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Abstract: This paper describes the active damping of a flexible beam connected to the end-effector of a robot manipulator. An observer-based feedback controller is developed and experimental results are presented. Iterative feedback tuning (IFT) is applied to shape the step response.

Keywords: Active Damping, Robotics, Observer-Based Control, Iterative Feedback Tuning, Force Sensor

1. INTRODUCTION

In this paper the position control of a flexible beam connected to the end-effector of an industrial manipulator is considered. The system dynamics is very similar to the linear flexible spring-damper systems commonly used in control labs for education. The experimental setup has a much larger operating range than the ordinary lab processes and offers a variety of different control actions using the robot to actively damp the oscillations in the beam. Active damping of flexible beams and poorly damped systems is a well established area, (R. H. Cannon and Schmitz, 1984; Starr, 1985; Landau *et al.*, 1995; Schlechter and Henrich, 2002). The control algorithms are implemented in Matlab/Simulink, where the same controller is used for either simulation or code-generation for download to the open robot control architecture system in the robotics lab at the Department of Automatic Control, Lund (Nilsson, 1996; Nilsson and Johansson, 1999).

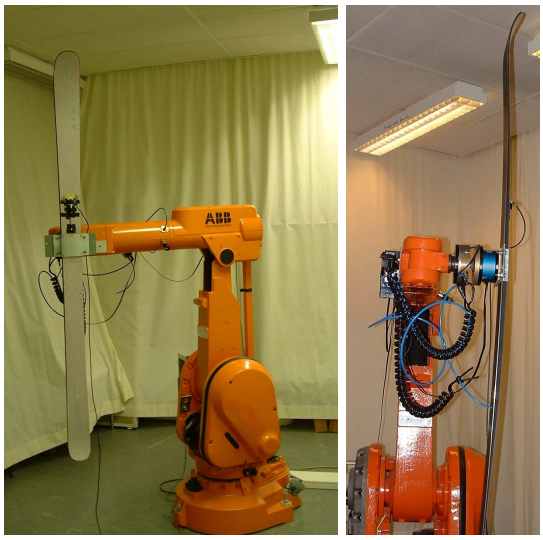

Fig. 1. ABB IRB2000 with ski mounted for identification experiment.

Joint one of the robot will be manipulated and the goal is to damp out the oscillations in the beam after a step in the reference signal. In the project a system identification of the robot

and the beam has been performed, a Kalman-filter and a state feedback have been derived. Iterative feedback tuning is applied to shape the step response.

2. EXPERIMENTAL SETUP

For the identification part different beams have been used. Amongst others two pair of skis with different stiffness have been investigated, see Figure 1. The final choice of beam used for the active damping experiments was a one millimeter thick aluminium sheet with length about thirty centimeters long and width of five centimeters. Different ways for (indirectly) measuring the deflection of the beam has been considered: strain gages or torque measurements from a wrist mounted force/torque sensor (JR3). The beam is connected to the force sensor at the end-effector of the robot. Two strain gages have been glued to the different sides of the beam or on the same side but with different configurations for the skis, see Figure 2. The strain gages are used together with an instrument amplifier to measure the bending of the beam.

Alternatively, the force sensor can be used to measure the bending of the beam. The moment on the force sensor (M_x and M_y) are logged by the robot control system. The measurement signals are sampled in the robot control system with a sampling time of five milliseconds.

Fig. 2. The strain gages mounted on the ski.

During the experiments only the base joint (joint one) of the robot has been used as an input to the system, see Figure 1 and 3.

Fig. 3. The beam connected to the end-effector of the robot manipulator.

3. MODELING

Different system identification techniques have been used to model the behavior of the system. Models for describing the system from position reference to position and to moment on the force sensor have been created as well models from position to moment on the force sensor. The input to the system have been pseudo random binary (PRBS) signals and steps. The System Identification Toolbox in Matlab has been used to decide the model structures and parameter estimations. The robot position is controlled by a PID, which might not be a good idea since this may affect the identification. Here no such problems has been encountered. The models were validated against measurement data, see Figure 4. The system seems to be of 6th order where the two poles with highest frequency are the poles of the robot. This was verified by running the robot without the flexible beam with a weight attached to the force sensor, see Figure 5 for the frequency response.

We decided to try different controllers. First we only look at the first resonance and try to dampen it out with observer-based state feedback. The data is needed to be filtered otherwise a fourth order model will try to capture all the dynamics and place the poles in between the real poles, see Figure 6. The second controller will be based on observer-based state feedback with the 6th order model.

4. CONTROL

The goal of the controller design is to damp out oscillations, i.e. make the beam stiff while still moving the robot arm according to a given position reference. We will use an observer based feedback controller in combination with an outer controller tuned by IFT to achieve this goal.

4.1 State Feedback

Assume that we could measure all the states. If so, we could place the poles for the closed loop

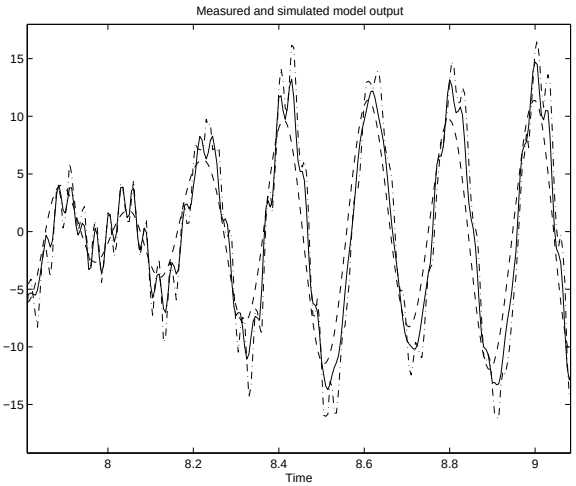

Fig. 4. Position reference to M_y. Validation of 6th order model (solid) and 4th order model from filtered data (dashed) against validation data (dash-dotted).

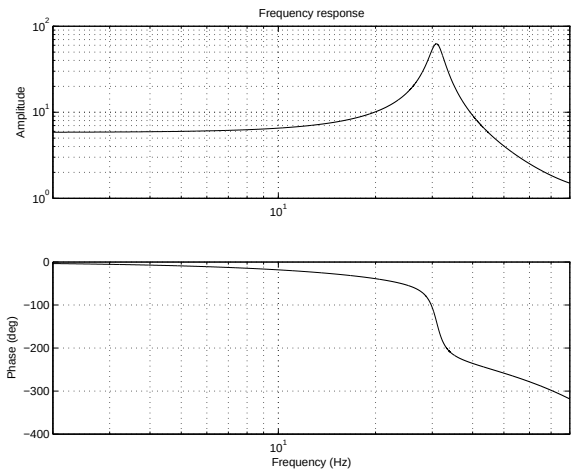

Fig. 5. Frequency response from position reference to M_y without the flexible beam.

system by freely by using the control law

$$u(t) = -Lx(t) + l_r y_r(t)$$

by properly choosing the parameters in the vector L. y_r is the reference value and l_r is a scalar gain affecting the overall gain, see Figure 7. l_r is chosen to get the correct stationary gain. Since we cannot measure all the states we will construct an observer to approximate the four states. In this first step no integrator was implemented in the controller.

4.2 Observer

Let the observer be described by

$$\frac{d\hat{x}(t)}{dt} = A\hat{x}(t) + Bu(t) + K(y_1(t) - C_1\hat{x}(t))$$

where $\hat{x}(t)$ denotes the states of the observer. K can be chosen so that the observer states are

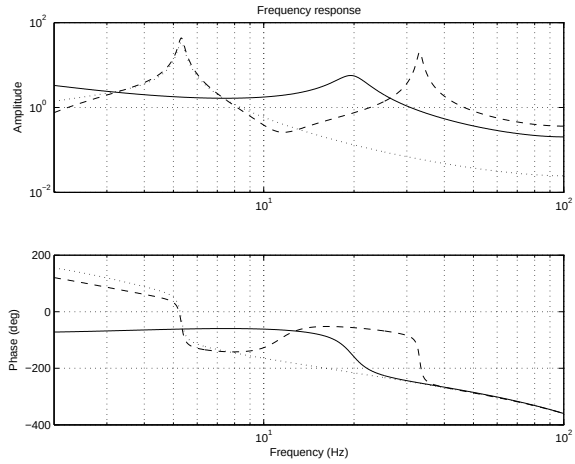

Fig. 6. Position reference to M_y. 6th order model (dashed), 4th order model (solid) and 4th order model from filtered data (dotted).

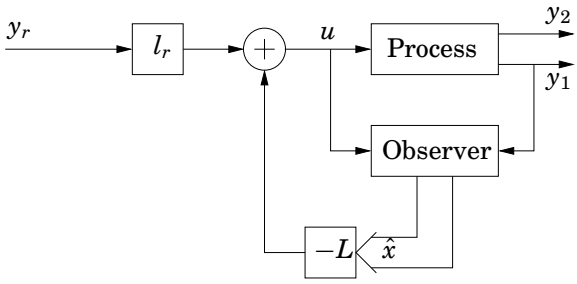

Fig. 7. State feedback from observed states.

approaching the real states with an arbitrarily fast rate of convergence. We will use the observer states in the feedback law instead of the real states which we can not measure. Figure 7 shows feedback from observer states. The poles of the observer were chosen to be one and a half times faster than the closed loop poles.

The observer was tested on measurement data by using a simulink model, see Figure 8. The results are shown in Figure 9 and 10 for the 4th order model.

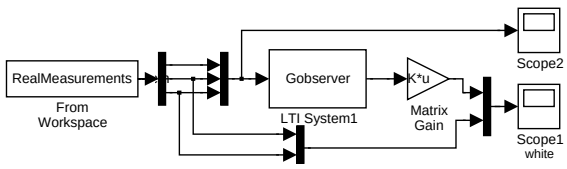

Fig. 8. Simulink model to test the observer against measurements.

4.3 Observer Based State Feedback Control

The undamped poles of the open loop system were moved to $\zeta = 0.74$ by using state feedback, see Figure 11 for the 4th order model. The controller was implemented in simulink and tested on the robot system IRB2000, see Figure 12.

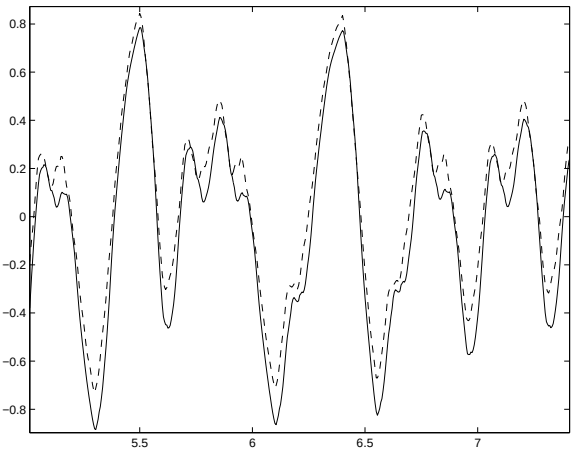

Fig. 9. Results from the observer (dashed) and measurements (solid) for the position (4th order model).

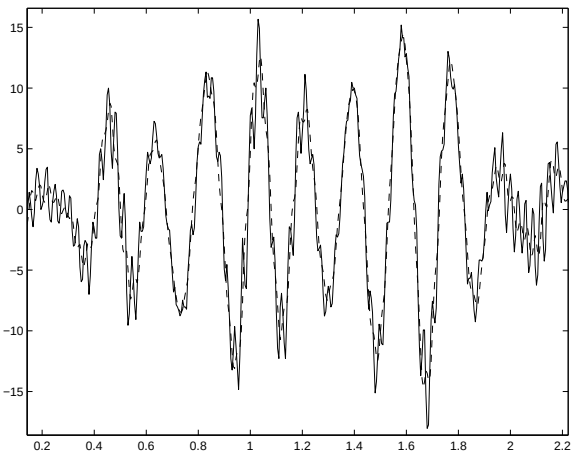

Fig. 10. Results from the observer (dashed) and measurement (solid) for M_y (4th order model).

The same simulink controller can either be used for simulation or for code generation with Real-Time Workshop (RTW). The controller can be downloaded and dynamically linked to the robot control system in the Robotics Lab at the Department of Automatic Control, Lund (Nilsson *et al.*, 1998).

Steps in position of joint number one and the vibrations in the beam for the uncontrolled system, the 4th order controller, and the 6th order controller can be seen in Figure 13. The step in the position gets a bit slower when dampening out the vibrations. When using the 4th order model the vibrations of the robot became too large so an extra notch filter has been added to the control signal, therefor the responses of the two controllers look very similar.

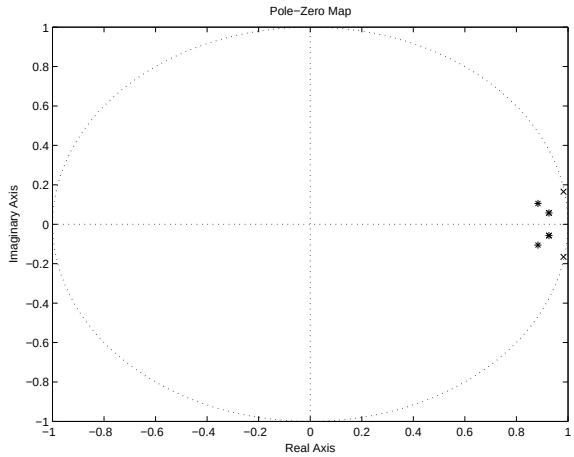

Fig. 11. The open loop poles ($\times$) and the closed loop poles ($*$) (4th order model).

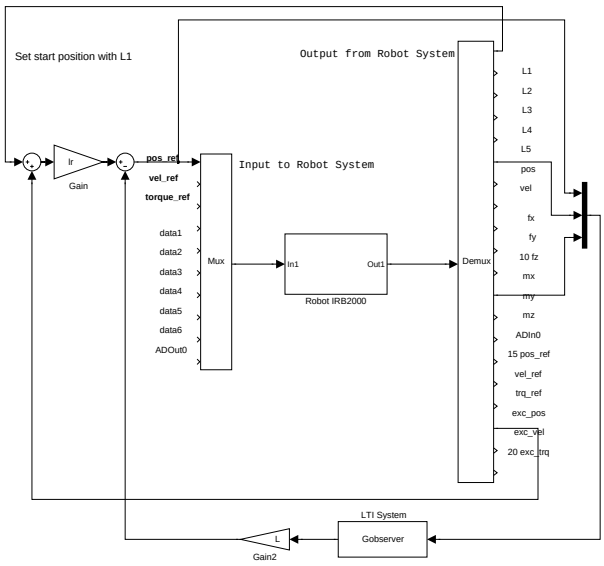

Fig. 12. Simulink model for observer based state feedback control of the beam (4th order).

4.4 Iterative feedback tuning

The results reported in the previous section shows effective damping of the beam oscillation whereas a small overshoot in the robot arm position has been introduced, see Figure 13. This is of course an outcome of our pole placement design, but in this section we consider an alternative way of re-tuning the controller to diminish the overshoot while still damping the flexible beam.

In general the optimization of a control performance criterion typically requires iterative gradient-based minimization procedures. The major difficulty for the solution of this optimal control problem is the computation of the gradient of the criterion function with respect to the controller parameters: it is a fairly complicated function of the plant and disturbance dynamics. *Iterative Feedback Tuning* (IFT) is a input-

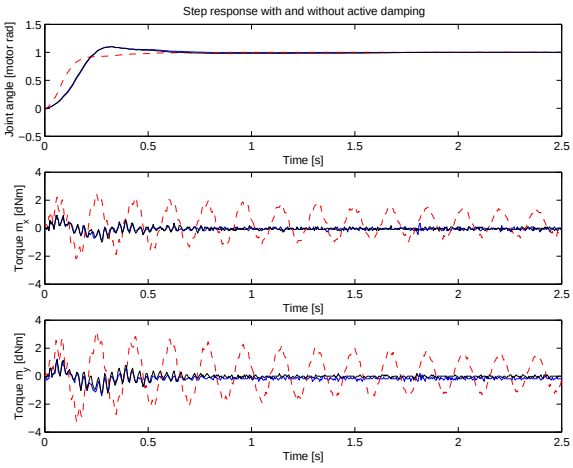

Fig. 13. Step in position, torque M_y, and torque M_x for controlled (solid) and uncontrolled system (dashed). The step responses are normalized to unit stationary gain.

output data-based design method for the tuning of restricted complexity controllers. It does not depend on the plant model, and utilizes I/O data only, (Hjalmarsson *et al.*, 1998; Hjalmarsson, 2002). The results in this section are based on (Bindi, 2003), where more details also can be found.

Instead of considering the re-tuning of all the parameters in the feedback gain L and in the observer gain K we consider a cascaded structure around the observer-based controller of the previous section according to Figure 14. For $\alpha = 1$, $\beta_0 = 0$, and $\beta_1 = 0$ we have the nominal controller.

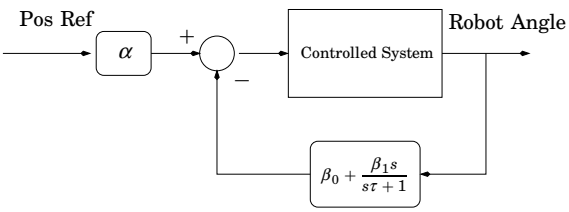

Fig. 14. Cascaded control structure for iterative feedback tuning to reduce the overshoot of the robot.

To reduce the overshoot we use a time weighting sum of squares of the output error. The cost function criterion looks as

$$
\begin{aligned}
J(\rho) &= \frac{1}{2N}\sum_{t=1}^{N}\left[w_y(t)(y_t - y^d)^2\right] \\
\rho &= \left[\alpha \;\; \beta_0 \;\; \beta_1\right]^T \\
w_y(t) &= \begin{cases} 10 & 0<t<0.7 \\ 1 & t>0.7 \end{cases}
\end{aligned}
\tag{1}
$$

As seen in Figure 15 the step responses and the stationary gain are improved, whereas the

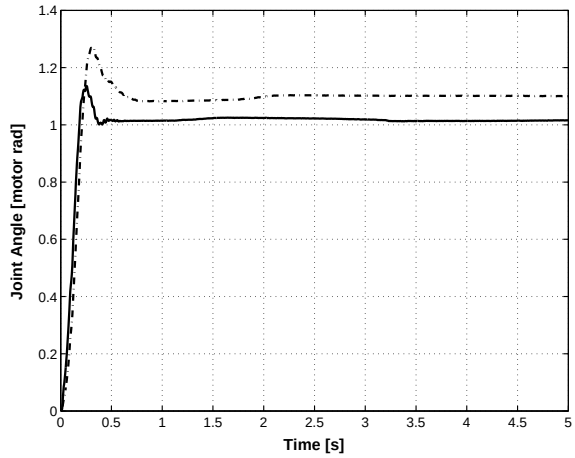

Fig. 15. Iterative feedback tuning to reduce the overshoot of the robot and to restore the nominal gain. ($\rho_0 = [1, 0, 0]^T$, $\rho_5 = [1.69, 0.74, 0.05]^T$. Step responses initially (dash-dotted) and after 5 iterations (solid).

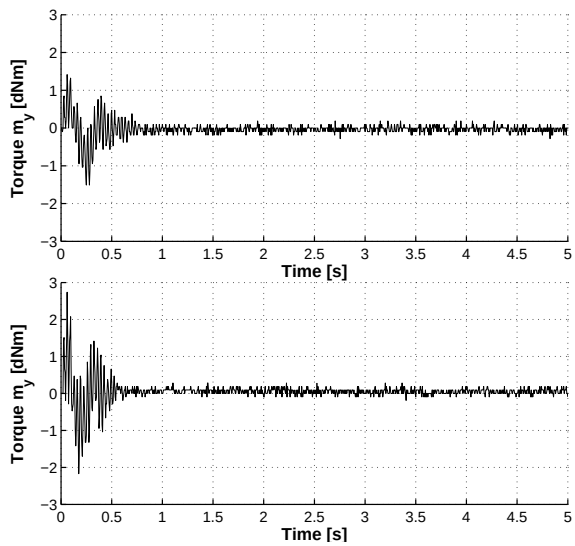

Fig. 16. Beam deflection initially (upper plot) and after 5 iterations (lower plot). The deflection increases slightly while the settling time decreases.

transient of the beam deflection is increased Figure 16. This should be no surprise as it is not part of the cost criterion, Eq. (1). The cost function for the five iterations can be seen in Figure 17.

5. DISCUSSION AND CONCLUSIONS

The paper has considered an experimental setup for active damping of a flexible beam connected to the end-effector of a robot manipulator. Parametric identification has been made for different beams and using both strain gages and a wrist mounted force/torque sensor.

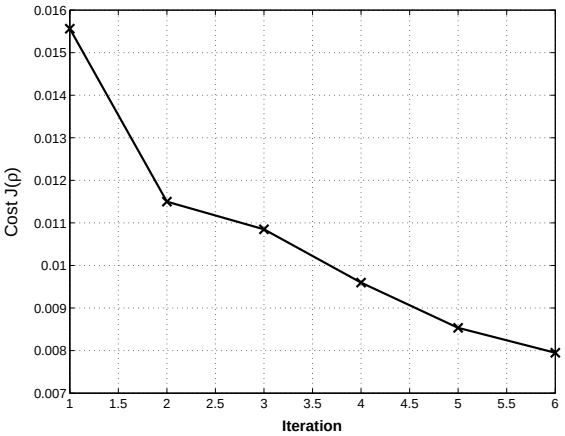

Fig. 17. Cost function $J(\rho)$, Eq.(1), after 5 iterations in IFT.

An observer-based feedback controller is developed and experimental results are presented. The derived controller is then used in an inner (cascaded) control loop, when iterative feedback tuning is applied to shape the step response by updating the parameters of the outer control loop.

6. ACKNOWLEDGMENT

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