Institute for Design and Control
of Mechatronical Systems

Masters Thesis:

Adaptive Control of a Hydraulic Press Brake with Load-Compensation

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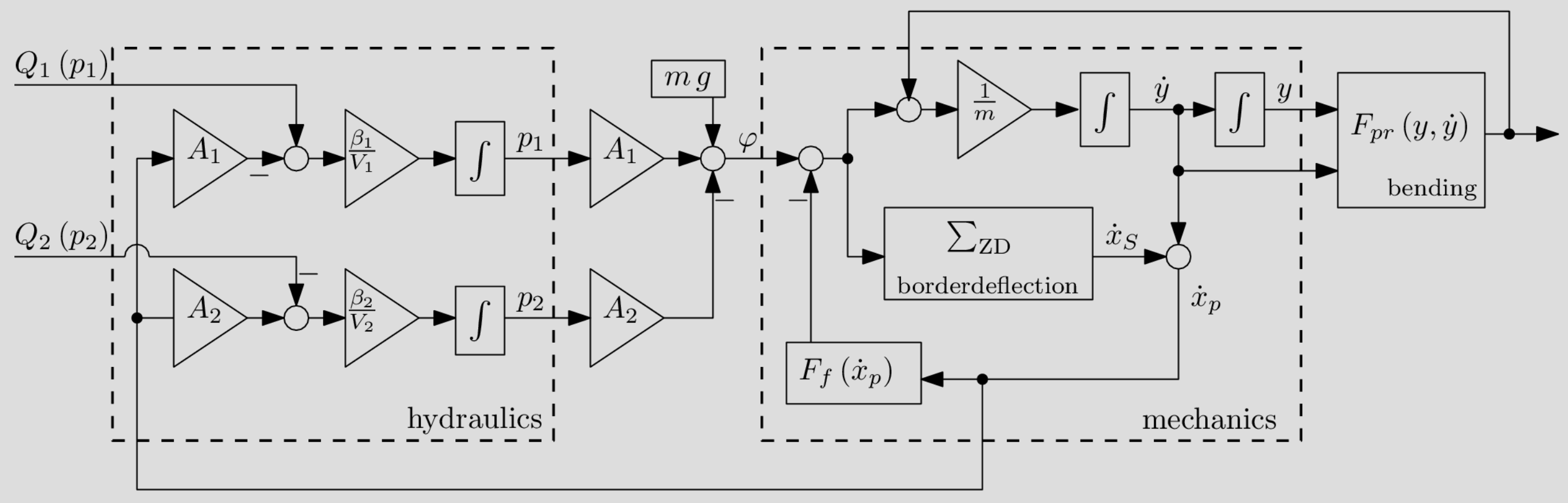
Abstract

Press brakes are efficient machines for sheet metal bending. The press bar position (y-axis) of the press brake under consideration is driven by double acting hydraulic cylinders which in turn are actuated by separate pumps and control valves for the left and right side. This unconventional hydraulic design enables to independently control volume flows into both chambers giving an additional degree of freedom for control. A dynamic model of the system considers frame deflection and process force, and therefore differs from ordinary hydraulic servo-systems.
The system is control affine and eligible to feedback linearisation methods. This methodology is used to decouple motion and pressure control and is the basis of an inverse feedforward control including the compensation of load force based on online parameter estimation. For the motion during the deformation of material an adaptive control relying on the linearization of the nominal plant and material stiffness estimation was developed. This control compensates a weakly damped complex pair of roots and adapts the control gain to maintain configurable closed loop damping and stability.
Furthermore a control algorithm based on backstepping and passivity was evaluated for rapid motion without sheet contact.

Press & Return Stroke Control

A typical bending cycle can be divided into rapid motion, press stroke and return stroke. During press and return stroke process force - especially the process load stiffness - has a significant influence on the system dynamics. The model of the system can be divided into a hydraulic and a mechanical subsystem. The structure is outlined in the figure below.



The volume flows Q_1 and Q_2 include an additional input nonlinearity in the figure. They depend on the hydraulic configuration, which changes during a bending cycle. In order to eliminate this nonlinearity and to use the second degree of freedom for pressure control, MIMO feedback linearisation of the hydraulic subsystem can be used. A state transformation is used to avoid the compensation of the piston velocity coupling and subsequently to maintain the load stiffness of the hydraulic drive. v_1 is the new control input for the superimposed press bar motion control.
By further replacing frame dynamics with the stationary solution a simplified outer loop system results.

$$\dddot{y} = \frac{1}{m}\Big[-\underbrace{\frac{A_1^2\beta_1}{V_1}}_{\text{coupling}}\,\kappa\,\dot{y} - d_f\,\hat{\kappa}\,\ddot{y} - \underbrace{\frac{\partial F_{pr}\,(y,\dot{y})}{\partial y}}_{\text{process stiffness } c_{pr}}\,\dot{y} - \underbrace{\frac{\partial F_{pr}\,(y,\dot{y})}{\partial y}}_{\text{die friction}}\,\ddot{y} + v_1 \Big]$$

An inverse feedforward control that relies on recursive least squares online estimation of $\kappa = 1 + \frac{c_s}{c_{pr}}$ or c_{pr} can be derived from this model.

Cascade position and velocity feedback control is suggested for press bar motion control during press and return stroke.
The linearisation and discretisation of the model along the trajectory leads to a time variant system representation, that depends on the online load stiffness estimation.

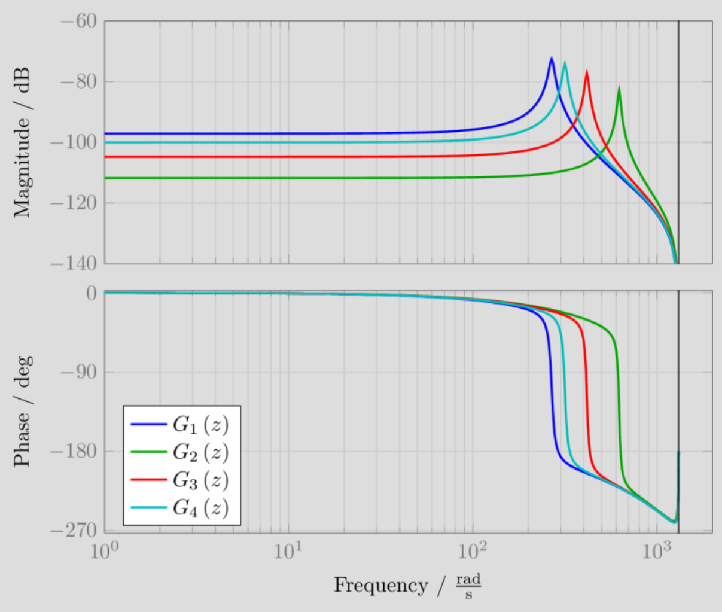
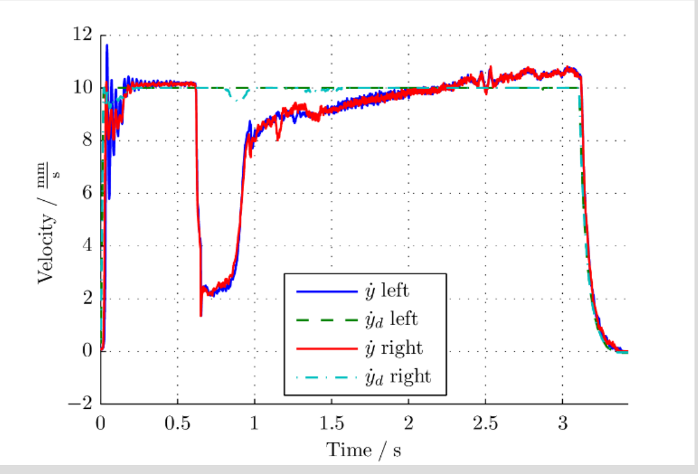


Figure: Linearisation at different operating points

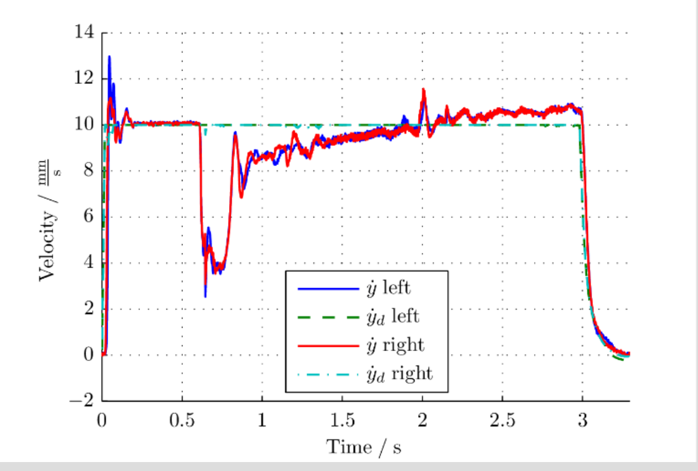
Using this model for the design of a feedback control in frequency domain leads to a time variant control that adapts with the estimated process load stiffness. As a first step the varying stationary gain and the resonance is compensated. Two poles are required for the controller to be realisable. These are used to shape the open loop transfer function. In order to achieve configurable damping, the root locus method is used.

Prototype Experiments

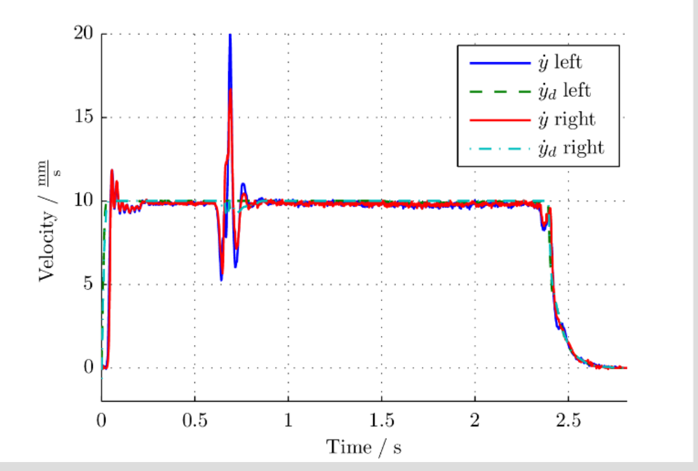
well tuned conventional control:



new feedback control only



new feedforward + feedback

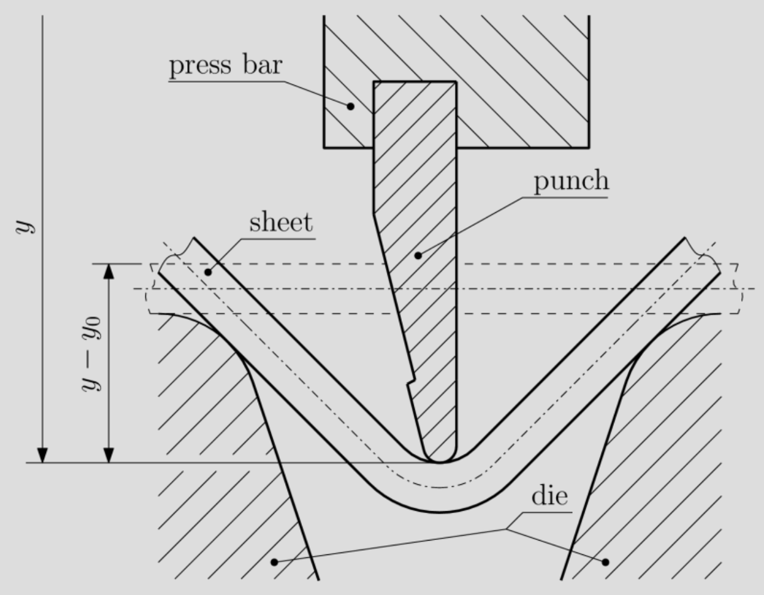


Air Bending Process Model:

The process force required to bend sheet metal is usually orders of magnitude higher than inertia and friction forces. Therefore, model based control should take account of this uncertain part of the process. In air bending clamping at the end of the stroke is avoided.
The Stiffness of the load is part of inverse control and model linearisations and is therefore important for control. Initially, during elastic material deformation, the load is very stiff, but the stiffness drops rapidly during plastic deformation.

The following figures show the geometry, the stress in a cut surface below the punch, the steps to derive a process force model, and a validation, where the parameters of the model have been optimized for the downward stroke.

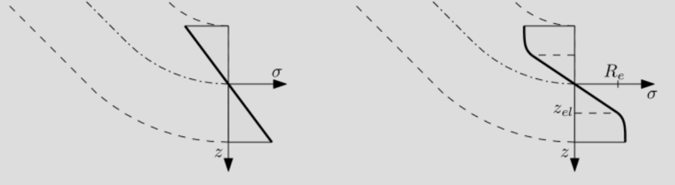
Geometry



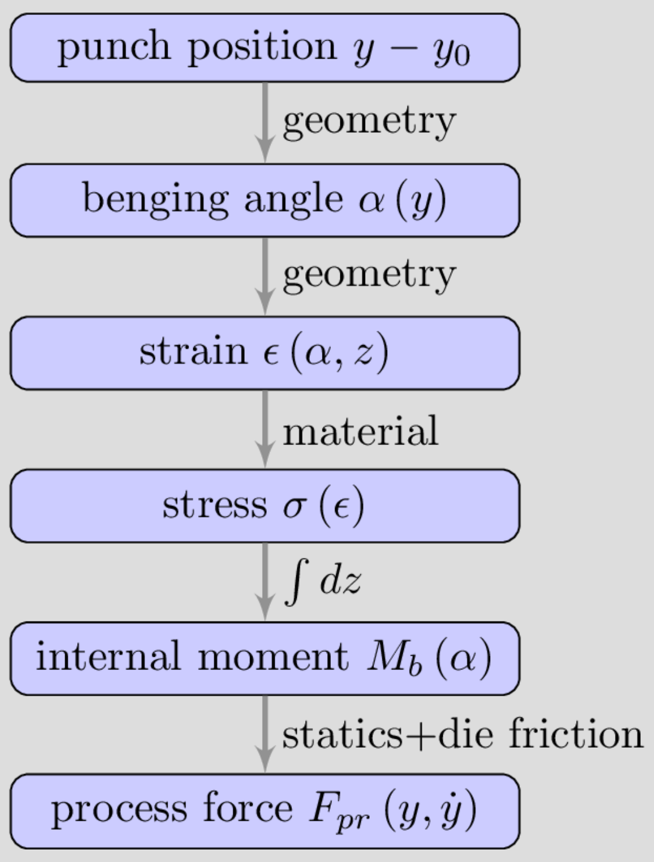
Stress curve below the punch

elastic

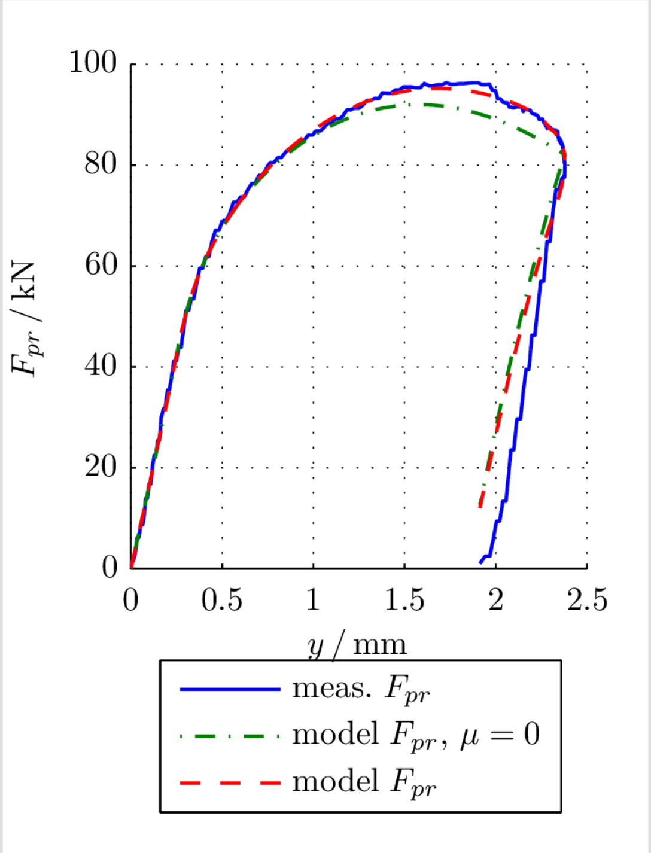
plastic



Derivation Process


punch position $y - y_0$
geometry
benging angle $\alpha\,(y)$
geometry
strain $\epsilon\,(\alpha, z)$
material
stress $\sigma\,(\epsilon)$
$\int dz$
internal moment $M_b\,(\alpha)$
statics+die friction
process force $F_{pr}\,(y,\dot{y})$

Validation



Rapid Motion Control

In the rapid motion configuration only the pump is used for control, no process force is present and frame deflection is negligible. The cylinder is actually single-acting with gravity as the counteracting force. Hence, the system is similar to ordinary hydraulic systems and is therefore eligible to standard methods for trajectory tracking control of hydraulic systems.
A control algorithm based on backstepping and passivity published by Perry Y Li and Meng Wang ["Passivity based nonlinear control of hydraulic actuators based on an euler-lagrange formulation". In: Proc. of the ASME 2011 Dynamic Systems and Control Conference, Arlington, VA. 2011.] was evaluated for this configuration.

Kalman Filtering

Nonlinear variants of the popular Kalman Filter, like the Extended Kalman Filter, can be used to estimate the states of the system instead of numerical differentiation of the piston stroke and frame deflection measurements.
In order to reduce the influence of quantisation on the noise of the state estimates, quantisation is considered as nonlinearity rather than implicitly assuming Gaussian Noise by using Kalman Fitler variants. The suggested method can reduce noise, if accurate models for prediction are available. This implies the knowledge of accurate model parameters. Therefore simultaneous estimation of states and parameters by Unscented Kalman Filters was evaluated. The Unscented variant of the Kalman Filter is chosen because it does not require the laborious algebraic computation of the Jacobian matrix for states and parameters of the discretised plant.

Conclusions

- The process load heavily influences system characteristics and therefore should be considered by the design of model based control.
- Process load parameters are uncertain or even unknown. Online estimation of the process load stiffness was proven to be an effective method to consider the process load in control.
- The feedforward control algorithm significantly improved velocity tracking during plastic material deformation and decreased cycle times, but lead to an overshoot at the transition from elastic to plastic deformation.
- A solution for the problematic overshoot is provided in the thesis and was tested in simulation.
- The feedback control shows comparable performance to conventional control by significantly reduced tuning effort.