Optimising mirror manipulator performance by means of robustness analysis of dynamics and control

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Abstract

The performance of manipulators of optical elements is often limited by the structural dynamics of its components. Moreover, the structural dynamics is subject to tolerances, parameter variations, and modelling errors, further limiting the achievable performance of the manipulator. In order to account for these uncertainties, this paper proposes the application of a robustness analysis in the process of the manipulator design. This approach optimises the manipulators mechanical design for maximum performance and ensures its achievement in practice.

1. Introduction

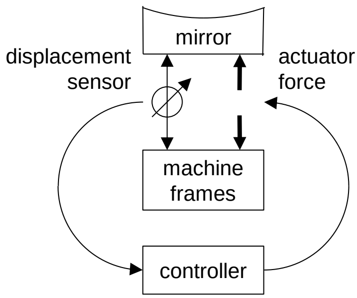

Figure 1: Scheme of a manipulator for optical elements

Lithography optics has taken the step from lenses for VUV (193 nm) to mirrors for EUV (13.5 nm). This step puts high demands on the position stability of the actively manipulated mirrors. Compared to lens-based systems, mirror-based systems have a significantly higher sensitivity of image stability to mirror motion. In terms of mechatronics, this translates into tough requirements on the control bandwidth for the position control loop of the actively controlled manipulators.

The task of the manipulator for optical elements, here in particular mirrors, is to keep the element stable at a certain displaceable position. The mechatronic components of the manipulators are a set of displacement sensors, a set of actuators and a multivariable position controller. In addition, the manipulator comprises one or more frames providing a position reference for the sensors and for absorbing the actuator reaction forces (figure 1).

In practice the bandwidth of the control loop is limited by the undesired but inevitable flexible natural modes of the mirror and of the involved components such as actuators and frames. This limitation cannot be overcome by controller tuning, if the natural frequencies are too close to the desired bandwidth. Therefore, the focus lies on designing the plant rather than the controller. This means designing the structural dynamics of the mirror and its surrounding components. This is done by repeated modelling and analysis of the control loop and by subsequent improvement of the shape and topology of the mechanical components.

It is state of the art to model the structural dynamics of the components by the finite element method (FEM) and to integrate these FEM-models into the dynamic model of the control loop. This allows to analyse the impact of the components structural dynamics on the control loop and to motivate design modifications of the components [1]. However, FEM models do not exactly match reality. Further, the structural dynamics can be sensitive to tolerances and/or parameter variations of critical components. To achieve the designed performance in practice while pushing the performance to its limit, these uncertainties need to be considered in the design.

2. Robustness Analysis

FEM-models reflect the dynamical response of the mechanical system for the designed parameters. The real dynamics might deviate from it for the following reasons: Tolerances of the mechanical parts, expected parameter variations and uncertainties of the modelling. The tolerances of mechanical parts are unavoidable. For dynamically sensitive parts such as monolithic hinges, they can have a significant impact on the system dynamics. The same is valid for expected parameter variations, for instance variations of the payload of a machine or macroscopic moves of machine parts such as stages or portals. Uncertainties in the FEM-modelling, like modelling of contacts and connections also lead to errors in the resulting dynamics of the model. For a robust and optimal design these uncertainties need to be considered in the analysis and design process.

2.1 Uncertainty Modelling

Ad hoc, modelling of parameter variations would mean to repeatedly built FEM-models with changed parameters. The course of action from CAD via FEM-modelling to a modal state-space representation is very labour-intensive. To reduce the workload the concept of Linear Fractional Transforms (LFT) is applied. It allows to use a single model for robustness analysis [2]. The parameters are varied by feeding back additional outputs to additional inputs. For mechanical systems, which are in the scope of this paper, two types of uncertainty models are of special interest: the uncertainty of lumped parameters and the uncertainty in natural frequencies.

Uncertainties of lumped mechanical parameters such as springs, dampers and/or masses are useful to model critical tolerances and parameter variations. These uncertain elements can be added effectively to a nominal FEM-model. Furthermore, FEM-modelling of flexible structures is typically quite precise in the shapes of fundamental modes, but the belonging natural frequencies can have a considerable error. Moreover, even small uncertainties of natural frequencies can show a significant impact on the FRF at a particular frequency of interest due to the sharpness of the resonances of lightly damped structures. Thus, modelling of uncertainty in natural frequencies can be very beneficial. These two modelling techniques are explained in detail in [3, 4].

2.1 Robustness Analysis

The development of a model with a LFT representation of the uncertainty opens the door to robustness analysis. There are several approaches to perform the robustness analysis. The brute-force approach is a grid search. For each uncertainty variable a grid over its range is defined. The system is analysed by permuting all combinations of the gridded uncertainty values. This approach gives great freedom in choosing the aspects of the analysis such as pole locations or FRFs and further probability of those properties can be predicted. This approach is efficient, if the number of uncertainty variables is small. To analyse systems with a larger number of uncertainties, μ-analysis [2] is one of the most established algorithms. Though, the analysis is restricted to the worst-case in frequency domain.

3. Examples

Two illustrating examples, the robustness analysis of the tolerance of actuator natural frequencies and the analysis of the effect of coinciding natural frequencies found in systems with multiple frames, are given in [4]. Figure 2 shows the closed-loop pole map for the first example, the uncertainty in actuator natural frequencies.

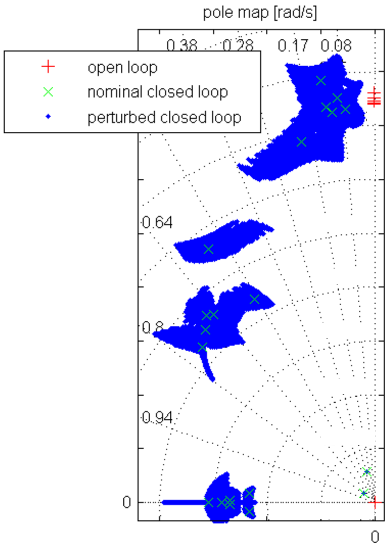

Figure 2: Pole map in presence of uncertainties[4].

4. Conclusions

This extended abstract introduces the application of robustness analysis techniques for the design of manipulators for optical elements. This technique allows to identify and quantify the sensitivity of a design to uncertainties in the structural dynamics. Thereby, it serves to optimise the components design regarding the obtainable control bandwidth and ultimately regarding the image stability.

References:

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