Modal decoupling of a lightweight motion stage using algebraic constraints on the decoupling matrices

Modal Decoupling of a Lightweight Motion Stage Using Algebraic Constraints on the Decoupling Matrices

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1 Introduction

Current trends towards lightweight positioning systems from the lithography industry demand the usage of advanced servo control design methods that can actively control the unavoidable flexibilities. One solution is to use over-actuation, [1], and over-sensing and to control the rigid and flexible modes of the system in a decentralized manner.

Compared with the traditional decentralized control approach, in this work a more effective and a less conservative way towards a decentralized modal control is investigated for a 6 degrees of freedom motion stage. This paper describes a method to compute decoupling matrices Φ_u and Φ_y (Figure 1) that decouple the system in its rigid body(RB) modes and a number of non-rigid body(NRB) modes. Alignment and scaling of the rigid body modes are ensured. The decoupling enables the design of multi-loop SISO controllers, K, for the decoupled MIMO system, G_d.

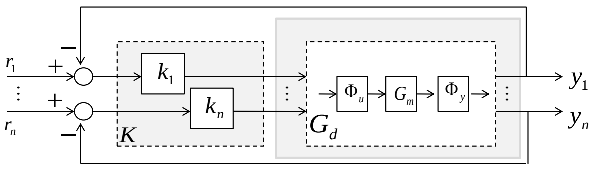

Figure 1. Multi-loop SISO modal control.

2 A new decoupling method for flexible motion systems

As described in [2] the transfer function of a dynamical system in modal coordinates $G_m(s)$ can be written as a sum of transfer functions for each mode i,

$$G_m(s) \quad = \sum_{i=1}^{n} C_{mi}(sI - A_{mi})^{-1} B_{mi}, \tag{1}$$

where A_m, B_m and C_m refer to the state space matrices in modal coordinates with compatible dimensions and n is the number of degrees of freedom of the system. When only positioning sensors are used the term $(sI - A_{mi})^{-1}$ from (1) will be diagonal.

In theory $\Phi_u = B_m^{-1}$ and $\Phi_y = C_m^{-1}$, but this is not possible since in practice the number of modes is larger then the number of inputs and outputs. Typically the RB modes are decoupled and controlled for high-feedback gains and the NRB modes critical for performance are damped using active vibration control methods.

The key idea is to decouple the modal system using geometric knowledge and by imposing a set of constrains. Therefore, to decouple for each mode i in terms of the modal input, the following equations should hold for the input matrix Φ_u

$$B_{mi} \cdot \Phi_{uj} = 1 \;\; for \;\; i = j, \tag{2a}$$

$$B_{mi} \cdot \Phi_{uj} = 0 \;\; for \;\; i \neq j, \tag{2b}$$

where $i = 1...n_d$ represents the $i-th$ row of B_m and $j = 1...n_d$ represents the $j-th$ column on Φ_u. Equation (2a) ensures that the mode i is controllable. By following the same approach the output decoupling matrix Φ_y can be found.

3 Results and conclusions

The proposed approach is applied to an experimental setup that has 14 inputs and 14 outputs. The traditional approach, 6 RB decoupled modes (case 1) is compared with the approach described in this paper, where beside the 6 RB also 7 NRB modes have been considered for decoupling (case 2). The results in Figure 2 clearly show a better decoupling (especially in low frequencies). This can enable the achievability of better servo-performance with control.

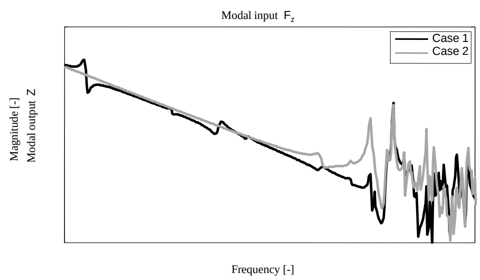

Figure 2. Z-direction mode for two decoupling cases: (case 1) when only the 6 RB modes are decoupled and (case 2) when 7 more NRB are decoupled together with the 6 RB modes .

If the system is oversensed/overactuated, then by a proper choice of modes to be made explicitly controllable, observable or uncontrollable/unobservable the maximum values of achievable bandwidths can be increased.

References

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[2] Wodek K. Gawronski. *Advanced Structural Dynamics and Active Control of Structures*. Springer, 2004.