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Magnetically levitated linear drive with repulsive magnetic guidance and nearly zero power emission

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Abstract

Magnetically levitated linear drives are used in applications of precision engineering. Most systems require a constant electric current for static levitation, which results in static power dissipation. A magnetically levitated linear motor with nearly zero watts power emission for static levitation has been developed. Three axes of the guidance are stabilized using repulsive permanent magnet forces. The remaining axes are controlled by Lorentz coils which are using the same magnetic field as the repulsive guidance. As only three axes instead of six need to be controlled, the complexity of the system and the amount of power and sensing electronic is reduced.

Keywords: Control, Linear, Magnetic bearing, Mechatronic

1. Introduction and state of the art

Magnetic levitation for linear drives was mainly used in applications of highest precision [1] or for human transport [2] because of the complexity of the system. Most levitation concepts are using electromagnetism or the electrodynamic effect [3]. Both principles require a constant electric current to compensate the force of gravity which results in power dissipation in the guidance. Additionally, an active control in six degrees of freedom is required which results in a high amount of power and sensing electronics.

In the last years magnetic levitation can be seen in industrial applications using superconductivity [4]. When using this technique there is no active control required for guidance and the gravity is compensated by the force of the magnetic field. The disadvantage of this levitation technique is, that a cooling down to 77 K is required.

Another option is the use of repulsive magnet forces, as it is proposed by Nguyen [5]. In this configuration, the gravity is compensated by permanent magnetic forces, and the number of degrees of freedom which have to be actively controlled can be reduced.

In the present work a magnetically levitated linear drive is presented. The motor is built as a flat coil linear motor. Three axes of the magnetic guidance are stabilized by repulsive permanent magnet forces. Using this technique, magnetic levitation with nearly zero watts power emission can be achieved.

2. Conceptual design

Permanent magnets can be used to apply static attractive or repulsive forces. When repulsive forces are used, a positive spring stiffness in at least one axis is achieved. On the other hand, a permanent magnet suspension will always result in negative spring stiffness in another axis.

The design shown in Figure 1 uses two tracks of permanent magnets which are mounted on the stator.

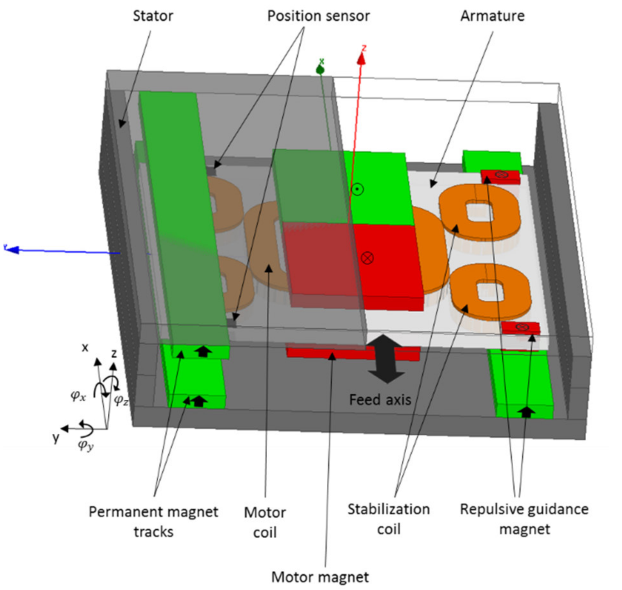

Figure 1. Motor and guidance concept

At the armature of the motor four permanent magnets are mounted in repulsive configuration. The permanent magnet configuration is designed using finite element method, to achieve a positive stiffness in the Z axis of the motor of 9100 N/m, which is illustrated in Figure 2. This value fits to the simulated value as given in Table 1. Also the rotational degrees of freedom φ_x and φ_y are stabilized by a positive spring stiffness. Therefore, these axes do not need to be actively controlled.

Due to the positive stiffness in the three axes, the force of gravity of the armature is compensated up to a maximum load of 700 g. For a specific load, the armature will levitate at the same height over the whole travelling range of the motor. Nevertheless, a pitch and roll error occurs when the stage is moving. This is created by a disturbance torque, which results from the distance between force application and centre of gravity. In the built setup (Figure 5) this error is calculated to be below four minute of arc.

In addition, the repulsive guidance magnets create negative spring stiffness in the Y and φ_z axis of the guidance, which destabilizes the system (Figure 2). This requires actuators with an active control to stabilize these two axes.

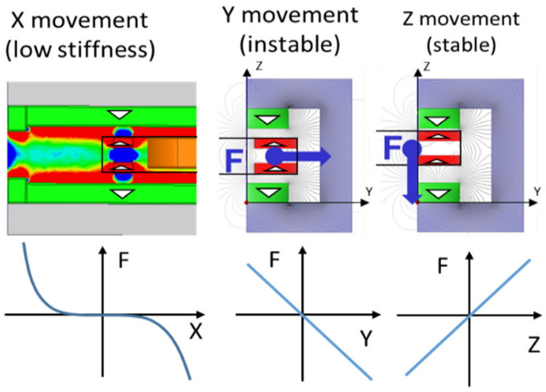

Figure 2. Schematics of the stable and Instable guidance axes

Table 1. Simulated and measured guidance stiffness

	Y axis	Z axis
Simulation	-11,5 N/mm	10,7 N/mm
Measurement	-11,0 N/mm	9,2 N/mm

The stabilization in the guidance is done by four coils which are placed in the magnetic field of the permanent magnet tracks as depicted in Figure 1. Due to the Lorentz force of this coils the destabilized axes can be actuated.
For the position detection of the armature in Y and φ_z, two Hall-Elements are placed at the armature for measuring the magnetic field of the permanent magnet tracks on the stator. In this configuration a combined use of the permanent magnet tracks for stabilization in five DOF as well as for sensing the armature position is possible.
The linear drive itself is designed as a flat coils linear motor having movable coils and stationary magnets. As this principle is based on the Lorentz force and the movable coil has no ferromagnetic part, there is no additional parasitic force created in the system.

3. Control

The position control is done by a decoupled PID control algorithm. The two hall sensor values of the guidance are transformed into the Cartesian coordinates Y and φ_z. Two independent PID controllers for these two axes are designed by the loop shaping method, using a model based design approach. For a decoupling of the two axis the controller output is transformed into the resulting current of each coil. A schematic of the control is shown in Figure 3. The crossover frequency of both axes is set to 70 Hz with a phase margin of 30°.

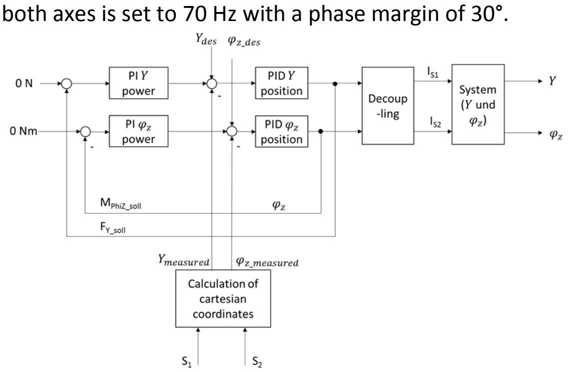

Figure 3. Control for minimization of the levitation power

For the control of the feed axis, a PID controller is used having a crossover frequency of 50 Hz. The measured and simulated step responses of the system are shown in Figure 4. Overall, a good comparability between model predictions and actual measurements can be observed.
When the armature is centred exactly in the middle of the guidance, no electrical power is required for levitation, independently of the armature load. This is achieved by using an additional cascaded control loop which is also shown in Figure 3. By this, the levitation power can be reduced to a value, lower than one mW.

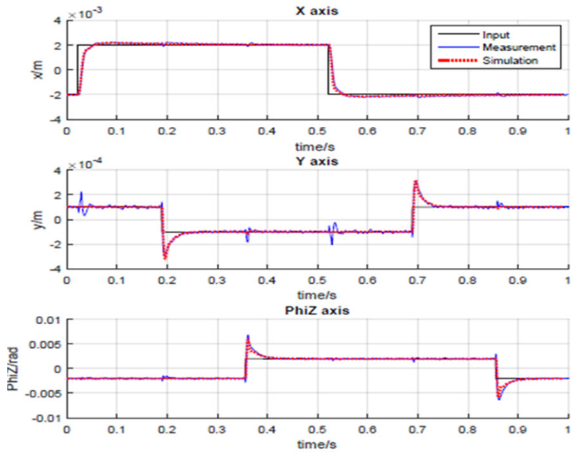

Figure 4. Step responses of the controlled axes

4. Conclusion

A magnetically levitated linear motor with repulsive magnetic guidance and three controlled axes was presented. Using this concept magnetic levitation with almost zero watts power emission is possible. This makes the system power and cost efficient for industrial applications. The following figure shows the real setup.

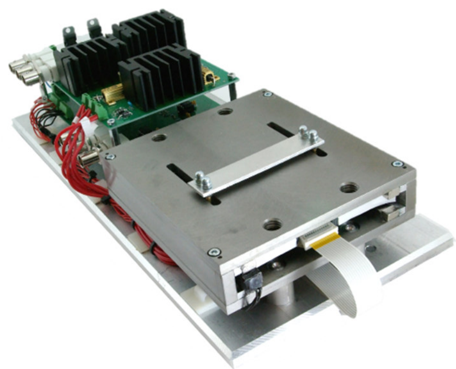

Figure 5 Motor setup

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