POLE-PLACEMENT VS. LOOP-SHAPING DESIGN FOR GAIN-SCHEDULING CONTROL OF MACHINE TOOLS WITH POSITION DEPENDENT DYNAMICS

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Abstract

The high accelerations together with the high controller bandwidths required from present-day machine tools are likely to excite the vibration modes of the machine structure. In order to achieve a high control bandwidth and high contouring accuracy, these structural eigenfrequencies need to be incorporated in the controller design. An additional complication with machine tools is that the structural eigenfrequencies are not constant but depend on the position of the tool in the workspace of the machine tool, with as consequence that the machine model is position dependent and therefore cannot be modelled as a single linear time-invariant (LTI) model. To control such linear time-varying (LTV) systems, two approaches are possible: (i) the controller is such that the system behaviour is largely independent from system parameter variations (robust control), and (ii) adapt the controller structure or parameters to the system parameter variations, e.g. by gain-scheduling. 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. Pole-placement and loop-shaping controllers are designed for several constant arm lengths and these controllers are linearly scheduled in a global gain-scheduling controller. Experiments show that scheduling is necessary if high-performance controllers are demanded.

1 Introduction

The ever growing competition on the international markets pushes manufacturers towards shorter design cycles and decreasing manufacturing times for their products. This reduced time-to-market pressure generates a demand for faster machine tools that can reduce machining time, while preserving or improving the final accuracy. Machine tool producers try to meet these goals by designing light, but rigid, mechanical structures. With the existing materials, it is presently very difficult to further reduce the mass in an economic way, without reducing the stiffness. This makes it difficult to achieve higher acceleration, without losing accuracy. High accelerations excite the machine structure up to high frequencies thereby exciting the structure's modes of vibrations. These structural vibrations need to be damped if accurate positioning or trajectory tracking is required.

An additional problem in machine tools (and other 3-axis machines like for example co-ordinate measuring machines (CMMs)) 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. An analysis of such behaviour for a finite-element model of a milling machine is given in [5]. This analysis shows that the variations in dynamical behaviour (e.g. shift in natural frequencies) of a machine tool between two extreme configurations can be considerable. Such time-varying behaviour cannot be controlled by classical linear control methods [6] as these methods require an LTI (Linear Time Invariant) 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. In [5] an H_∞ controller is designed, based on a nominal LTI model, that makes the controlled system robustly stable for all dynamical variations between extreme tool positions while still achieving nominal performance. In [3] both H_∞ and sliding-mode techniques are used to design robust motion controllers for high-performance machine tools driven by linear motors.

The above mentioned robust control techniques only assume that the dynamical behaviour of the system is situated within a certain band around the nominal dynamical behaviour, without knowing the dynamics exactly. In machine tools, the dynamical behaviour depends on the position of the tool, and since this position can be measured in real-time, the dynamics are always known. The performance of the closed loop behaviour therefore could be improved if this knowledge could be included in the controller, that is, making the controller also depending on the instantaneous configuration of the machine tool. This can be done based on *adaptive* control techniques, where the LTI model is updated based on real-time measurements [2], or with *gain-scheduling*, where the controller depends on a measurable variable. The first method is more suited for slowly varying systems, which can be identified on-line, as is for example the case for the influence of the ambient temperature on the dynamical behaviour of the machine tool. The second method assumes that the dynamical model as a function of an externally measurable parameter is known beforehand, and thus does not need an on-line identification. As the dependence of the dynamical behaviour of the machine tool is known beforehand, the *gain-scheduling* technique is chosen to design a high-performance controller for machine tools with position-dependent dynamics. In classical gain-scheduling [2], an LTI model of the system is identified for different values of the scheduling parameter. For these LTI models, LTI controllers are designed, which are then scheduled ad hoc, for example in a linear way [13]. Because of this ad-hoc scheduling, extensive simulations or experiments are needed to guarantee robustness of the closed loop system. More recent design methods for gain-scheduling controllers start from an LPV (Linear Parameter Varying) [1]description of the model. Using this kind of models, criteria for robustness can be analytically derived.

In the rest of the paper, section 2 gives a detailed description of the set-up under consideration. Section 3 describes the identification of the set-up. The results of this identification are used in section 4 to design different controllers. Section 5 shows the experimental results obtained with the designed controllers. Finally some conclusions and directions for further research are highlighted in section 6.

2 Description of the set-up

In this paper, the control of one axis of a Philips 4-axis pick-and-place machine (FlexCell) is considered (Figure 1). The total machine consist of a gantry driven by two linear motors taking care of the y-motion. The x-motion of the carriage over the gantry is also driven by a linear motor. The vertical z-motion is a traditional rotary motor drive with ball screw/ball nut combination. Rotation of the quill around the z-axis constitutes the fourth axis. For this analysis only the x-axis linear motor is used together with the rotative motor to move the arm along the vertical z-axis. Using these motors the end point of the arm can be moved in the x-z plane.

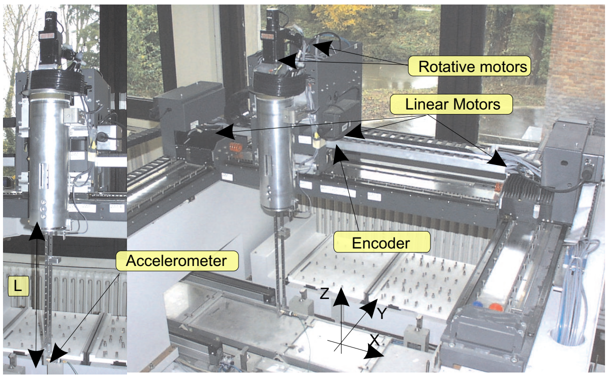


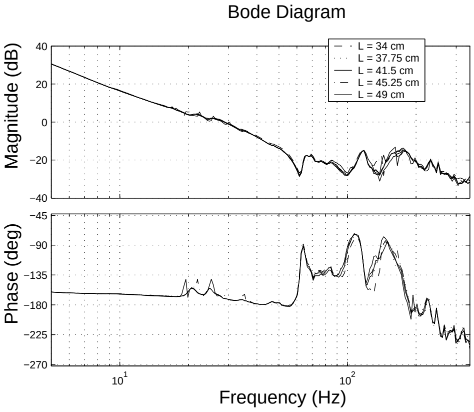
Figure 1: Set-up: pick-and-place machine

The position of the linear motor and the length of the beam are measured with an optical linear encoder. An accelerometer measures the accelearation of the end point of the arm.

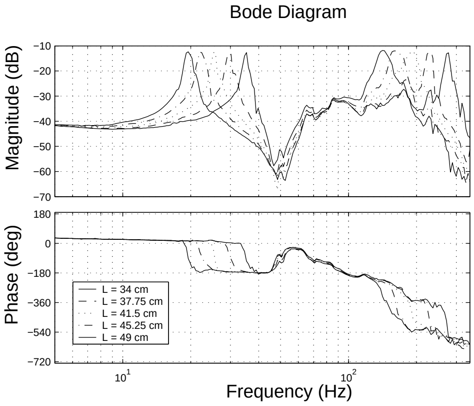
The objective is to move the end point of the arm as accurate and fast as possible along a predescribed trajectory in the x-z plane. Fast movements of the linear motor will however excite the eigenfrequencies of the flexible arm. During the motion, the length of the arm is continuously changed, giving rise to varying vibration frequencies and hence an LTV system to be controlled. The controllers to be designed have to damp out these vibrations in a robust way.

3 Experimental identification of the set-up

To design LTI controllers, LTI models are needed. These models can be obtained by different time- or frequency-domain methods [10]. Figure 2 shows frequency response functions (FRFs) from the linear motor force excitation (input) to the linear motor position (output) and end point acceleration (output), for different lengths of the arm, using a stepped-sine input signal.



(a) FRF for linear motor force excitation (N) to motor position (μm)



(b) FRF for linear motor force excitation (N) to end point acceleration (m/s^2)

Figure 2: FRFs for linear motor force excitation

Figure 2(b) clearly shows the dependency of the first two eigenfrequencies of the arm on the length of the arm. These eigenfrequencies do not depend on the amplitude of the excitation signal.

As can be inferred from Figure 2(a), the system has a mass-line characteristic (-40 dB/decade for the position output FRF) for low frequencies and some resonances at higher frequencies. The effect of the length of the arm on these FRFs can however be neglected.

As one excitation signal and two measurement signals are available, a SIMO model should be fitted on the different FRFs. This is however much harder to realise than fitting two SISO models on the measured FRFs, and as the influence of the resonance of the flexible arm on the FRF of the motor is negligible, the choice is made to model the system as two SISO models.

The FRF from the rotative motor input torque to the z-position of the tool tip shows a mass-line characteristic and is omitted for reasons of brevity.

4 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.

As shown by previous experimental studies [4] an appropriate way to design a controller for such a system is to design the motion controller around the system with a vibration controller in a Hac-Lac structure [9]. Figure 3 shows this control scheme in which the High- Authority motion controller (Hac) is built around the Low-Authority vibration controller (Lac). This structure however demands that the motion controller is redesigned for every vibration controller and thus also depends on the length of the arm. Figure 2(a) however shows that in open loop the FRF to the motor position is influenced little by the arm length and experiments also show that this is the case for the closed loop system. Therefore an adapted Hac-Lac structure is chosen where the motion controller is designed independent from the vibration controller.

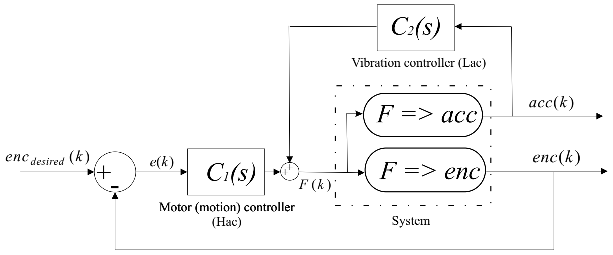


Figure 3: Control scheme

The position of the motor is used for the position control of the end point of the arm. An error is thus made, which is however small when the vibration controller works properly.

4.1 Linear and rotative motor motion controller

The motion controller for the x and z-movement are lead-lag controllers designed following the procedure in [6]. The model used for this controller is a pure mass-line identified on the FRF in Figure 2(a). The desired bandwidth of the closed loop system is 35 Hz. No roll-off is needed in the controller, because of the roll-off resulting from the mass-line characteristic.

4.2 Vibration controller

In this section, vibration controllers aiming at damping the first eigenfrequency of the flexible arm are presented. Only the first eigenfrequency is damped because the required bandwidth only exceeds this eigenfrequency.

Both pole-placement controllers and loop-shaping controllers are designed for the vibration suppression.

Pole-placement controllers

In the pole-placement control design method [6], the poles of the original system are shifted to desired positions by a constant state feedback matrix K. As the objective is to damp the first resonance of the flexible arm, which corresponds to one pair of complex poles of the global system, pole-placement seems to be the most appropriate controller design method.

To implement this pole-placement controller, all the states of the system need to be known. As not all states can be measured, an observer needs to be designed. A rule of thumb to design this observer is that the poles of the observer need to be at least ten times faster than those of the controller [6]. Observers that are that fast however react nervously to the second resonance of the flexible arm, thereby deteriorating the performance of the controller. This is also observed in [12] where a pole-placement controller is used to control a nonlinear car suspension. Therefore the poles of the observer are chosen as fast as the original poles and damping is added to the lowly damped poles. Because we are only interested in the first resonance of the flexible arm, only this resonance is modelled for the design of the pole-placement controller. Figure 4 shows these models for four different arm lengths: 34, 39.3, 44.6 and 49.9 cm. An additional advantage of only modelling the first resonance is that the controller is of lower order.

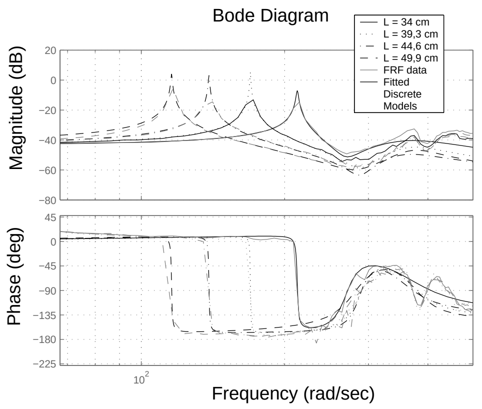


Figure 4: Models for pole-placement controllers

The desired poles of the closed loop system are the same as those of the open loop system, except for the first resonance of the flexible arm, for which damping is added. The pole-placement controller is implemented as a tracking error estimator. More details about the implementation of this controller can be found in [8].

A pole-placement controller is designed for the four different arm lengths. Each controller is only valid for the arm length for which it is designed. The closed loop system can even become unstable when a pole-placement controller designed for one arm length is used for another arm length as is shown in Section 4. Only when a very low performance is demanded, is the controller stable for all the arm lengths. This shows that a gain-scheduling controller is needed to obtain a high-performance controller for all arm lengths. The question now arises how to schedule the four different controllers. An indication to derive the gain-scheduling scheme is the dependence of the first eigenfrequency of a clamped beam on the length of the beam. Figure 5 shows this dependence together with the measured frequencies. From this figure it can be concluded that a small error is made when the different eigenfrequencies are linearly interpolated. This observation however does not theoretically validate the linear scheduling of the pole-placement controllers, as the controller signals do not linearly correspond to the eigenfrequency of the open loop system. Intuitively the error however is expected to be small and as linear scheduling is a simple way of interpolation the gain-scheduling controller is calculated as a linear interpolation of the two *nearest* controllers.

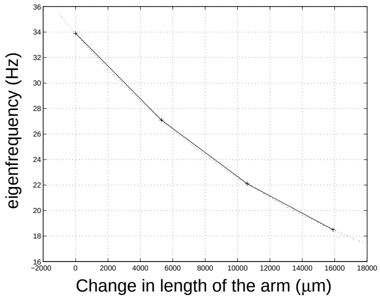


Figure 5: Evolution of the first eigenfrequency of a clamped beam

A more logical scheduling approach, instead of scheduling the output signals of the controllers, would be to schedule the parameters of the controllers and observers. This is however not possible for the pole-placement controllers as the values of these parameters do not vary smoothly (not even monotonically) for varying arm lengths.

Loop-shaping controller

The design of a feedback control system may also be viewed as a process of *loop-shaping*. This means that the feedback controller is designed such that the loop gain FRF has a suitable shape. This design procedure is described in for example [11]. The design goals are as follows: high gain at the frequency that needs to be damped, sufficient phase margin at the desired bandwidth and sufficient roll-off at high frequencies to prevent noise amplification and obtain sufficient robustness. Integral action is not needed as the acceleration signal is not used for tracking, only for vibration suppression. The integral action in included in the motion controller described in Section 4.1.The bandwidth of the controllers for the different arm lengths is set at 40 Hz. Remark that this is above the eigenfrequency of the arm in the upper position. This controller does not depend on the length of the arm, as the behaviour of the system around the break frequency does not depend on this variable.

Experiments show that a notch filter needs to be added to the controller at the second resonance frequency of the arm to prevent the closed loop system becoming unstable. Including this notch filter makes the controller again dependent on the length of the arm. Figure 6 shows these loop-shaping controllers for the different arm lengths.

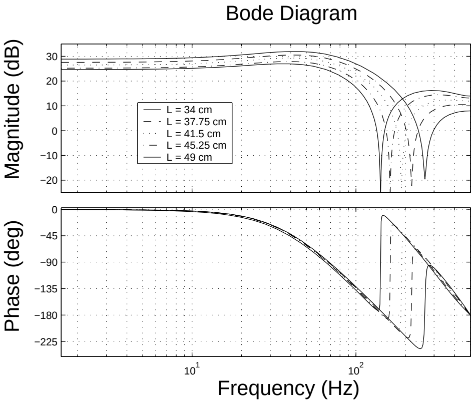


Figure 6: Loop-shaping controllers

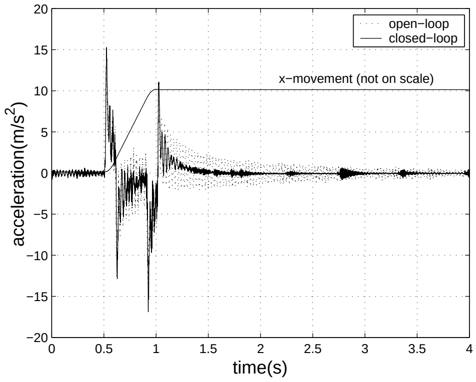
As in the case of the pole-placement controllers, the closed loop system can become unstable when a controller is used for an arm length different from the one it is designed for. Therefore gain-scheduling is also needed for these controllers to get high performance when the length of the arm changes. As in the pole-placement case, a linear scheduling scheme is applied. Now this scheduling can be done on the parameters of the controller as they vary smoothly. Another advantage of the loop-shaping controller is that it can be designed directly starting from the FRF and no LTI model needs to be fitted to the FRF first.

The design of a globally stable controller also in this case leads to a less performant controller as it was not possible to add enough roll-off with the current controller bandwidth to avoid the second resonance to lead to instability for one of the arm lengths.

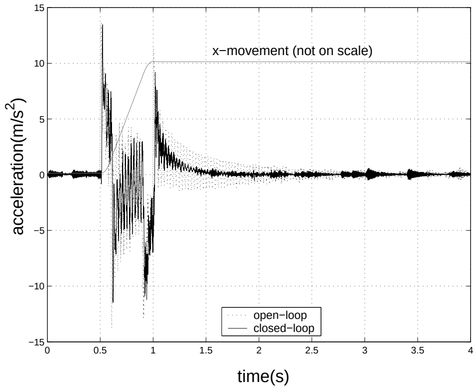
5 Experimental results

To validate the different controllers a trajectory is needed that sufficiently excites the first resonance of the beam. A reference trajectory of 400 mm, based on a constant acceleration and deceleration profile of (-)10 m/s^2 and a constant velocity of 1 m/s, is chosen. The acceleration and deceleration steps result in sufficient vibration of the arm.

Figure 7 shows the acceleration signal for the reference trajectory with and without vibration control for both the pole-placement and loop-shaping controller for the highest position of the arm. The figure clearly shows the damping effect of both vibration controllers. Similar results are obtained for the other arm lengths.



(a) Pole-placement controller



(b) Loop-shaping controller

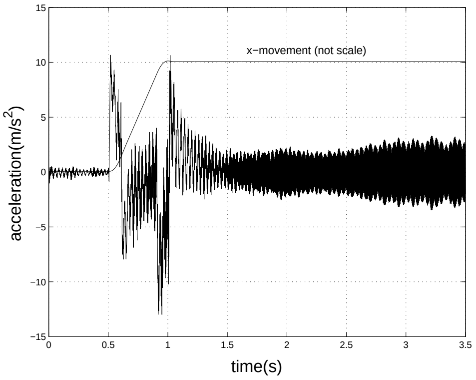
Figure 7: Performance of the pole-placement and loop-shaping controller for the highest position of the arm

Figure 8(a) shows the acceleration signal when the controller designed for a length of 34 mm is used for a length of 39.3 mm, whereas Figure 8(b) shows the performance of the pole-placement controller that is stable for all the arm lengths. From these figures clearly can be concluded that the controllers designed for specified arm lengths can become unstable for other lengths and that the performance of a globally stable controller is very low.

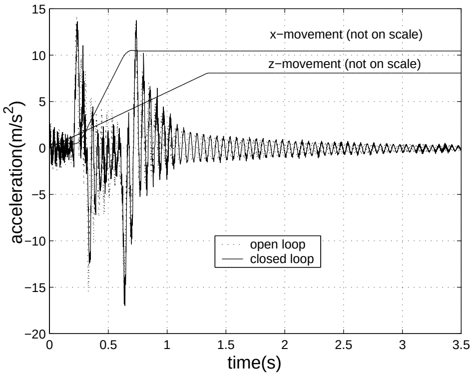
To test the performance of the gain-scheduling controller, the length of the arm is varied with a constant speed during the motion of the linear motor. Figure 9 shows the performance of the gain-scheduled controllers.

Discussion

As Figure 7 shows, both with the pole-placement and loop-shaping controllers significant damping can be added to the arm. Both types of controllers can become unstable when they are used for arm lengths different from the ones they are designed for. Linear gain-scheduling however solves this problem of instability for the test trajectory and leads to high-performance controllers.



(a) Unstability of a pole-placement controller used for a different arm length



(b) Performance of globally stable pole-placement controller

Figure 8: Unstability and global performance with pole-placement controllers

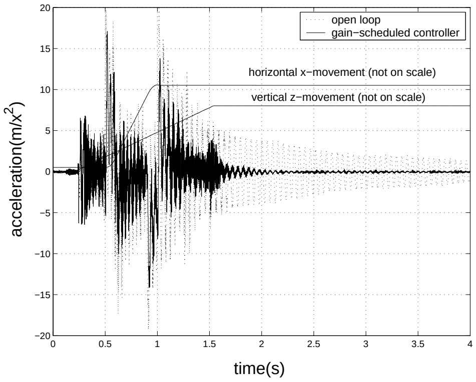
Although both controllers have similar performance, the loop-shaping controller is preferred above the pole-placement controller as it has some advantages:

- No linear model needs to be fitted to the FRF to design the controller.
- The loop-shaping controller is easier to implement as a gain-scheduling controller than the pole-placement controller as the controller coefficients vary smoothly for the first one.

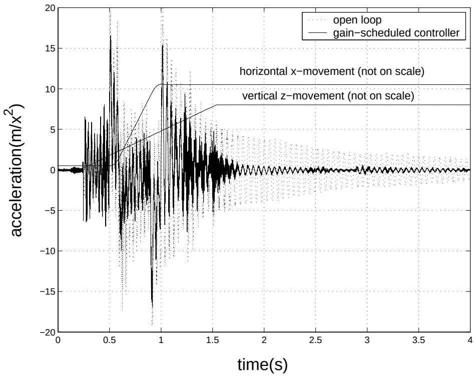
6 Conclusion

In this paper the experimental implementation of (linear) gain-scheduling vibration controllers for a machine tool with varying dynamic stiffness has been presented.

The set-up under consideration is a linear drive loaded with a flexible arm with varying length. Different pole-placement and loop-shaping controllers to damp the vibrations are designed for constant lengths of the arm. Experiments show that these controllers can become unstable when used for other lengths



(a) Gain-scheduled pole-placement controller



(b) Gain-scheduled loop-shaping controller

Figure 9: Gain-scheduled controllers

of the arm than the ones they are designed for. This validates the idea that gain-scheduling controllers are necessary to obtain high-performance vibration controllers.

The gain-scheduling controller is based on a linear interpolation of multiple pole-placement or loop-shaping controllers. Although the pole-placement method seems to be the most appropriate to design the controller, as the main aim is to damp a resonance, this paper shows experimentally that with loop-shaping controllers similar performances can be obtained. The loop-shaping controller moreover has two advantages over the pole-placement controller: (i) an LTI model does not need to be fitted on the FRF to design the controller, and (ii) the implementation of gain-scheduling is more straightforward as the controller coefficients vary smoothly.

The gain scheduling procedure of the controllers in this paper is still done on an ad-hoc basis. Ongoing research is orientated towards obtaining an LPV model of the structure and designing gain-scheduled controllers based on this analytical model.

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