

State estimation for high tech flexible systems

Citation for published version (APA):

Verkerk, K. W., Butler, H., & Bosch, van den, P. P. J. (2014). *State estimation for high tech flexible systems*. Abstract from 33rd Benelux Meeting on Systems and Control, March 25-27, 2014, Heijen, The Netherlands, Heijen, Netherlands.

Document status and date:

Published: 01/01/2014

Document Version:

Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

State estimation for high tech flexible systems

K.W. Verkerk, H. Butler and P.P.J. v.d. Bosch

Eindhoven University of Technology - Electrical Engineering, Control Systems Group

k.w.verkerk@tue.nl

1 Introduction

In high tech positioning systems the goal is positioning of the moving part, hereafter called stage, within nanometers of the reference value. Due to the high accuracy required, we cannot view the stage as a purely rigid structure. In addition to the rigid body behavior we want to control, the limited stiffness of the stage results in lightly damped flexible modes. A flexible mode can be described by a temporal part, an oscillating state that slowly damps out, and a spatial part, the deformation of the stage caused by the flexible mode.

When reconstructing the position of the stage from the measurements the flexible modes are mapped on the six rigid body degrees of freedom. As a result the transfer function from forces in one direction to displacement in that same direction is not the expected mass line but instead contains (anti) resonance pairs. The sensors are placed on the fixed world and the stage moves relative to them. Therefore, the manner in which a sensor sees a flexible mode changes with position. This directly translates to a position dependent phase behavior of the (anti) resonance in the transfer functions. The position dependency makes it extremely hard to design a controller with a bandwidth that includes the flexible mode frequency. The limited bandwidth means the disturbance rejection in the system is limited as well.

These are the two major factors that make up the error between reference and actual position. The limited disturbance rejection results in errors due to disturbances in the system and the deformation of the stage results in additional mismatch between reference and actual position. To improve the positioning error we can either remove the flexible behavior from the system or ensure that it is at least removed from the transfer function. In this research we investigate how we can use state estimators to achieve these effects.

2 System description

The dynamics of the positioning system have been extensively modeled over the years. We know that the states of the system can be split in a rigid and flexible part, denoted by η_r and η_f respectively. The state space form (Σ_P) of these systems has the following structure

$$\Sigma_P \begin{cases} \begin{bmatrix} \dot{\eta}_r \\ \dot{\eta}_f \end{bmatrix} = \begin{bmatrix} A_r & 0 \\ 0 & A_f \end{bmatrix} \begin{bmatrix} \eta_r \\ \eta_f \end{bmatrix} + \begin{bmatrix} B_r \\ B_f \end{bmatrix} u \\ y = \begin{bmatrix} C_r & C_f \end{bmatrix} \begin{bmatrix} \eta_r \\ \eta_f \end{bmatrix} \end{cases} \quad (1)$$

For the observer (Σ_O) we will take a Luenberger type observer and investigate how we can use its estimate to improve the control performance.

$$\Sigma_O \begin{cases} \dot{\hat{\eta}} &= A\hat{\eta} + Bu + L(y - C\hat{\eta}) \\ z &= C_o\hat{\eta} \end{cases} \quad (2)$$

Here the A , B and C matrices are identical to those of the system and L is the observer gain to be designed. The matrix C_o is used to obtain the proper output for our observer such that we can use it in the control loop.

3 Possible solutions

As discussed before there are two main causes of the positioning error, the flexible modes in the system and the limited bandwidth due to flexible modes being mapped onto rigid body transfer functions.

When we want to remove the flexible mode from the system we can use the estimate of the flexible mode to close an extra feedback loop. This approach has the added benefit that removing the flexible mode from the system also removes its effect from the transfer function. We have added a degree of freedom, in addition to the rigid body modes we want to control a flexible mode as well. Because we need to have as many independent inputs to the system as degrees of freedom we want to control this method can only be applied if we have enough inputs.

In the case where no additional inputs are present we can still try to remove the flexible mode from the transfer function. For instance we could estimate the rigid body modes and use them for feedback or subtract the effect of the estimated flexible modes from the sensor measurements. Both ways result in a decreased visibility of the flexible modes in the transfer function. This allows for an increased control bandwidth and thereby, an increased disturbance rejection. We have to take into account that an increase in bandwidth will increase the energy we supply to the flexible modes and thus increase their influence on the positioning error. This leaves us with a tradeoff, we can increase the control bandwidth but the cost is an increase in energy supplied to the flexible mode. As long as the added disturbance rejection outweighs the increase in flexible deformation an increased bandwidth is viable.

We will apply both cases to a numerical example and investigate the effects on control performance. Model mismatch and unmodeled dynamics will also be taken into account.