2-DoF magnetic actuator for a 6-DoF stage with long-stroke gravity compensation

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Abstract

High-precision positioning systems, such as lithography wafer scanners, vibration isolators and gravity compensation systems require multi-DoF stages. These stages generally apply magnetic actuators because of their contactless operation and high-force capacity. The working range of current magnetic actuators in the levitating direction is limited to around 1mm [1]. However, in some applications such as wafer loading in nanoimprint lithography, a long-stroke motion is required. Although increasing the airgap width would increase the working range, it would also require a larger driving current and, thus, more heat dissipation, which is undesirable for high-precision systems. *To alleviate this problem, the design of a novel 2-DoF magnetic actuator is presented in this paper*. The actuator, presented in Section 1, is capable of both long-stroke (20mm) and short-stroke (2mm) motions in two perpendicular axes. In the long-stroke direction the actuator can achieve high-precision positioning with low power and a tuneable constant force, which is confirmed both by simulation and experiments. In the short-stroke direction, it works as a conventional reluctance actuator. Moreover, as shown in Section 2, the actuator could also be used to design 6-DoF maglev positioning stages with gravity compensation (see Figure 1).

1 Basic configuration and working principles of the 2-DoF actuator

The actuator consists of an iron mover and an iron C-core stator with two permanent magnets and two coils ($Coil_1$ and $Coil_2$), as shown in Figure 2. The two permanent magnets have the same orientation in the X-axis and provide a static force that allows for gravity compensation with minimal power consumption (i.e., low coil current), thus reducing the heat in the system. $Coil_2$ provides a 2mm short-stroke conventional reluctance actuation in the X-axis with initial negative stiffness, while $Coil_1$ provides a 20mm long-stroke actuation in the Z-axis (dynamic force) with initial low stiffness over the full stroke.

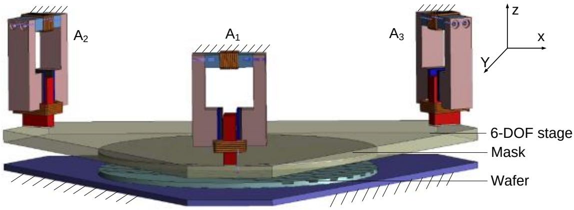

Figure 1

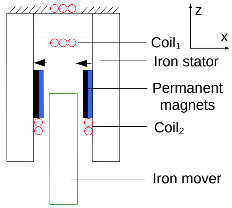

Figure 2

Figure 1: Proposed 6-DoF high-precision positioning stage concept using three 2-DoF actuators. The stage is capable of a 20mm stroke in the Z-axis with gravity compensation and a 1mm stroke in the XY plane.

Figure 2: Proposed 2-DoF actuator configuration with iron stator and mover. The two permanent magnets on the stator are in the same orientation allowing for gravity compensation. Coil$_1$ and Coil$_2$ are both mounted on the stator allowing for active mover position control along the Z and X axes, respectively.

1.1 Gravity compensation and actuation in Z-axis

The total flux used for Z-axis levitation and actuation is the sum of the fluxes of the two permanent magnets and that of Coil$_1$. The latter changes the field strength in the airgap to achieve different levels of constant force or to actuate in the Z-axis. On the assumption that there is no stray flux, no saturation, nor iron reluctance, the levitation force in the Z-axis can be derived from the magnetic energy stored in the airgaps as follows: The effective airgap volume $V_g = (y_d z) \cdot x_g$, where $y_d z$ is the overlap surface between the magnet and the mover (the actuator thickness out of plane × the overlap length between the magnet and the mover), x_g is the total airgap.

The total magnetic energy stored in the airgap is $E_m = B_g H V_g = \frac{B_g^2}{\mu_0} x_g y_d z$.

Here, μ_0 is the magnetic permeability in vacuum, H is the magnetic field strength, and B_g is the flux density in the airgap given by $B_g = \frac{\lambda B_r l_m}{\mu_0 R_t A_g} = \frac{\lambda B_r l_m}{2l_m + x_g}$,

where λ, B_r, A_g, and R_t are, respectively, the loss factor, the remnant flux density, the overlap magnet surface with the mover, and the total reluctance. The latter is given by $R_t = R_m + R_g = 2\frac{l_m}{\mu_0 y_d z} + \frac{x_g}{\mu_0 y_d z} = \frac{2l_m + x_g}{\mu_0 y_d z}$.

Thus, the magnetic force in the Z-axis is $F_z = \frac{\partial E_m}{\partial z} = \frac{B_g^2}{\mu_0} x_g y_d = \frac{\lambda^2 B_r^2 l_m^2}{\mu_0 (2l_m + x_g)} x_g y_d$.

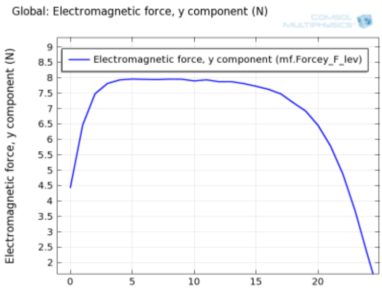

Figure 3: F_z COMSOL simulation with no coil activated. From Z-position 2mm to 18mm the force stays around 8N (Y-axis in COMSOL represents Z-axis here).

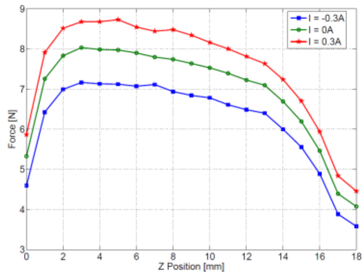

Figure 4: F_z in experiments. The middle line is the force when no coil is activated. The ones above and below are forces with current in Coil$_1$ in two directions.

The force F_z as function of the Z-position is modelled with real material parameters by means of 2D COMSOL and the results in Figure 3 show a nice flat top at 8N. This implies an initial low stiffness and low-power gravity compensation for 0.8kg. Figure 4 shows the experimental validation using a linear stage and a force sensor: F_z was measured at 20 Z-positions and 3 Coil$_1$ current levels (0A, ±0.3A), showing that F_z can be both increased and decreased by varying the current in Coil$_1$. The force level (gravity compensation) and stiffness in the Z-axis can also be tuned by modifying the stator or/and the mover geometries around the airgap. The Z-force profile also can be shaped by locally modifying the permanent magnets field strength. Finally, the efficiency of the X-axis actuation could be increased with additional iron paths.

1.2 Actuation in X-axis

The 2-DoF actuator works as a conventional reluctance actuator in the X-axis. It has negative stiffness and a lateral force, F_x, which is quadratic with the current and the position. As Figure 5 shows, F_x presents a large linear range around the working point (the middle position) because of the actuator symmetry. The total airgap in the X-axis is 2mm. Coil$_2$ can actively control the mover position in a range of ±0.5mm around the central working point.

2 6-DoF positioning stage concept

Figure 1 shows a first concept for a 6-DoF stage using three described 2-DoF actuators (A_1, A_2, A_3). This stage would allow a 20mm stroke in the Z-axis of which about 10mm with gravity compensation, initial low stiffness in Z, R_x and R_y. In the XY plane the stage would have a 1mm stroke with initial negative stiffness.

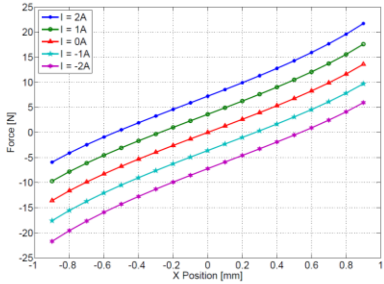

Figure 5: F_x COMSOL simulation. At 10mm Z-position, with 100 windings, 0A, ±1A, ±2A current in Coil$_2$, the mover can work in the range of ±0.5mm around the working point.

The stage position could be controlled using a 6-DoF MIMO controller and a 6-DoF laser interferometer measuring system. In case of a limited planar working range, three optical encoders measuring the long-stroke displacement and three capacitive or inductive sensors measuring short-stroke displacement could be an alternative.

The 6-DoF stage could be used for nanoimprint, using Z-axis actuation to generate both the printing and releasing forces. In such case, accelerometers would be needed to control the releasing force which is known to be impulsive [2]. Additionally, the current in the coils could be used to infer the forces in the Z-axis, which could be used in both feed-forward and feedback control.

3 Discussion and conclusion

The proposed 2-DoF actuator can achieve tuneable constant force in the Z-axis with a long stroke. The force level in the whole working range can be tuned either by changing the current in Coil$_1$ or by modifying the stator or/and the mover geometries around the airgap.

The demonstrated 2-DoF actuator is easy to design and build and can be used as a flexible component for a 6-DoF positioning system. Another application could be a vibration isolation stage because of its initial low stiffness in the Z-axis. This and other applications and the tradeoffs between actuator and control design are currently under investigation.

References:

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[2] H. Atasoy, M. Vogler, T. Haatainen, et al. Novel thermoplastic polymers with improved release properties for thermal NIL, Microelectronic Engineering 88 (2011) 1902–1905