Modeling and Design of a Short-Stroke High-Precision Reluctance Actuator

Background
Semiconductor lithography systems:
- High-precision: accuracy of ± 1 nanometer
  (=1/1.000.000.000 m)
- High-speed:
  ± 230 wafers/hour
- Long-stroke range: ± 2 m
- Short-stroke range: ± 1 mm

Improvement of the throughput/speed and accuracy of the motion stage will be achieved by:
- Increasing the wafer size from 300 to 450 mm
- Decreasing the moving mass

Multiple actuators are used to suppress the flexible modes of a 450 mm wafer stage. Reluctance actuators are investigated, which can achieve a 10 times higher force density than currently applied voice coil actuators as shown in Fig. 2.

Challenges reluctance actuators
- High stiffness
- Nonlinear current-force
- Nonlinear position-force
- Magnetic hysteresis
- Eddy currents

Analysis methods
1. Ferromagnetic material characterization.
2. Preischach model combined with a dynamic MEC model:
   \[ B_{m}(H) = B_{rev}(H) + B_{m}(H, H_{nom}) \]
   \[ B_{m}(H) = \int_{\alpha,\beta}^{\alpha,\beta} p(\alpha,\beta) \gamma_{\alpha\beta} H(t) \, d\alpha \, d\beta \]
   \[ H_{m,fc}(t) = H_{fc}(t) - \frac{d^{2} \, dB_{m}(t)}{dt^{2}} \]
3. 3d-FEM simulations (Opera 15.0) with an anisotropic conductivity to include eddy currents for laminated structures.
4. Flux measurements on ferromagnetic laminated toroids and force measurements on an E-core reluctance actuator.

Magnetic hysteresis and eddy currents

![Figure 1: TWINSCAN NXT1960Bl, a dual-stage immersion lithography system.](image1)

![Figure 2: Power dissipation vs. moving mass of two optimized voice coil actuators and an optimized reluctance actuator.](image2)

![Figure 3: Dc and ac measurements on a toroid vs. the static and dynamic Preisach model.](image3)

![Figure 4: Dc and ac measurements (at 400 Hz) on a toroid vs. 3d-FEM simulations.](image4)

![Figure 5: (left) The measured force vs. the simulated force and (right) the difference between the measured or simulated force of the E-core actuator and the non-hysteretic MEC model.](image5)

The Preisach model including dynamic MEC model shows a factor two improvement of the force prediction compared to the non-hysteretic MEC model, as shown in Fig. 5, while the 3d-FEM simulation overestimates the eddy current effects for a 320 Hz excitation.

Conclusions
The force density of short-stroke actuation systems can be improved by the use of reluctance actuators instead of voice-coil actuators. Actuator models are obtained to accurately estimate magnetic hysteresis and eddy currents in reluctance actuators. The results show good agreement with measurements, for both the flux density and the force for frequencies up to 400 Hz.

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