GAIN-SCHEDULING CONTROL OF MACHINE TOOLS WITH VARYING STRUCTURAL FLEXIBILITIES

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Summary In this paper an experimental set-up, consisting of one axis of an industrial pick-and-place machine, driven by a linear motor, is controlled based on the gain-scheduling approach. The set-up contains a flexible arm of which the stiffness depends on its length. Next to an ad-hoc scheduled H∞ controller, analytically scheduled controllers are designed using a global linear time varying (LTV) model of the set-up. Experiments show that scheduling is necessary if high-performance controllers are demanded.

INTRODUCTION

The growing competition on the international markets pushes manufacturers towards faster machine tools while preserving or improving final accuracy. High accelerations of the fast machines excite the machine structure up to high frequencies thereby exciting the structure's modes of vibration. These structural vibrations need to be damped if accurate positioning or trajectory tracking is required.
An additional problem is that the dynamical behaviour of the machine tool depends on the position of the work tool as a consequence of the varying machine configuration during machining. Such time-varying behaviour cannot be controlled by classical linear control methods as these methods require a linear time invariant (LTI) model of the system. One solution to this problem is to ensure that the designed LTI-controller makes the system behaviour robustly stable against the varying dynamics of the machine tool. The performance of the closed loop behaviour however could be improved if the variations could be included in the controller by making the controller also dependent on the instantaneous configuration of the machine tool by *gain-scheduling*. In classical gain-scheduling, LTI controllers are designed for several fixed positions of the machine, and these controllers are scheduled ad-hoc. More recent design methods for gain-scheduling controllers start from a linear parameter varying (LPV) description of the model [1]. Using this kind of models, criteria for robustness can be derived analytically. The most up-to-date and generalised framework for LPV-based control design is given in [3].

DESCRIPTION OF THE SET-UP

In this paper, the control of the X-Z axis of a Philips 4-axis pick-and-place machine (FlexCell) is considered (Fig. 1). The position of the X-motor and the length of the vertical arm are measured with an optical encoder. An accelerometer measures the acceleration of the end point of the arm. The objective is to move the end point of the arm accurate and fast along a prescribed trajectory in the X-Z plane. Fast movements of the linear motor will excite the eigenfrequencies of the flexible arm.

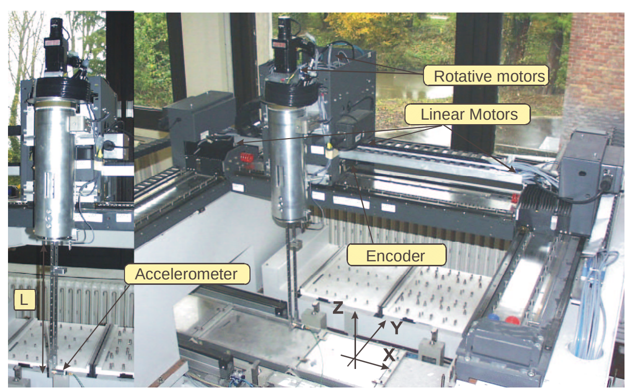

Fig. 1: Set-up: pick-and-place machine.

EXPERIMENTAL IDENTIFICATION OF THE SET-UP

Fig. 2 shows frequency response functions (FRFs) from the linear motor force excitation to end point acceleration, for different lengths of the arm. This figure clearly shows the dependency of the first two eigenfrequencies of the arm on the length of the arm. The FRFs from the motor force to the motor displacement and from the rotative motor input torque to the Z-position of the tool tip do not depend on the length of the beam and are omitted for reasons of brevity.

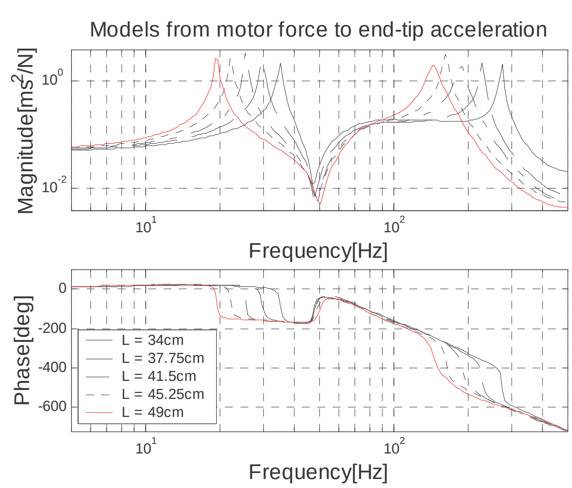

Fig. 2:FRFs from linear motor force excitation (N) to end point acceleration (m/s^2).

CONTROL DESIGN

The objective of the control design is to move the end point of the arm as accurate and fast as possible using the actuators that are present on the machine tool. For the set-up the motion controller is designed with a vibration controller in a HAC-LAC structure [2] (Fig. 3). The position of the motor is used for the position control of the end point of the arm and the acceleration of the arm tip is used to damp the vibrations.

VIBRATION CONTROLLER

In this section, vibration controllers aimed at damping the first eigenfrequency of the flexible arm are presented.

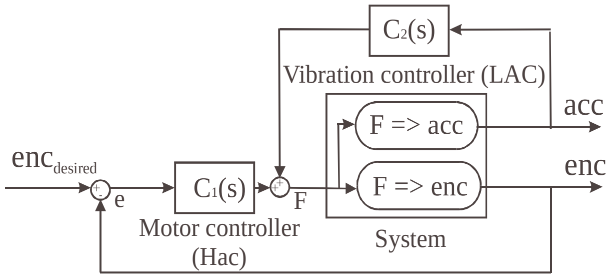

Fig. 3: Control scheme.

Ad-hoc scheduled H∞ controller

H∞ controllers [4] are designed for constant arm lengths to suppress both disturbances entering at the motor input and at the end point of the arm. These controllers are linearly scheduled based on the arm length and result in a controller with high performance as will be shown in the next section.

Analytically scheduled LPV controller

The robustness of the ad-hoc scheduled H∞ controller is not guaranteed theoretically. To guarantee this stability a model is needed that depends on the length of the arm. Such a model is called a linear parameter varying (LPV) model.
The most general framework for LPV-control design is presented in [3] and writes the design problem as a linear matrix inequality (LMI) that needs to be solved to obtain the controller. An LPV model of the set-up is identified and used to design an LPV controller. The performance of this controller is very low compared to the scheduled H∞ controller. The inherent conservatism of the used LPV-design method and bad numerical conditioning of the resulting LMI design problem explain this low performance.
As the synthesis of LPV controllers proved to be conservative and the analysis tools for LPV systems are less conservative, an LPV model is identified for the ad-hoc scheduled H∞ controller and the resulting closed-loop system is analysed for stability and performance. Even the state-of-the-art analysis tools are however not able to predict the correct stability region of this closed loop LPV system as they are still conservative to an extended degree.

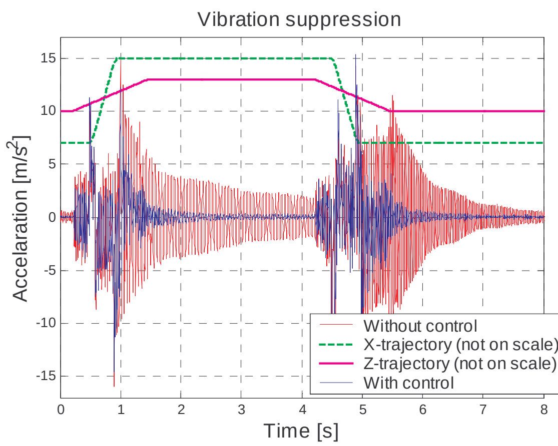

Fig. 5: Response with and without the scheduled H∞ controller.

EXPERIMENTAL RESULTS

To validate the different controllers a reference trajectory is applied to the set-up. Fig. 5 shows the acceleration signal for this trajectory with and without vibration control for the scheduled H∞ controller. The figure clearly shows the damping effect of the controller. For reasons of brevity the (poor) results of the analytically scheduled controller is not shown in the paper.

CONCLUSIONS

In this paper ad-hoc scheduled H∞ controllers and analytically scheduled LPV vibration controllers are designed for a machine tool with varying dynamic stiffness. The performance of the analytically scheduled controller is much lower than this of the ad-hoc scheduled controller. This can be explained by the extended degree of conservatism that is introduced in the LPV design methods and numerical limitations of present day LMI solvers.
This study shows that further development of the LPV-tools is necessary to be able to design high-performance analytically scheduled LPV controllers for motion and vibration control systems for machine tools.

Acknowledgments

This research is sponsored by the Belgian program of Interuniversity Poles of Attraction by the Belgian State, Prime Minister's Office, Science Policy Programming (IUAP). W. Symens was a Research Assistant of the Fund for Scientific Research - Flanders (Belgium) (F.W.O.) in the period that this research was performed (1999-2003).
The authors would like to thank Carsten Scherer for providing a draft version of the LPV-synthesis toolbox.

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