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Modeling and Localized Feedforward Control of Thermal Deformations Induced by a Moving Heat Load

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1 Background

In high-tech machinery, changes in thermoelasticity of materials and components are often an undesirable side effect which is due to the operation of the machine. This is especially important for optical lithography equipment, where accuracies in the order of nanometers are required to meet customer demands. In the optical lithography process, a wafer is exposed by a light-source that images a chip pattern onto it. The light used for the exposure adds a significant thermal load to the wafer which causes it to heat up. This effect, called wafer heating, ultimately results in deformations of the wafer which reduce performance of the lithography tool in terms of properties as overlay and focus [1][2]. With increasing source powers and performance requirements for next generation lithography tools, this effect is becoming ever more important.

2 Problem description

In this presentation we consider the modeling and control of the thermal induced deformations of a cross-section of the wafer, which is modeled as a beam. The control inputs are forces, in- and out-of-plane, supplied by a high number of actuators which are located below the beam. The complexity of this problem mainly lies in the spatio-temporal nature of the heat load and area of interest (AOI), which in this case are equal. In the lithography process, only a small section of the wafer is exposed at any given time and only deformations in this AOI need to be minimal. Additionally, the high number of control inputs further increases complexity.

3 Wafer Heating Model

For prediction of the induced deformations, quasi-stationary thermoelasticity is considered. This is a valid simplification, as the difference in time scales of both processes, thermal diffusion τ_d and mechanical elasticity τ_e , is so large, e.g.

$$\frac{\tau_d}{\tau_e} = \frac{\rho c_p \sqrt{\frac{\rho}{2\mu + \lambda}} L}{\kappa} > 10^8. \quad (1)$$

This model is then solved using the finite element method

(FEM) to give accurate temperature and deformation profiles.

4 Localized Feedforward Control

The control objective is to compute the optimal actuator forces $F_{act}(x, t)$, which minimize the worst case deformations of the wafer in the AOI, as a result of thermal induced deformations $d_{th}(x, t)$. This is achieved by the proposed controller using indicator functions to localize the problem to the AOI and relevant actuators. The effect each actuator has on the deformations of the beam is stored in $S(x, t)$. Relevant actuators are then those which have an effect in the AOI. This way a distributed controller is created which reduces the computational complexity of the problem significantly. Finally, the controller solves the constrained optimization problem,

$$\min_{F_{act}(x, t)} \|\beta(t) (d_{th}(x, t) + S(x, t) F_{act}(x, t))\|_{\infty}$$

$$\text{s.t. } F_{min} \leq F_{act}(x, t) \leq F_{max},$$

pointwise in time, to determine optimal actuator forces in x- and y-direction which are then applied in feedforward. Solving this problem over the length of the beam, gives the results shown in Figure 1.

Figure 1: Relative improvement of the ∞ -norm when optimizing deformations in x- and y-direction simultaneously.

References

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- [2] P. Kochersperger, Overlay correction by reducing wafer slipping after alignment, Patent US 20 070 165 357 A1.