constant speed a variation of the power dissipation can be seen in Fig. 6. This arises because as a result of the switching between different coil sets the same force has to be produced by between 15 and 24 active coils.

CONCLUSIONS

A magnetically levitated ironless planar actuator with an, in principle, infinitely long stroke in the xy plane has been presented. During the movements in the xy plane, the set of active coils is switched by weighing functions in the decoupling algorithm. As a result, the stroke can be simply extended by adding extra coils to the coil array. Measurements on the realized prototype show that no significant change of the position or angle error can be measured in consequence of the switching between active coil sets.

¹J. C. Compter, *Precis. Eng.* **28**, 171 (2004).

²W. J. Kim, D. L. Trumper, and J. H. Lang, *IEEE Trans. Ind. Appl.* **34**, 1254 (1998).

³A. J. Hazelton, M. B. Binnard, and J. M. Gery, U.S. Patent No. 6,208,045 (16 November 1998).

⁴N. Korenaga, U.S. Patent No. 7,075,198 (12 July 2005).

⁵J. C. Compter, P. C. M. Frissen, and J. van Eijk, Patent WO 2006/075291 A2 (20 July 2006).

⁶J. W. Jansen, C. M. M. van Lierop, E. A. Lomonova, and A. J. A. Vandenput, *Proceedings of International Electric Machines and Drives Conference, 2007* (unpublished), p. 272.

⁷C. M. M. van Lierop, J. W. Jansen, A. A. H. Damen, and P. P. J. van den Bosch, *Proceedings of IEEE International Conference on Control Applications, 2006* (unpublished), p. 2516.