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 \( \Phi_m \) and \( \Phi_s \) (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, \( G_d \).

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 \( i \),

\[
G_m(s) = \sum_{i=1}^{n} C_m(sI - A_m)^{-1} B_m i,
\]

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 \( (sI - A_m)^{-1} \) from (1) will be diagonal.

In theory \( \Phi_m = B_m^{-1} \) and \( \Phi_s = C_m^{-1} \), but this is not possible since in practice the number of modes is larger than 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 \( \Phi_m \)

\[
B_{mi} \cdot \Phi_{mij} = 1 \quad \text{for} \quad i = j, \quad (2a)
\]

\[
B_{mi} \cdot \Phi_{mij} = 0 \quad \text{for} \quad i \neq j, \quad (2b)
\]

where \( i = 1...n_1 \) represents the \( i \)-th row of \( B_m \) and \( j = 1...n_2 \) represents the \( j \)-th column of \( \Phi_m \). Equation (2a) ensures that the mode \( i \) is controllable. By following the same approach the output decoupling matrix \( \Phi_s \) 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 achievement of better servo-performance with control.

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
