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Data-Based Motion Control of Wafer Scanners

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Abstract: This paper gives an exposition of examples of data-based control and optimization that found their way to successful application in the motion systems of industrial wafer scanners. The examples represent selective works brought together in an overview that highlights the possibilities, challenges, and open issues in data-based motion control of wafer scanners.

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1. INTRODUCTION

Motion control is a key enabler for high-precision manufacturing. This is especially apparent in the semiconductor industry that involves the mass production of microchips. The key aspect in the production of these chips involves lithography (Levinson, 2010), responsible for creating the nano-scale patterns on a semiconductor substrate. The lithographic process is executed by wafer scanners that achieve sub-nanometer positioning accuracy of a mask's image during high-speed scanning motion (Butler, 2011).

Control of wafer scanners involves both feedforward and feedback control design. It concerns the wafer scanner modules: (a) the motion stages, (b) the optical column, (c) the material handlers, (d) the illuminator, and (e) the source, and deals with the multi-physical aspects associated with these modules like thermal dynamics, fluid dynamics/mechanics, and solid mechanics. If we restrict the scope to motion control systems alone, still the number of control loops in a lithographic tool is in the order of several hundred. It should be clear that manual tuning of such an amount simply becomes unmanageable, the more because machine-specific characteristics and disturbances increasingly require machine-dedicated tunings in meeting specifications. For this reason, the control of wafer scanners witnessed a steady trend toward data-based control and optimization; see in this regard also Steinbuch et al. (2005); Oomen et al. (2014) and the overviews therein. Data-based control is considered from the perspective of machine-in-the-loop adjustments of the controller parameters according to some cost criterion minimization, see also Hjalmarsson (2005); Van der Meulen et al. (2008). The adjustments are done on the basis of on-line measurements. The broader perspective of control without the explicit use of parametric models like data-based LQG control (Skelton & Shi, 1994), gradient-based $\mathcal{H}_\infty$ control (Den Hamer et al., 2009), and unfalsified control (Cabral & Safonov, 2003) or the model-free approaches such as considered in extremum seeking (Tan et al., 2010) or in nonlinear stochastic systems (Spall & Cristion, 1998) are considered beyond the scope of this paper. Instead, a selective set of data-based methods (tested by the author) is used to study and benchmark the possibilities, challenges, and open issues in data-based motion control. The selection is based on personal favor and does not attempt to be complete, not even in the closed context of wafer scanners.

The remainder of this paper is organized as follows. In Section 2 the motion control context in wafer scanners is discussed. This precedes an introduction on the principles of data-based optimization in Section 3. In Section 4, two examples of data-based feedforward control are given: (a) finite impulse response (FIR) feedforward control and (b) disturbance feedforward control. In Section 5, three examples of data-based feedback control are discussed: (a) dynamic decoupling, (b) iterative feedback tuning, and (c) variable gain control. In Section 6 an outlook is given on the main challenges and open issues.

2. MOTION CONTROL OF WAFER SCANNERS

Wafer scanners are lithography machines used to produce integrated circuits. A schematic representation of a wafer scanner is depicted in Fig. 1. Ultraviolet light travels from a source (located outside the tool) via an illumination system and through projection optics to the light sensitive layers of a wafer; typically a silicon disk of 300 mm in diameter. The light contains an image of the integrated circuits to be processed. The image is obtained from the reticle which is part of the reticle stage motion system. Similarly, the wafer is part of the wafer stage motion system. During wafer scanning, i.e., the dose-controlled wafer exposure by an (extreme or deep) ultraviolet light beam, both the reticle and the wafer stage systems conduct a series of synchronized point-to-point motions.

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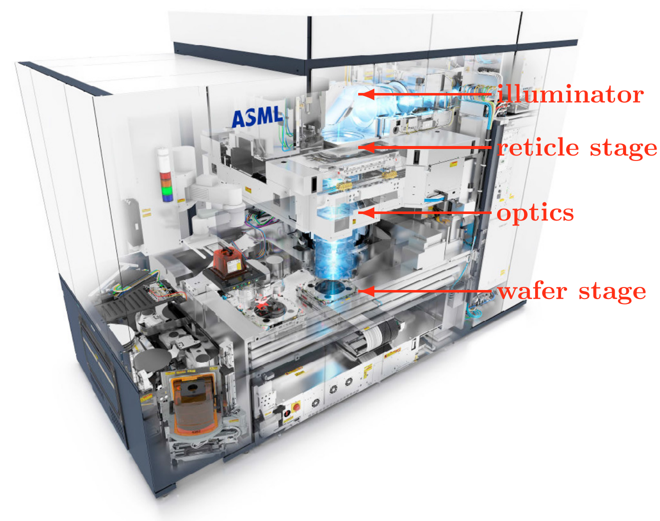

Fig. 1. Artist impression of a wafer scanner.

2.1 Motion Control Context

The simplified motion control context of a wafer stage system is depicted in Fig. 2. Assume the wafer stage plant

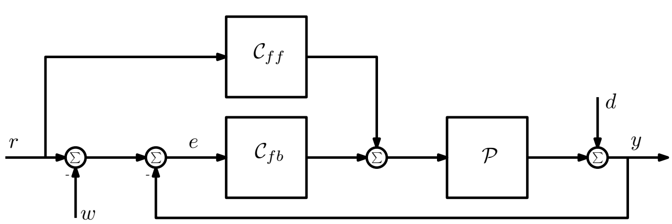

Fig. 2. Simplified motion control context.

$\mathcal{P}$ to be linear time-invariant (LTI) and single-input single-output (SISO) unless otherwise stated. $\mathcal{P}$ has output y which is corrupted by disturbances d and is controlled by feedforward controller $\mathcal{C}_{ff}$ and feedback controller $\mathcal{C}_{fb}$, which (for the time being) are assumed to be LTI too. In conducting point-to-point motion, tracking performance is given by the closed-loop error signal $e = r - w - y$, i.e., the difference between the reference command r, the output y, and an auxiliary input w to be defined.

2.2 Plant Description

Consider the wafer stage plant $\mathcal{P}$ in Laplace domain:

$$\mathcal{P}(s) = \frac{1}{ms^2} + \sum_{i=1}^{n} \frac{k_i}{m_i(s^2 + 2\zeta_i\omega_i s + \omega_i^2)} + \sum_{i=n+1}^{\infty} \frac{k_i}{m_i\omega_i^2}, \tag{1}$$

with m the mass of the system, n the number of truncated non-rigid body (NRB) modes, $\omega_i, \zeta_i, k_i, m_i$ the mode's resonance frequency, damping, gain, and mass respectively, and s the Laplace variable.

In the Bode diagram representation of Fig. 3, it can be seen by frequency response measurements that the short-stroke wafer stage according to (1) essentially boils down to a double-integrator based system with a mass of approximately 17.7 kg. At low frequencies, a poor signal-to-noise ratio leads to a poor identification result, see Oomen et al. (2014, Appendix A). At high frequencies, several resonances appear that associate with the structural flexibilities of the stage system.

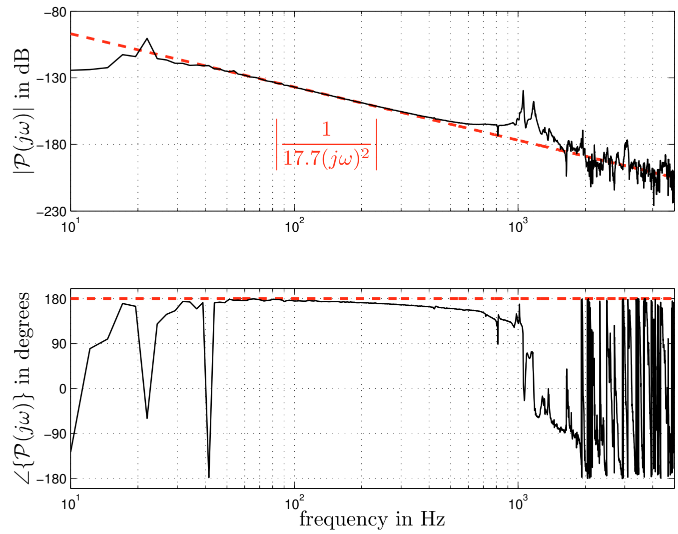

Fig. 3. Bode diagram of the measured frequency response data of a short-stroke wafer stage; 0dB = 1Nm^{-1}.

2.3 Feedback Control

Plant $\mathcal{P}$ from Figs. 2 and 3 is typically controlled by feedback controller $\mathcal{C}_{fb}$ of the form:

$$\mathcal{C}_{fb}(s) = \mathcal{C}_{PID}(s)\mathcal{C}_{LP}(s)\mathcal{C}_{N}(s). \tag{2}$$

The PID-controller part $\mathcal{C}_{PID}$, the low-pass part $\mathcal{C}_{LP}$, and the notch part $\mathcal{C}_N$ are given in frequency domain by

$$\mathcal{C}_{PID}(s) = \frac{k_p(s^2 + \omega_d s + \omega_i\omega_d)}{\omega_d s},$$
$$\mathcal{C}_{LP}(s) = \frac{\omega_{lp}^2}{s^2 + 2\zeta_{lp}\omega_{lp}s + \omega_{lp}^2}, \text{ and } \mathcal{C}_N(s) = \prod_{i=1}^{n} \mathcal{N}_i(s), \tag{3}$$

with the second-order notch filters

$$\mathcal{N}_i(s) = \left(\frac{\omega_{p,i}}{\omega_{z,i}}\right)^2 \frac{s^2 + 2\zeta_{z,i}\omega_{z,i}s + \omega_{z,i}^2}{s^2 + 2\zeta_{p,i}\omega_{p,i}s + \omega_{p,i}^2}. \tag{4}$$

Notch filters $\mathcal{N}_1, \mathcal{N}_2, \ldots$ are used (a) to deal with the dominant plant resonances and (b) to properly shape the open-loop characteristics as to achieve high controller bandwidth with sufficient robustness margins. Atop the basic PID controller structure in (2), (3), (4), many advancements have been proposed. Examples include (but are not limited to) multivariable $\mathcal{H}_\infty/\mu$ feedback control design (Van de Wal et al., 2002), linear parameter varying (LPV) control (Groot-Wassink et al., 2005), and nonlinear (variable gain) control (Heertjes et al., 2016).

2.4 Feedforward Control

Feedforward control is essential to achieve tracking performance at the nanometer scale while conducting aggressive motion profiles to guarantee productivity and (at the same time) meet settling time requirements. Feedforward control generally exploits the principles of plant inversion.

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