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IFAC-PapersOnLine 49-13 (2016) 076–081

Continuous compliance compensation of position-dependent flexible structures

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Abstract:
The implementation of lightweight high-performance motion systems in lithography and other applications imposes lower requirements on actuators, amplifiers, and cooling. However, the decreased stiffness of lightweight designs increases the effect of structural flexibilities especially when the point of interest is not at a fixed location. This is for example occurring when exposing a silicon wafer. The present work addresses the problem of compliance compensation in flexible structures, when the performance location is time-varying. The compliance function is derived using the frequency domain representation of the solution of the partial differential equation (PDE) describing the structure. The method is validated by simulation results.

Keywords: partial differential equation, PDE, flexible structures, Euler-Bernoulli beam, feedforward, compliance compensation.

1. INTRODUCTION

In the semiconductor industry, the focus on ever improving throughput, overlay, and imaging of exposed silicon wafers traditionally lead to more aggressive motion profiles, i.e. higher accelerations, and structural designs with higher stiffness and mass. The required forces to be applied during operation are therefore higher, and thus increasing the demands on actuators, amplifiers, and cooling. The resulting force density and heat generation necessitated to accelerate the mass therefore becomes increasingly infeasible, which prompts for a paradigm shift toward more flexible lightweight designs. As a consequence, when the performance location changes with time during wafer exposure, the dynamics of the system change due to significant contributions from structural modes. This leads to the requirement of taking the time-varying aspect of the plant into account when calculating feedforward compensation forces, which are key in achieving position accuracy.

The traditional approach toward the positioning problem would be an acceleration (or mass) feedforward controller, but this is not sufficient to compensate for flexible dynamics. Moreover, snap feedforward control (Boerlage (2006)) can only account for structural flexibilities to a certain extend. Namely, it cannot cope easily with time or parameter varying dynamics. Iterative learning control (ILC) (Dijkstra (2004)), (van de Wijdeven (2008)), which exploits a converged feedforward signal (rather than a filter) using the measured error from consecutive experiments, has the limitation of being setpoint trajectory dependent. Additionaly, ILC is not likely to take the exact plant variation with respect to time into account, but can possibly use an uncertainty model to encapsulate this instead. More recently, spatial feedforward control (Ronde et al. (2012)) has been developed in order to prevent excitation of the structural modes of the positioning system. However this method uses over-actuation. Hence, the output of structural modes to be suppressed should equal the amount of additional actuators. Inferential motion control has been opted to tackle the problem of taking into account position-dependent dynamics (Oomen et al. (2015)), however with limitations, e.g. a fixed point-of-interest, and not yet in a feedforward framework. In Sato (2003) a method is presented to design a gain-scheduled inverse of a Linear Parameter-Varying (LPV) system. For this method, an infinite number of Linear Matrix Inequalities (LMIs) has to be solved, which poses a challenge. This issue is solved in Sato (2008), however, the solution is based on LMI formulations, which do not always render feasible solutions in the case of high-order industrial systems. In (Ronde et al. (2013)), the work closest to compliance compensation presented here, a feedforward method for flexible systems with time-varying performance locations is presented. The method utilizes a lifted feedforward (discrete-time) representation, however, it does not take the manner of plant variation in-between the time-intervals into account.

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10.1016/j.ifacol.2016.07.930

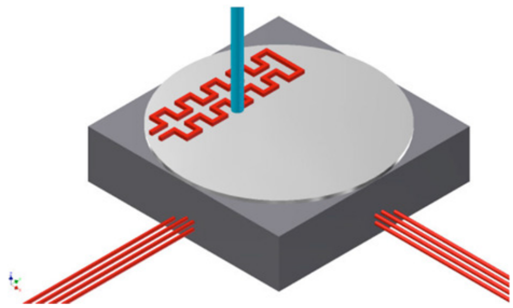

Fig. 1. Wafer stage of a lithographic system, where the sensors lie at the edges of the stage. During exposure of the silicon wafer to the laser beam, the performance location changes in time.

The contribution of this work is twofold. First, a position-dependent compliance compensation method is introduced, which accounts for the compliant part of the structural dynamics in the motion system. This is an extension of the work in Vervoordeldonk, Baggen (2009), and includes cases with a time-varying performance location such as occurring during wafer exposure. Secondly, the spatially continuous dynamics of the flexible structure (simplified by an Euler-Bernoulli beam) are derived from a partial differential equation (PDE). The PDE representation is exploited to derive the position-dependent compliance function of the beam. The method is validated by continuous-time simulation, using a simulation model containing a single structural mode, which is corrected to obtain the compliance of the original infinite-dimensional model.

The remainder of this paper is organized as follows. Section 2 introduces the compliance compensation control scheme and problem statement. Section 3 extends the compliance compensation concept to position-dependent distributed parameter systems with time-varying performance locations. Section 4 discusses the simulation environment and the results which validate the method. Finally, in Section 5, some concluding remarks are given.

2. PROBLEM STATEMENT

During the production of chips, a silicon wafer is positioned atop the wafer stage of the lithographic system. A source emanating (extreme) ultraviolet (EUV) light passes through the reticle, which is part of the reticle stage, and which contains a blueprint of the integrated circuits (ICs) to be processed. Beyond the reticle, light passes an optical system with controlled mirrors before it exposes the photo-sensitive layers of the wafer's surface. An illustration of the wafer stage during exposure is shown in Fig. 1. Assuming that it is a lightweight structure, i.e. its dynamics are substantially dependent on position, it follows that during exposure the time-varying performance location is subjected to position-dependent dynamics.

In light of these position-dependent dynamics, the compliance compensation method will be considered for infinite-dimensional flexible structures in Section 3 (see Vervoordeldonk, Baggen (2009)). In this section, the concept of compliance compensation is explained for the static output case only.

The block diagram of the proposed control scheme is given in Fig. 2, and consists of the following components,

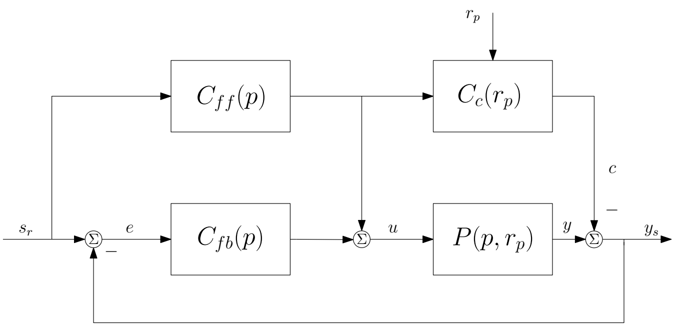

Fig. 2. Continuous compliance compensation control scheme. Since this block diagram contains time-varying dynamics, the *Laplace* variable s is replaced by the time differential operator, $p = \mathrm{d}/\mathrm{d}t$.

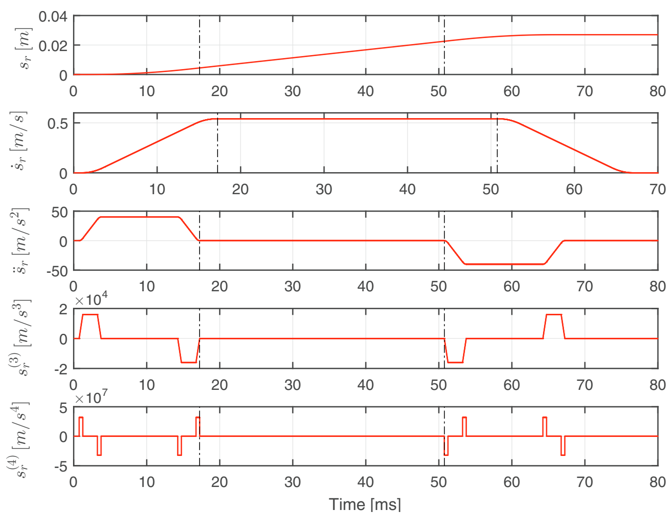

Fig. 3. Fourth-order reference setpoint s_r. The black dashed lines enclose the critical scanning interval (constant velocity).

(1) *Tracking setpoint:* The signal s_r is a fourth-order setpoint (see Fig. 3), which means that it is smooth up to its second derivative (acceleration), that is $s_r \in \mathcal{C}^3(0, \infty)$; note that the scanning interval of constant velocity (between the dashed lines) is the interval in which the tracking error is required to be small.
(2) *Plant:* The plant $P(p, r_p)$ is defined by either a finite or infinite-dimensional Single-Input Single-Output (SISO) flexible motion system, whose output location can be static or time-varying in nature. The performance location function r_p denotes the point-of-interest with respect (see below), and p is the time differential operator $p = \mathrm{d}/\mathrm{d}t$.
(3) *Feedback controller:* The Linear Time-Invariant (LTI) feedback controller $C_{fb}(s)$ (or $C_{fb}(p)$ in the time domain) acts on the error e between the setpoint and the plant output.
(4) *Performance location function:* In the case of position-dependent dynamics, which is considered in Section 3, a real function r_p is required, which indicates the performance location as a function of time $t \in \mathbb{R}$. For a distributed parameter system, we take $r_p \in \mathcal{C}^1$.