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Data-based spatial feedforward for over-actuated motion systems

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ABSTRACT

For advanced motion systems there is an increasing demand for higher production throughput and accuracy. Traditionally, such systems are designed using a rigid-body design paradigm, which aims at designs with high stiffness. The alternative is to design a lightweight system and deal with the resulting flexibilities by over-actuation and over-sensing. This paper presents a data-based spatial feedforward method based on previous task trials, which aims at reducing the vibrations over the complete structure during motion. The proposed method is experimentally validated on an industrial prototype and compared to standard mass feedforward using rigid-body decoupling.

1. Introduction

In the semiconductor industry there is an ever increasing demand for higher throughput and accuracy [1]. These demands lead to more aggressive motions and larger wafer sizes, which both lead to larger required forces to actuate the system. Moreover, miniaturization leads to higher demands on accuracy, which results in a higher required bandwidth of the system. Therefore, a system with increased stiffness is required, which possibly leads to more mass. The increased forces, due to increased mass and acceleration, lead to higher specifications on the actuators, amplifiers and cooling. In the rigid-body design paradigm this leads in an evolutionary way to systems with an increasing mass, which is expected to become infeasible in the near future due to thermal constraints. For a general introduction to the control of advanced motion systems see [2–4].

Therefore, the next generation of advanced motion systems, e.g. wafer-stages, pick-and-place machines and planar motors, will be lightweight. Compared to a rigid-body design, the differences in control design are:

1. mechanical resonances near the desired bandwidth of the feedback controlled system, and
2. due to the elastic deformations in the moving stage, the relation between the measured variables y and the performance variables z cannot be considered to be static anymore. Therefore, it does not suffice anymore to use geometric relations to calculate/control the performance variables. The difference between measurement and performance variables is illustrated in Fig. 1.

To deal with the challenges of advanced lightweight systems, such systems can be equipped with extra sensors and actuators compared to traditional design, i.e. over-sensing and over-actuation is applied [5–7]. Furthermore, to obtain the desired performance it is typically required to apply feedforward control. However, traditional feedforward methods do not any take advantage of over-sensing and over-actuation.

Snap feedforward [8,9] compensates the low-frequency contributions of the flexible modes, i.e. the deformation due to compliance during motion. However, such approaches only guarantee the performance at the sensors locations and not for the whole structure.

In [10,11] the parameters of a fixed-structure feedforward controller are optimized based on the measured tracking error of a previous experiment. Since this fixed-structure is based on snap feedforward, it suffers from the same drawbacks. In [12,13] a multivariable gradient-approximation-based algorithm is used to optimize a set of FIR feedforward filters. Since these feedforward filters can be of high order, it is possible to compensate more than the deformation due to compliance during motion. Nevertheless, no guarantees can be provided about the performance over the

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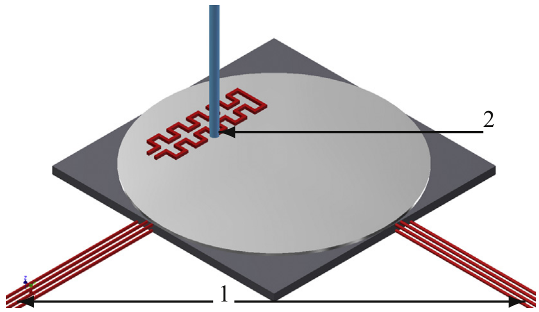

Fig. 1. Illustration of a wafer-stage, with the sensors at the edges of the stage (1), while the area to be processed is indicated by (2).

complete flexible structure. Additionally, in [14] it is shown that a second FIR filter is required to exactly obtain a zero error at the sensor locations in the ideal case. All fixed-structure feedforward methods can be regarded as ILC with basis functions, as shown in [15].

Learning control methods [16–19], such as iterative learning control (ILC) and repetitive control, use data from previous task trials to improve the performance. However, such methods do not provide any guarantees on global performance. Furthermore, the learned feedforward signal is specific for a chosen setpoint trajectory.

A different approach is presented in [20], where the feedforward signal from a converged ILC sequence is mapped into a FIR filter. In this way a setpoint trajectory invariant filter is created, which removes one of the common drawbacks of ILC.

In [21], an adaptive feedforward method with application to a long-stroke stage is presented. The advantage of this method is that differences due to position dependency can be compensated for, in contrast to ILC and fixed-structure feedforward. The presented framework aims at correcting the rigid-body behavior due to position dependency and does not exploit over-actuation. Therefore, only performance at the sensor locations can be guaranteed and it is expected that this will not result in the desired global performance for lightweight systems. Furthermore, actuators at fixed locations are considered in this paper, which typically have less or no position dependency.

A common approach to prevent the excitation of flexible modes is input shaping [22,23]. Typically, the setpoint trajectory is convolved with an input shaping filter, such that the resonance frequencies of the system are removed from the setpoint trajectory. Input shapers with positive coefficients are designed, such that the filtered signal satisfies the same bound as the original signal. However, by using such methods, a delay is introduced, which is typically not desired in the intended applications. It is possible to overcome this drawback by allowing negative coefficients for the input shaper. However, by doing so there are no guarantees for the filtered signals.

Model-based spatial feedforward [24,25] is a novel feedforward method for over-actuated systems, which provides guarantees for performance over the whole structure, i.e. *global performance*. However, this method relies heavily on the availability of a complex MIMO plant model to compute a (non-square) feedforward decoupling, such that the excitation of flexible modes by the feedforward can be prevented. Spatial feedforward can in fact be viewed as a special case of static input–output decoupling, see [26]. However, the typical aim and design freedom are quite different from standard input–output decoupling. In standard input–output decoupling the aim is to diagonalize the coupled plant, in order to facilitate decentralized feedback control design. Furthermore, static pre- and post-transformation matrices are available in contrast to spatial feedforward, where only a pre-transformation matrix is available. Therefore, standard input–output decoupling methods cannot be applied in a straightforward manner.

The approach presented in this paper shows an analogy with iterative feedback tuning (IFT). For an overview of IFT see [27–29]. The method presented in this paper has the advantage over IFT that closed-loop stability is not endangered, since only the feedforward controller is optimized. An IFT approach to decoupling is presented in [30,31], which both suffer from the same drawbacks as standard input–output decoupling methods.

In contrast to [25], it is assumed that only a model of the rigid-body behavior is available, i.e. without the flexible behavior. The intermediate step of obtaining a parametric MIMO plant model, such as is illustrated in [32], is replaced by dedicated parameter identification experiment. Furthermore, a data-based approach results in optimal controller parameters with respect to the actual plant, which is typically not the case for manual tuning or model-based approaches.

In contrast to the approaches in [10–13], this paper deals with over-actuated feedforward control, which results in feedforward controllers with an unequal number of input and outputs. Thereby exploiting the additional design freedom. Moreover, the class of systems considered in this paper, i.e. lightweight motion systems, can be considered as proportionally damped systems due to their low damping. This allows for the representation of these systems in modal form, which is exploited in this paper. The use of an initial feedforward controller with inaccurate estimates of the mass and principle moments of inertia of the system can cause errors which are orders of magnitude larger than the vibrations of the system. Therefore, the feedforward controller and feedforward decoupling are combined in one simultaneous optimization.

The contribution of the paper is fourfold, namely to provide a method which:

1. optimizes the over-actuated feedforward design, based on measurement data, as an extension of [24,25],
2. estimates mass and principle moments of inertia,
3. does not require the selection of modes, and finally
4. exploits the use of over-sensing.

Moreover, similar to model-based spatial feedforward [25] the presented method results in a parametric feedforward controller, i.e. suitable for different setpoint trajectories. Furthermore, this method does not introduce any delay or modification of the setpoint trajectory in contrast to input shaping.

The outline of this chapter is as follows. In Section 2 the problem is formulated. Subsequently, in Section 3 spatial feedforward is briefly discussed. The proposed data-based optimization algorithm is presented in Section 4. Also different methods for gradient estimation are presented. The data-based optimization is applied to an industrial prototype motion system in Section 5, where the method is also compared to mass feedforward with standard body-mode decoupling. Finally, in Section 6 the conclusions and recommendations are presented.

2. Problem formulation

Consider a motion system with modal or proportionally damped modes. Such systems can be written in the following modal description [33],

$$G(s) = C_m\left[Is^2 + 2Z\Omega s + \Omega^2\right]^{-1} B_m, = \left[C_b \mid C_{int}\right] \left[\begin{array}{c|c} \Theta^{(b)}(s) & \\ \hline & \Theta^{(int)}(s) \end{array}\right] \left[\begin{array}{c} B_b \\ \hline B_{int} \end{array}\right], \tag{1}$$

where B_m and C_m represent the model input- and output matrices respectively. The matrices Z and Ω contain the damping and