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Citation for published version (APA):
Acht, van, V. M. G., Damen, A. A. H., Bosch, van den, P. P. J., & Kamerbeek, E. M. H. (2000). Topology of six degrees of freedom magnetic bearing. *Journal of Applied Physics*, *87*(9), 6920-6922.
https://doi.org/10.1063/1.372886

DOI:
10.1063/1.372886

Document status and date:
Published: 01/01/2000

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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• The final published version features the final layout of the paper including the volume, issue and page numbers.

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JOURNAL OF APPLIED PHYSICS VOLUME 87, NUMBER 9 1 MAY 2000

Power Magnetics and Magnetic Fluids Claudio Serpico, Chairman

Topology of six degrees of freedom magnetic bearing

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A novel magnetic topology has been designed for a six degrees of freedom, magnetically levitated and driven mirror, to be used in a three dimensional (3D) measurement system based on laser interferometry. The translations of the mirror are to be kept small, whereas the rotations are to be controlled over a large range with a high bandwidth and high accuracy. Finite element modelling (FEM) is used to analyze the proposed topology. For computational load reduction, a 2D FEM model has been derived from the actual 3D topology, which incorporates most of the magnetic subsystems. Simulations show that cross-influence between the actuators is small, that the forces and torques are proportional to the applied currents and that the angle of the rotor is of little influence. This allows the multiple in multiple out system to be regarded as multiple linear single in single out systems. [S0021-8979(00)41308-3]

I. INTRODUCTION

At the Eindhoven University of Technology, Measurement and Control Group, research is done on the deflection system for a three dimensional measurement system, based on laser interferometry.[1] One subsystem is a mirror that can rotate simultaneously about two perpendicular axes. This device should reflect the laser beam of an interferometer in a predescribed direction. We aim at accuracies in the order of 1 μrad over ranges of 1 rad with a bandwidth of at least 300 Hz. The optical reflection point should be fixed in space with an accuracy of 1 μm. Because of these extreme requirements, magnetic levitation and propulsion are currently being investigated.

The main part of the laser deflection system is a mirror with six degrees of freedom (DOF): three translational DOFs (x, y, z) and three rotational (Θ, Φ, Ψ), respectively about the x, y, and z axes. Translations of the mirror must be suppressed $(<1\ \mu\mathrm{m})$, whereas the orientation of the mirror Θ, Φ must be controlled over a large range. The rotation of the mirror about its normal axis Ψ has no optical effect, but should be kept within limits to avoid gyroscopic effects etc. This gives two distinct problems: The first is to keep the mirror levitated in its operating point $(x=0,\ y=0,\ z=0,\ \Psi=0)$, with extremely high stiffness. The second is to accurately control Θ and Φ over a large range with a high bandwidth. When designing the magnetic topology for the laser deflection system, it is preferable with respect to the control system that the actuators are decoupled and forces and torques proportional to the applied currents. Also, to avoid thermal effects, low power dissipation is a necessity.

In this article a magnetic topology is presented which meets these demands to a large extent. For analysis of the proposed topology finite element modelling (FEM) is used. To reduce computational load, a two dimensional (2D) model which shares the main features with the actual 3D topology is used. This model is therefore useful for examining the properties of the magnetic topology.

II. 3D MAGNETIC TOPOLOGY

The full 3D magnetic topology of the six DOF laser deflection system is depicted in Fig. 1. A top view and two vertical cross sections are plotted in Fig. 2. Also some flux lines are drawn in this picture. These pictures only show the principle of operation, and do not necessarily reflect the optimized length and width of permanent magnets and other magnetic materials.

The rotor consists of four cylindrical permanent magnets, and a high permeability X-shaped center. The permanent magnets are mounted on the center and magnetized radially from the center of the rotor (see Fig. 2). The mirror is in the same plane as the permanent magnets. The stator consists of two high permeability rings in the horizontal plane, with eight vertical high permeability bars between them (see Fig. 1). Around four of those bars coils are wound. Four horizontal coils with a high permeability core are connected to the other four bars. Small air gaps exist between the twor-

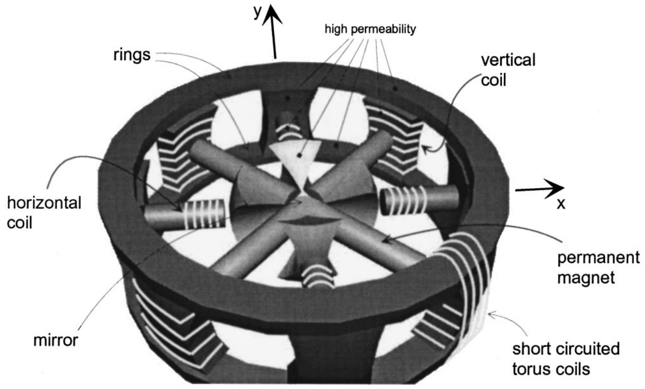

FIG. 1. 3D view of the magnetic topology.

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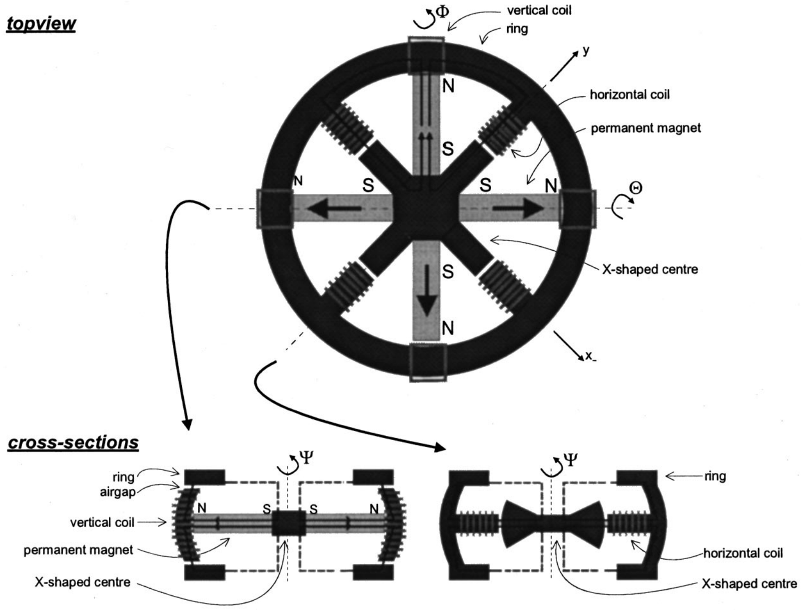

FIG. 2. Top view and cross sections of the magnetic topology.

ings and the four vertical coils (see Fig. 2). The rotor is located such that the four permanent magnets are opposite to the vertical coils of the stator and that the legs of the X-shaped center are opposite to the horizontal coils.

The flux of each of the permanent magnets flows as follows: After crossing the air gap between rotor and stator, the flux splits in two parts in the vertical coil. One part goes up towards the upper ring, the other part goes down. In the two rings the two fluxes split again. One part goes left, the other part goes right. (This gives a total of four flux paths.) Through the upper and bottom rings the fluxes reach the bars on the left and the right of the vertical coil. The upper and bottom fluxes join and go through the horizontal coils and the air gap between stator and rotor to the X-shaped rotor center. There, the left and right fluxes join and return to the permanent magnet.

Torques and forces can be applied to the rotor as follows:

(i) *z translation, ΦΘ rotations:* When a current is forced through the vertical coils, a vertical Lorentz force is generated in each of these coils. If the forces of all four coils act in the same direction, the rotor can be moved up and down. If two opposite coils generate forces in opposite directions, the rotor is rotated.

(ii) *xy translations:* Using the four horizontal coils, one flux path can be made more ''attractive'' so that the distribution of the flux in ''left'' and ''right'' is not symmetric. This causes the rotor to translate in the horizontal plane.

(iii) Ψ *rotation:* Because the air gap between stator and rotor has a high magnetic resistance, the permanent magnets tend to aim themselves towards the vertical coils, and the legs of the X-shaped center towards the horizontal coils, thus rotation of the rotor about the normal axis of the mirror is prevented. Note that, as this force acts like a stiff spring without much damping, a high frequency oscillation with small amplitude about this axis is possible. This oscillation is damped by eddy currents or additional short circuited torus windings (see Fig. 1). Of course these windings can also be used to *control* this sixth degree of freedom to some extent.

In accordance with Earnshaw's theorem,[2] the position and orientation of the rotor in its operating point ($x=0$, $y=0$, $z=0$, $\Psi=0$) is unstable. An active position control system is necessary to keep the rotor in its operating point.

When the rotor is not in the exact center of the stator, the distribution of the flux is not symmetrical. This means that a horizontal force is generated, which also has to be compensated by the control system. Something similar applies when the magnetization of the four permanent magnets is not exactly the same.

The small air gaps in the stator between rings and vertical coils are to avoid extremely high impedance of the coils and saturation of the magnetic material. When the upper air gaps are not equal to the lower air gaps, a constant vertical force is generated. This force can be used to compensate the gravitational force.

In Sec. III, it will be shown by simulation that the topology gives linear relations between the applied currents and the exerted forces and torques.[3] Also the forces and torques are independent of the angle of the rotor. Note that a *translation* of the rotor does influence forces and torques. However, because the maximum position error of the rotor is

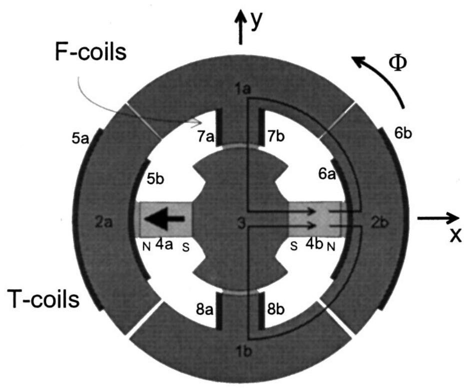

FIG. 3. 2D model of 3D topology for FEM.

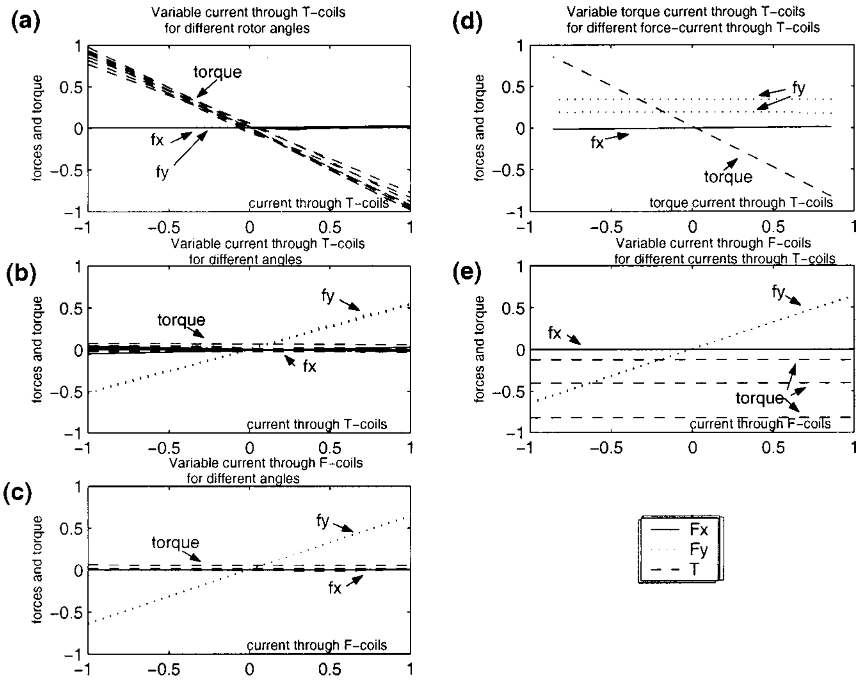

FIG. 4. FEM simulation results.

specified to be much smaller than the air gap, this can be neglected.

III. FEM SIMULATION

Because FEM of the proposed 3D topology is computationally extremely complex, a 2D model incorporating most of the magnetic subsystems of the 3D topology has been considered. This 2D model is depicted in Fig. 3.

The rotor has three degrees of freedom (two translations x,y, and 1 rotation Φ.) Areas 3 and 4 form the rotor, where 4a and 4b are two radially magnetized permanent magnets and area 3 is a high permeability material. The stator consists of four parts (1a, 1b, 2a, 2b), separated by four air gaps. Four coils have been wound around the stator (5, 6, 7, 8). One set (5,6) for rotation and vertical translation using Lorentz forces (comparable with vertical coils in 3D topology, further on called T coils). The other set (7,8) is for vertical translation using flux distribution (comparable with horizontal coils in 3D topology, further on called F coils).

Using this 2D model dozens of simulations have been carried out in the FEM package ''Opera 2d'' by Vector Fields[4] for different currents through the coils and different rotor angles. In the simulations nonlinear magnetic materials are used including magnetic saturation to simulate realistic iron and permanent magnet properties.

In the plots forces, torques and currents are all normalized to their maximum nominal value.

In Fig. 4(a), the forces and torques on the rotor are plotted as a function of the current through the T coils in such a way that a torque is generated. This is done for different rotor angles. Apart from some numerical noise, it is shown that the torque is linear with the applied current and independent of the rotor angle.

The T coils can also be used to exert a vertical force on the rotor. This is plotted in Fig. 4(b). The plot shows that the vertical force by the T coils is linear with the current and independent of the rotor angle. The F coils can also be used to generate a vertical force. This is plotted in Fig. 4(c). Again the vertical force is linear with the applied current and independent of the rotor angle.

The T coils may be used for both generating torque and vertical force. This could lead to coupling between the two. This is shown in Fig. 4(d). For different torque currents the forces are plotted as a function of extra force currents flowing through the same T coils. One can see that there is no coupling between the two. Also the torque generated by the T coils and the force generated by the F coils are decoupled. This is shown in Fig. 4(e). Here for different currents through the F coils, the torque is plotted as a function of the current through the T coils.

IV. CONCLUSIONS

In this article a magnetic topology has been presented for a six DOF magnetically levitated and driven mirror, which decouples all six degrees of freedom and gives proportional relations between current and force. This allows that a much simpler control system can be designed for multiple single input single output (SISO) systems instead of a nonlinear multiple input multiple output system. A 2D model of the proposed topology has been designed and simulated in a FEM package. The simulation results confirm that the system can be regarded as multiple linear SISO systems.

[1] P. P. J. van den Bosch and A. A. H Damen, ''Air and magnetic bearings for a laser beam deflection unit,'' Proceedings American Control Conference '97, Albuquerque, June 1997, pp. 2987–2991.
[2] S. Earnshaw, Trans. Cambridge Philos. Soc. **7**, 97–112 (1839).
[3] T. Mizuno, E. Kitahara, and H. Ueyama, ''Linear Carrier Systems with Self-Sensing Magnetic Suspension Tracks,'' Proceedings Sixth International Symposium on Magnetic Bearings, Cambridge, August 1998, pp. 631–640.
[4] Opera-2d Reference Manual, Vector Fields Limited, 24 Bankside, Kidlington, Oxford, England.