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Nonlinear iterative learning control with applications to lithographic machinery

Marcel Heertjes[a,b,*], Tim Tso[c]

[a]Philips Applied Technologies, Mechatronics Technologies, 5656 AE Eindhoven, The Netherlands
[b]Eindhoven University of Technology, Faculty of Mechanical Engineering, Dynamics and Control Technology, 5600 MD Eindhoven, The Netherlands
[c]ASML, Mechatronic Systems Development, 5504 DR Veldhoven, The Netherlands

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Abstract

An experimental demonstration is given of (nonlinear) iterative learning control applied to a reticle stage of a lithographic wafer scanner. To limit the presence of noise in the learned forces, a nonlinear amplitude-dependent learning gain is proposed. With this gain, high-amplitude signal contents is separated from low-amplitude noise, the former being compensated by the learning algorithm. Contrary to the underlying linear design, the continuously varying trade-off between high-gain convergence rates and low-gain noise transmission demonstrates a significant improvement of the nonlinear design in achieving performance.

Keywords: Iterative learning control; Feedforward control; Lifted system approach; Lithographic machinery; Lyapunov theory; Nonlinear control

1. Introduction

In the past decades, the fabrication of integrated circuits has greatly benefited from improved lithographic technologies. Herein the control design of a reticle stage containing the patterns needed for illumination and a wafer stage containing the wafers to be illuminated is of major importance. In terms of feedback control, both reticle and wafer stages are controlled using PID-based control schemes on a single-input single-output basis. To obtain nano-scale position accuracy within less than milliseconds of settling time, the main part of the control effort, however, is induced by feedforward control.

In terms of feedforward, this paper considers iterative learning control (ILC) as a means to obtain zero settling times on a reticle stage in scanning direction; see, for example, Bien and Xu (1998), Moore and Xu (2000), Norrlöf (2000), and Xu and Tan (2003) for a thorough treatment of ILC, its design methods, and fields of usage. Roughly speaking, ILC refers to the iterative process of finding the learned commands needed to improve performance under repetitive motion using information from previous executions of such motion. In the lithographic field, the application of ILC is not new, see for example Rotariu, Ellenbroek, and Steinbuch (2003), Rotariu, Dijkstra, and Steinbuch (2004), Dijkstra (2004), but application on an industrial scale is not often seen. The main contribution of this paper, however, is the introduction of a nonlinear learning gain to continuously balance the trade-off between noise transmission/amplification and error convergence rates as a means to surpass linear control performance; all linear ILC techniques suffer to a certain extent from noise amplification—recurring disturbances are attenuated, nonrecurring are amplified; in this context, see Moore (1999) and Tayebi and Islam (2006). Under nonlinear learning, signal contents beyond a pre-defined threshold level is subjected to nonlinear weighting: larger signal levels correspond to larger learning gains. Below this level signals like small noises induce a zero learning gain and as such are excluded from the learning process.

Stability of the discrete-time nonlinear learning control is derived on the basis of Lyapunov theory, see also French

*Corresponding author. Philips Applied Technologies, Mechatronics Technologies, 5656 AE Eindhoven, The Netherlands.
Tel.: +31 40 27 33424; fax: +31 40 27 33201.
E-mail addresses: m.f.heertjes@tue.nl, marcel.heertjes@philips.com (M. Heertjes), tim.tso@asml.nl (T. Tso).

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and Rogers (2000) and Yakubovich, Leonov, and Gelig (2004), the latter for a recent contribution to this field. Herein a distinction is made between the nonperturbed case with no external inputs like noises and the perturbed case having such inputs. In both cases exponential convergence of the learning scheme is derived as long as the servo errors during subsequent iterations contain elements that exceed the pre-defined threshold level. Performance is expressed in terms of convergence as well as time-domain (settling) behavior. By adapting learning gains, rates of convergence are obtained at which the underlying linear learning schemes become unstable. In fact, nonlinear learning is shown to combine fast convergence with robust stability, see de Roover (1996), Gunnarsson and Norrlöf (2001), and Tousain and Van de Meché (2001) for linear approaches based on optimal control with a similar aim. Zero settling is demonstrated on an industrial reticle stage module. By itself, this significantly contributes in optimizing wafer throughput and, therefore, helps improving general performance of lithographic machinery.

The paper is organized as follows. First, the modelling, dynamics and control of a reticle stage are considered. Second, the ILC scheme is proposed including the introduction of the nonlinear gain filter and a motivation for nonlinear learning. Third, a Lyapunov-based stability and performance analysis is conducted with special focus on convergence and robustness properties. Fourth, an experimental demonstration in time-domain is given towards zero settling times on a reticle stage of an industrial wafer scanner. This paper is concluded with a summary of the main findings regarding nonlinear learning in the context of lithographic machinery.

2. Modelling, dynamics, and control of a reticle stage

In the manufacturing of integrated circuits (ICs) wafer scanners provide the means to achieve both position accuracy, resolution within 70 nm, and production speed: over hundred wafers an hour each wafer containing over hundred ICs. During the scanning process light from a laser passes a reticle through a lens and onto a silicon wafer. Both reticle and wafer are part of two separate motion controlled sub-systems: the reticle stage and the wafer stage. For reasons of presentation, further discussion is limited to the reticle stage module. However, there is no fundamental reason to exclude the presented results from being applied to the wafer stage module, see, for example, Dijkstra and Bosgra (2002) for an approach in this direction.

Having two key modules, the long-stroke for fast positioning and the short-stroke for achieving position accuracy, see Fig. 1, the reticle stage mainly performs repetitive (scanning) motion in the indicated y-direction. Scanning refers to motion under constant velocity (typically 2.4 ms^{-1}) at which the process of wafer exposure takes place. It is performed in both the positive and negative direction within an effective stroke of 0.3 m. The short-stroke module—the long-stroke merely follows the short-stroke and as such is less relevant in the context of this paper—contains the reticle, a quartz object with a pattern of transparent and nontransparent regions; its terminology stems from retina being a light sensitive layer in the eyeball. It is controlled in six degrees-of-freedom on a single-input–single-output basis, see van de Wal, van Baars, Sperling, and Bosgra (2002) for a multi-input multi-output approach.

A simplified representation of the position tracking control scheme of the short-stroke reticle stage module in scanning direction is depicted in Fig. 2. On the basis of a reference signal r, an error signal e_y is constructed using the relation $e_y = r - y$ with y the position of the considered electro-mechanics given by P. The error signal e_y is fed into a controller C after which two signals are added: f_{ff} representing a simplified (inertial) feedforward signal based

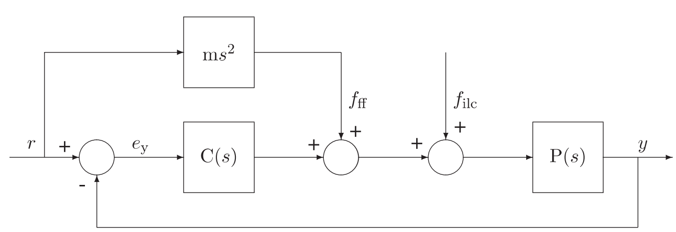

Fig. 2. Block-diagram representation (with s the Laplace variable) of a simplified position tracking control scheme for the short-stroke reticle stage module in scanning direction.

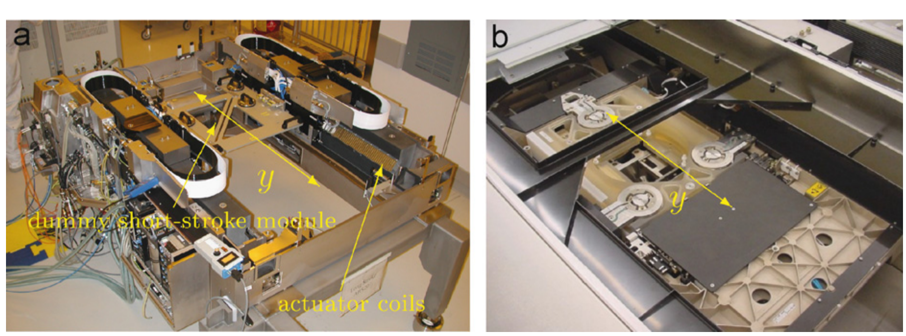

Fig. 1. Long-stroke (left) and short-stroke (right) reticle stage modules of an industrial wafer scanner: (a) long-stroke reticle stage module, (b) short-stroke reticle stage module.