Estimating deformation of a free-floating wafer chuck

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Abstract

The deformation of a thin wafer chuck impairs the wafer positioning accuracy during exposure. Earlier work [1] described deformation estimation for a chuck without rigid-body motion. This paper treats estimation for a free-floating chuck in closed-loop control. Experimental results show that estimation with a strain sensor could reduce the estimation error by a factor of 6. Drift in the strain sensors is, however, an important challenge.

1. Introduction

In lithography machines, the wafer to be exposed is supported by a wafer chuck. The chuck moves the wafer underneath a lens column. Current 300 mm wafer chucks are optimized for stiffness in order to limit deformation and guarantee the accuracy of the exposure process. The possible transition to 450 mm wafer size will lead to an increase of chuck size and mass. The latter is unwanted, as the actuation forces and heat production during acceleration of the chuck also increase. A solution may be to reduce the chuck's thickness and to accept its lower mechanical stiffness. An additional control system could then be used to correct for the deformation. This requires an additional measurement system, which is not trivial. Due to space limitations and the lack of a stable reference, a direct deformation measurement at the point that is exposed (the *point of interest*, PoI)

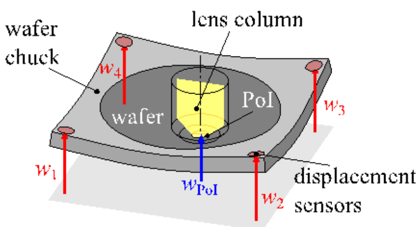

Figure 1. The metrology configuration in present lithography systems. The displacement at the PoI, w_{PoI}, can only be estimated from other measurements.

is not possible, see figure 1. Therefore, the deformation at the PoI needs to be estimated.

In previous work an estimation technique was developed that incorporated both knowledge of the chuck's mechanics and the typical disturbances that work on it [1]. It is known that mainly the low-frequency disturbances cause the wafer chuck deformation, so that the deformation may be considered *quasi-static*. Deformation was estimated in the absence of rigid-body motion.

This paper applies the estimation to a plate with a controlled rigid-body motion.

2. Rigid-body dynamics and flexible quasi-statics

Figure 2 shows the basic control system that is used for positioning wafer chucks. From the displacements measured at the corners of the chuck (w_1, w_2, w_3 and w_4) the rigid-body coordinates are estimated using transformation matrix $\mathbf{T}_y$. The estimate rigid-body coordinates are controlled using SISO PID controllers. Matrix $\mathbf{T}_u$ distributes the forces in rigid-body coordinates over four actuators near the chuck's corners [2].

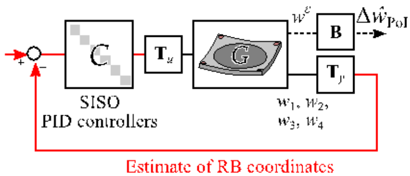

Figure 2. The control system that is used for positioning the wafer chuck.

The typical closed-loop transfer functions from a disturbance force at the centre of the chuck to the modal displacement contributions at the centre are plotted in figure 3. Clearly, the flexible modes have a flat magnitude and phase behaviour for frequencies below approx 10 Hz and can thus be considered *quasi-static*. The rigid-body modes, however, show *dynamic* behaviour, as their magnitude and phase is non-flat.

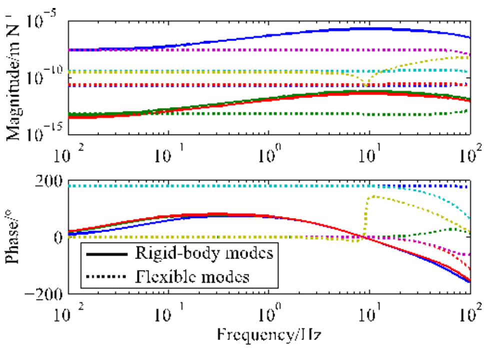

Figure 3. Transfer functions from a disturbance force to displacement at the centre of the chuck in terms of modal contributions.

3. Estimation algorithm

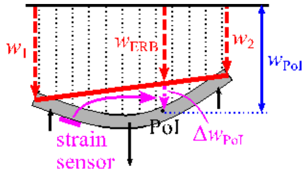

Figure 4. 2-D sketch of the estimation of w_{ERB} and w_{PoI}.

The estimate rigid-body (ERB) location of the PoI, w_{ERB}, can be calculated from displacement measurements w_1 to w_4 (figure 4) and consists of both rigid-body and flexible contributions. The difference between w_{ERB} and the actual displacement of the PoI, w_{PoI}, is called Δw_{PoI}. It is made up only from flexible contributions, which behave quasi-statically at low-frequency. Therefore, w_{PoI} could be estimated analogous to [1] as follows:

$$\hat{w}_{PoI}(t) = w_{ERB}(t) + \Delta w_{PoI} = w_{ERB}(t) + \mathbf{B}w^{\varepsilon}(t), \qquad (1)$$

where w^{ε} is a quantity proportional to deformation; for example, strain.

4. Method and results

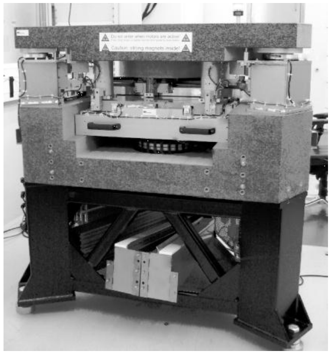

Figure 5. The experimental set-up.

A set-up consisting of a free-floating chuck was used for the experiments (figure 5). The chuck is suspended using four actuators, four displacement sensors at the corners and a control system as shown in figure 2. A fifth actuator at the centre of the plate was used to apply a predefined disturbance. The system's response was measured using a fifth displacement sensor at the centre.

The applied disturbance was a periodic signal composed of 3, 4 and 5 Hz sinusoids with an arbitrary magnitude and phase. The sensor signals were recorded and used to obtain the estimate rigid-body position, w_{ERB}. The additional deformation at the centre, Δw_{PoI}, was estimated using the signal of a piezoelectric strain sensor attached to the top surface of the chuck. As only one

Table 1. RMS values of the displacement signals and estimation errors with respect to the displacement signals. Measurement duration was 176 s.

RMS value/m	*original*	*drift-compensated*
Displacement signal (w_{PoI})	$1.135\cdot10^{-6}$	$1.135\cdot10^{-6}$
Error estimation rigid-body ($w_{ERB} - w_{PoI}$)	$0.093\cdot10^{-6}$	$0.074\cdot10^{-6}$
Error estim. rigid-body and strain ($\hat{w}_{PoI} - w_{PoI}$)	$0.103\cdot10^{-6}$	$0.013\cdot10^{-6}$

strain sensor and disturbance position were used, matrix **B** of (1) was simply a scalar, which was obtained from a calibration measurement. Finally, the total estimate, $\hat{w}_{\mathrm{PoI}}$, was compared to the direct measurement of the centre's displacement, w_{PoI}.

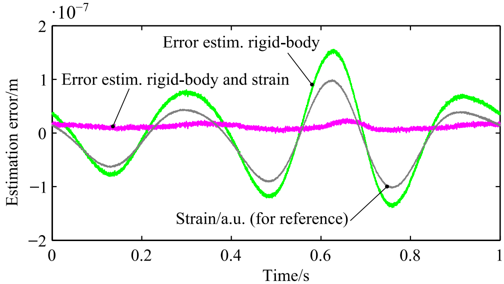

Figure 6. The estimation errors for one period of the drift-compensated signals.

Table 1 shows the RMS value of the displacement signal and the RMS values of the estimation errors. For the original signal, the estimation error with the strain measurement is larger than the one without. This is due to large drift of the sensor signal. In case the signal is drift compensated by period-wise averaging, use of the strain signal improves the estimate by a factor of 6. The graphs of the estimation errors for the period-wise averaged signals are compared in figure 6.

5. Conclusions and discussion

A wafer chuck subjected to low-frequency disturbances shows both rigid-body dynamics and quasi-static deformation. An estimate of the point of interest position based on rigid-body assumptions showed an error of around 7 %. The difference between the actual displacement and this rigid-body estimate is purely caused by the quasi-static deformation, which can be measured directly using strain sensors. The use of an additional strain measurement can potentially decrease the estimation error by a factor of 6; the current strain sensor, however, showed large drift.

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References:

[1] Vogel J G, Tejada A, Spronck J W and Munnig Schmidt R H 2013 *Proceedings of the ASPE Spring Topical Meeting* 70-5.

[2] Butler H 2011 *IEEE Control Systems Magazine* **31** 28-47.