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Attenuation of disturbances introduced by dynamic links in precision motion systems using model-based observers

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ABSTRACT

This paper presents an extension to the Unknown Input Disturbance Observer (UIDO) and the Disturbance Estimation Filter (DEF). This extension enables the inclusion of the mechanics of dynamic links to the observer model, in order to attenuate the specific disturbances introduced by those dynamic links. A design method of the state space feedback gain based on the dynamics, and an observer gain based on basic Kalman filter theory is given. It is shown how the observer is designed for a practical example; the cable schlepp within the wafer stage of a lithography machine. Using a simple model of the cable schlepp the disturbance observer design has been validated with an experiment on an actual machine.

1. Introduction

In high-speed nano-scale positioning systems, such as the stages used in the wafer scanning industry shown in Fig. 1, high-speed motion is combined with nano-scale tracking precision. In terms of achieving servo performance, the combination of both speed and accuracy puts heavy demands on the control systems and design. The amount of disturbance rejection of the control system is limited due to the fact that the servo bandwidth is restricted by the elastic modes of the wafer or reticle positioning system [1]. A main source of disturbance forces are the so-called dynamic links [2]. These are for instance:

- hoses for transportation of coolant and gas, and
- wires and flexible printed circuit boards for electrical power and sensor signals.

With the cross-links between stages, movement of one stage is linked to the other, and vibrations of the dynamic links itself introduce disturbances to the stages. One example of a dynamic link is the cable schlepp attached to the long stroke of a wafer stage, as shown in Fig. 2. Disturbances of the cable schlepp to the long stroke are a main cause of a long settling time of the long stoke, and improving this would allow for an increase of performance.

In order to achieve a reduction of the effect of disturbances on a controlled system, the Unknown Input (state space) Disturbance Observer (UIDO) was introduced [3]. Within this structure the plant model in the observer is augmented by an autonomous system that describes the disturbance acting on the plant. The observer is used to estimate the states of the plant and the disturbance force acting on it. The estimated disturbance force is then used as a feedback force signal so that the error introduced by the disturbance is attenuated. This observer does not control the full system, a feedback control loop, with for example a PID controller and a feed forward as shown in Fig. 3, is needed to achieve the desired performance for high performance stage control. The separation of tasks allows for the independent design of both the position controller and feed forward mechanism to achieve maximum performance, and the disturbance observer to enable maximum disturbance attenuation.

Model based observers allow for the use of prior knowledge of the system to be applied directly for disturbance attenuation, instead of modifying the response of controllers and input of feed forwards to achieve the same goal. The observer has the advantage over controller loop shaping or feed forward frequency input shaping as only a single design effort for both feedback and feed forward control is needed.

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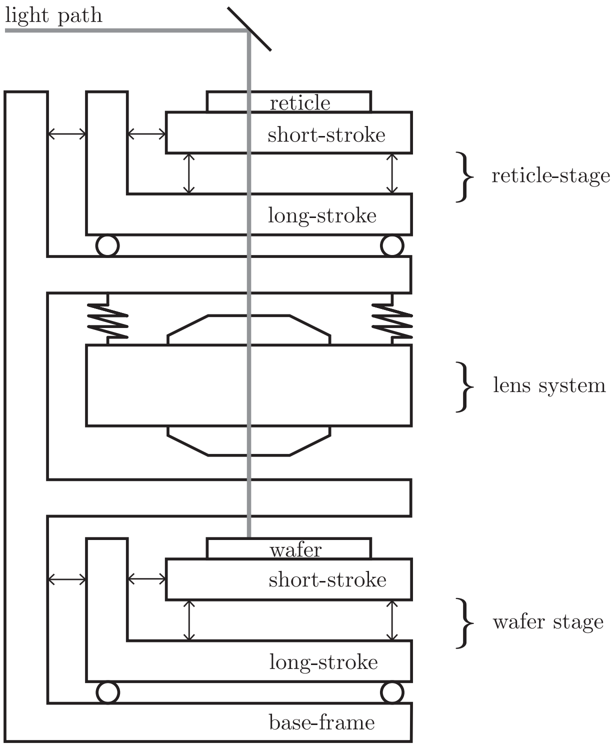

Fig. 1. Overview of the stages of a lithography machine.

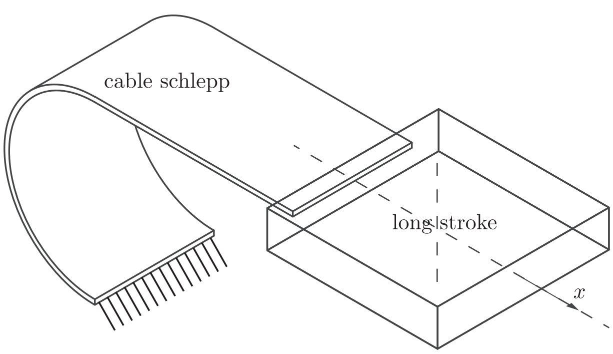

Fig. 2. Overview of a cable schlepp attached to the long stroke of the wafer stage. The length of the cable schlepp is in the order of a meter. For the purposes of this paper only moves in x-direction are considered.

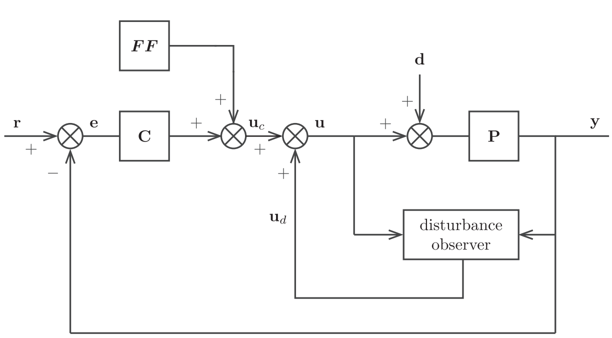

Fig. 3. Disturbance observer inside a control loop with the position controller C, feed forward FF and the plant P.

It was shown that the UIDO is a specific implementation of the Disturbance Observer (DO) or Disturbance Estimation Filter (DEF)

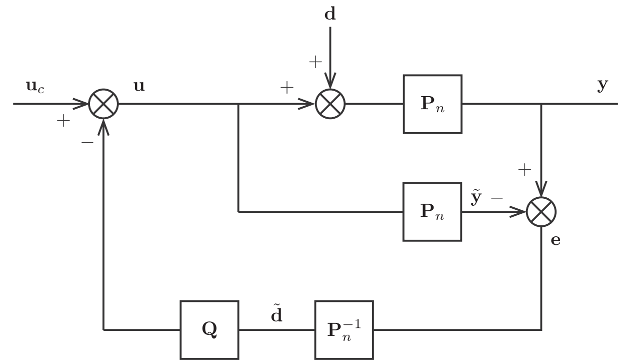

Fig. 4. General disturbance observer or disturbance estimation filter structure.

[4,5]. In Fig. 4 an implementation of the DEF structure is shown. By an inverse plant $\mathbf{P}_n^{-1}$ the disturbance force estimate $\tilde{\boldsymbol{d}}$ of $\mathbf{d}$ is reconstructed. With the filter $\mathbf{Q}$, the frequency content $\tilde{\mathbf{d}}$ is filtered such that stability of the observer is obtained. Fig. 4 emphasizes two general points of disturbance observers. The first is that disturbance estimation is effectively a plant inversion problem [6]. The second is that the source of the disturbance dynamics $\mathbf{d}$ is assumed not to be related to the input of the plant.

Both the UIDO and the more general DEF can be used to attenuate disturbances resulting from dynamic links. However, both do not use all information which can be gathered from the mechanics of the dynamic links. With application of analysis methods (e.g. FEM) for modeling dynamic links [7], more information about the nature of the disturbance is available which can be used to estimate and attenuate specific disturbances.

In this paper a method is presented which is an extension from both the DEF and UIDO, where the disturbance acting on a nominal plant is not assumed to be autonomous, but that the disturbance is an integrated part of the plant. The disturbance model is described with known parameters obtained from an analysis of the part of the system causing the disturbances on the nominal plant. Combined with an estimation of the states, this can be used to construct an estimation of the disturbance force on the nominal plant, creating an estimated input disturbance observer.

By considering this observer as an Internal Model Control (IMC) [8] problem, it is shown that the general disturbance observer problem is changed from dealing with the full input disturbance d (Fig. 4) to creating robustness for a possible model mismatch. It is shown that integration of the disturbance dynamics in the observer allows attenuation of disturbances close to the bandwidth of the control system.

This paper is organized as follows. In Section 2, the properties of the disturbances are modeled. In Section 3 it is derived how this model can be used to estimate the disturbance forces. In Section 4 the disturbance attenuation problem is rewritten to an IMC problem. In Section 5 it is shown how robustness to modeling errors is obtained. An experimental setup is described in Section 6. The disturbance observer design is validated with experiments on a lithography machine in Section 7. Finally in Section 8 some conclusions are given.

2. Modeling of the disturbance force

A dynamic link disturbance can be modeled as a linearized system shown in Fig. 5. The mass m_{stage}, for example representing a stage in a lithography machine, is position controlled in the degrees of freedom x_1 to x_n using a feedback system which has a force input F_1 to F_n. Connected to the mass m_{stage} with stiffness k_1 to k_n and damping c_1 to c_n are (smaller) masses $m_{d,1}$ to $m_{d,n}$ with