Improvement of hydraulic control quality for deep drawing presses through retrofit

Marcus Helmke
Automation, TRsystems GmbH, Eglishalde 16, 78647 Trossingen,
E-mail: marcus.helmke@trsystems.de

Herbert Majer
Automation, TRsystems GmbH, Eglishalde 16, 78647 Trossingen,
E-mail: herbert.majer@trsystems.de

Andreas Thanassakis
CEO, TR-Electronic, Eglishalde 6, 78647 Trossingen,
E-mail: andreas.thanassakis@tr-electronic.de

Abstract

Retrofits of hydraulic and mechanical deep drawing presses often stop with the exchange of the electrical and the hydraulic parts. But that is only half the job. The use of high definition control electronics, faster CPUs and more dynamic hydraulic actuators, offers the opportunity of redesigning the already existing control concepts of the press. In this paper we present how the performance of the press, i.e. the control quality, can be increased for hydraulic ram and cushion axes. The improvement in control quality is achieved through the use of intelligent closed-loop and open-loop-control algorithms. Therefore, creasing and crack formation can be reduced, since enhancements in control quality have direct influence on the quality of the forming process. Results will be shown for hydraulic drawing cushion control, i.e. pressure control, as well as for hydraulic ram control, i.e. position, velocity and parallelism control. We present findings for hydraulic cushion control of a mechanical press type Arisa S-4-1600-470-230-LDE (link-drive press with 10 hydraulic cushions) and for ram-/cushion-control of hydraulic press type Müller-Weingarten ZE2100 (multi-curve press with 8-point cushion).

KEYWORDS: hydraulic presses, retrofit, model based control
1. Introduction

Installation operators carry out retrofits for their hydraulic or mechanical presses to ensure the machine's availability in the long term. The machine's electrical components are mostly discontinued after 10-15 years. That results in predictive arrangements for the pressing plant's maintenance and production planning staff. The focus of those retrofits is on exchange of the machine's PLC and replacement of electrical components and wiring. If the desired plant has a hydraulic closed loop control system – e.g. drawing cushion – most of the time, the hydraulic control system will be replaced by a stand-alone module (e.g. Rexroth MAC 8). Those stand-alone systems have a large variety of functions and high number of usable parameters, but they can quickly reach their limits, since hydraulic and mechanical presses are special engineered machines and need an equally special engineered solution. The approach presented by TRsystems, describes a solution which refers to the machine's electrical, mechanical and hydraulic properties and thus is a tailored closed loop control. Most of the time, the existing hydraulic/mechanical remains untouched. The greater part of the changes will affect the electrical components only.

2. Mechanical press Arisa S-4-1600-470-230 LDE

2.1. Machine in detail

The Arisa S-4-1600-470-230 LDE (Arisa 1600) is a mechanical transfer press with

![Arisa 1600 – mechanical structure](image)

(1) sidestand, (2) ram, (3) bolster plate, (4) drawing cushion sleeves, (5) drawing cushion, (6) positioning and pressure cylinder, (7) basement

**Figure 1:** Arisa 1600 – mechanical structure
Link-Drive engine for the ram and 10 separate hydraulic drawing cushions (see Figure 1) /1/. The press' maximal force is at 16.000 kN. The drawing cushions have a 3-chamber-cylinder, which is designed for lifting and pressure functions. The cylinder is controlled by 2 servo valves (Rexroth 4WRTE nominal size 25 and 4WRDE nominal size 10, frequency of 30 Hz) and has a dynamical chamber-shift for pressure control. The machine’s 10 drawing cushions make a variety of forming steps possible. Workpieces, produced with this press include structural elements for vehicle constructions and cases for brake boosters. The machine’s master control system is a Siemens SIMATIC S7, which controls ram, transfer and blank loader. A Rexroth MX4 system takes care of the drawing cushion’s closed loop control.

2.2. Quality of drawing cushion closed loop control before retrofit

Figure 2 shows the quality of first cushion’s pressure control before retrofit. The measurements were done with an extern measuring system, connected with the drawing cushion via MINIMESS testpoints. Target pressure for this measurement was 240.0 bar (equals 600.0 kN cushion force), the ram speed was 13 strokes/minute and the drawing depth was set to 150.0 mm.

![Figure 2: Arisa 1600 – pressure control before retrofit](image)

We were able to verify the trend, recorded in Figure 2, for all possible parameter constellations (see Table 1 for parameter limitations). The pressure overshoots had a value of 50% or more of the target pressure and were eliminated after additional 30.0 till 50.0 mm drawing depth (depends on ram speed). A residual ripple could be recognized for the whole length of the process, till the ram’s bottom dead center. The measurements showed that the ripple had an average value of +/- 25% of the target pressure and that the controller was not able to eliminate the pressure fluctuations within the given time.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ram stroke speed</td>
<td>8 1/min</td>
<td>30 1/min</td>
</tr>
<tr>
<td>Cushion pressure</td>
<td>20.0 bar</td>
<td>240.0 bar</td>
</tr>
<tr>
<td>Draw depth</td>
<td>20.0 mm</td>
<td>200.0 mm</td>
</tr>
</tbody>
</table>

Table 1: Arisa 1600 - parameter limitations /1/

While the press was working with preselected cushion control, the maximum number of strokes had to be reduced to 15 strokes/minute, although the ram was able to drive with 30 strokes/minute. Working with a ram speed of 16 strokes/minute and more, could result in damaging the cushion’s hydraulic, since the rising pressure peaks were able to burst the hose lines between cylinders an servo valves.

2.3. Approach by TRsystems

The existing cushion control was replaced by a Beckhoff industrial PC (IPC), which is able to calculate in real-time. Via Profibus DP/DP, the IPC was connected to the superior machine control. The analogue and digital I/O-modules were connected via EtherCAT (see Figure 3).

![Figure 3: Arisa 1600 – network layout](image)

Our control algorithms are designed in C++ and are executed with the real-time extension TwinCAT. The TwinCAT software is part of the IPC and calculates our control algorithms with a cycle time of 125 µs /2/. The existing pressure sensors and servo valves remained unchanged. For analogue I/O-modules, we used fast high-resolution modules, which scaled the valve output and input signals (0 – 10 Volt), as
well as the pressure input signals (0 – 400 bar), to 16 bit digital values (before retrofit, inputs and outputs were scaled on 8 bit only) via EtherCAT.

The closed loop pressure control consisted of a PI controller with a model based feed forward control. The feed forward control was designed to reduce the PI controller’s part of the control signal and thus to reduce overshoots and residual ripples. We were able to reduce the PI controller signal to 10% and less, as part of the sum signal. Therefore, the feed forward control consisted of a three-dimensional valve characteristic (target pressure over drawing velocity over valve signal). The valve signal was recorded in the three-dimensional characteristic for all possible drawing velocities (8 – 30 strokes/minute) and for all possible pressures (20.0 bar - 240.0 bar) during drawing process. Since implementing the hydraulic characteristics of the whole system, we included disturbances like dead volumes, hidden capacities (hose lines) and current valve attrition.

**Figure 4:** ideal valve characteristic (left) and actual valve characteristic (right)

**Figure 5:** pressure control - calculated control signal

**Figure 5** shows, how the feed forward signal is generated. Target pressure and ram velocity are the inputs (x-axis and the y-axis of the characteristic), while the interpolated valve signal is the output (z-axis of the characteristic). The target pressure is parameterized by the machine’s operator as desired blank holder force. The ram’s velocity (in mm/s) is converted from the actual number of strokes (1/min) by the use of
the ram’s kinematics and the current crank angle (via crank angle – position – diagram).

2.4. Quality of drawing cushion closed loop control after retrofit

Figure 6 shows the pressure control for 13 strokes/minute, a drawing depth of 150.0 mm and a set pressure of 240.0 bar. There is nearly no overshoot identifiable and the residual ripple is close to zero percent, only at the end of the process minimal pressure fluctuations can be seen.

![Figure 6: Arisa 1600 – pressure control after retrofit](image)

Since we used modern model based control algorithms and real-time capable hardware (125 µs cycle time), we were able to make a decisive improvement in control quality. Furthermore, the press was now able to produce with a stroke speed up to 30 stokes per minute with preselected cushion control.

3. Hydraulic tryout press Müller-Weingarten ZE2100.45.2.2

3.1. Machine in detail

The Müller Weingarten ZE2100.45.2.2 (ZE2100) is a hydraulic tryout press consisting of 4 ram cylinders, an 8-point drawing cushion and a 1-point ram cushion. The 4 ram cylinders are supplied by 2 piston accumulators (2 x 325 l at 315 bar oil pressure) and 2 constant pumps (2 x 160kW at 1500 l/min) and are controlled by piston sided Rexroth 2WRCE valves (nominal size 63) /3/. The ram’s closed loop control includes position, velocity, parallelism and pressure control. In this paper, we will concentrate on velocity and parallelism control only. Using the MultiCurve-technology, the ram is capable of simulating kinematics of mechanical presses, between 90° crank angle before bottom dead center and bottom dead center. As a result, the drawing speed can reach up to 500.0 mm/s. The blankholder force is provided by an 8-point drawing cushion (8
pressure cylinders) and by a 1-point ram cushion. The ram cushion shall not be considered in detail in this paper. The drawing cushion’s pressure is controlled with 8 separate Moog D663 servo valves and the force can reach a maximum of 6000.0 kN, which equals 239.0 bar in each cylinder.

![Diagram](image)

**Figure 7: MW ZE 2100 – MultiCurve press**
(1) hydraulic block, (2) accumulator, (3) ram adjustment, (4) stamp dampening, (5) ram cylinder, (6) sidestand, (7) ram, (8) ram cushion cylinder, (9) ram cushion sleeves, (10) die top, (11) die bottom, (12) bolster plate, (13) drawing cushion sleeves, (14) drawing cushion, (15) pressure cylinder, (16) positioning cylinder, (17) basement

### 3.2. Quality of closed loop control before retrofit

**Figure 8** shows measurements for drawing cushion pressure control and ram velocity control before retrofit. The measurements were recorded with a special press die, consisting of several force transducers and laser sensors for path measurement.

![Graphs](image)

**Figure 8: ZE2100 before retrofit – pressure control (left) at 4 strokes/minute and ram velocity control (right) at 8 strokes/minute /4/
The measurements were made for 1600.0 kN, 2000.0 kN and 3150.0 kN cushion target force, while the simulated stroke rate was 4 strokes/minute, which equals about 100.0 mm/s drawing velocity. Figure 8 shows a nearly perfect pressure control quality for those force-velocity-combinations. But increasing the stroke rate, respectively the drawing speed, led to a malfunction of the drawing cushion control. Figure 9 shows the results for target forces 1250.0 kN, 2000.0 kN and 3150.0 kN at 8, 11 and 14 strokes/minute. It is obvious that with increasing stroke speed, the control quality rapidly decreases and - as a result – the desired forces cannot be kept constant.

![Figure 9: MW ZE2100 – pressure control before retrofit](image)

left: 8 strokes/minute, center: 11 strokes/minute, right: 14 strokes/minute

Taking a closer look at the ram’s velocity control (Figure 8), various fluctuations can be detected. The fluctuations before the ram is about to accelerate are not so important, since that is the phase, where the die top is about to touch down on the die bottom. The phase after the acceleration phase should look like the red marked area in Figure 10.

![Figure 10: position-velocity-time-diagram for MultiCurve presses](image)
3.3. Approach by TRsystems
We have done a complete electrical retrofit for this machine. That means that PLC, closed loop control, visualization, every I/O-module and all drawing cushion pressure control valves have been exchanged. The existing Moog D663 valves have been replaced by identically constructed but more wear-resistant and more dynamic valves (from 40 Hz frequency to 50 Hz frequency). We used a Beckhoff IPC with the real-time extension TwinCAT for closed loop control and high resolution I/O-modules for analogue inputs and outputs (12 bit modules before retrofit and 16 bit modules after retrofit). The changes in electrical hardware were quite the same as in chapter 2.3. Again, the architecture of the drawing cushion’s closed loop control consisted of a model based feed forward control and a PI controller. The retrofit also concentrated on optimizing the ram’s velocity and parallelism control. This was done by fitting the position feed forward control (for velocity control) and the target value generation (for parallelism control) on the machine’s behavior.

3.4. Quality of closed loop control after retrofit

Figure 11 shows the measurements made for drawing cushion pressure control and for ram velocity control after the retrofit. It is obvious that a massive improvement in drawing cushion pressure control could be gained. Furthermore, the ram’s velocity signal does now look much more like the velocity curve of a mechanical press (cf. Figure 10).

![Figure 11: ZE2100 after retrofit – pressure control (left) at 11 strokes/minute and ram velocity control (right) at 8 strokes/minute](image)

Figure 12 shows results for different target forces (1250.0 kN, 2000.0 kN and 3150.0 kN) and different stroke rates (8 strokes/minute, 11 strokes/minute and 14 strokes/minute). Higher drawing speeds are not a problem any longer for the drawing cushion’s pressure control. To put it in a nutshell, the controller is able to keep the desired forces nearly constant for the whole length of the process. And that is
achieved, because the PI controller’s output signal never reaches a value greater than 10% of the sum signal (feed forward control + PI controller).

Figure 12: MW ZE2100 – pressure control after retrofit
left: 8 strokes/minute, center: 11 strokes/minute, right: 14 strokes/minute /5/

The last retrofit aspect, mentioned in this paper, is the parallelism control of the ZE2100. The centerpiece of the parallelism control is the calculation of the setpoints. Differences between the 4 position signals (4 cylinders) are converted in responding tilting moments around the x- and y-axis (see Figure 13). The tilting moments on the other hand, are converted in resulting cylinder forces at the cylinder center. In the next step, the calculated cylinder forces are sent to the controller as process variables. The reference variable for the controller is a force with 0.0 kN in order to eliminate the tilting moments.

Figure 13: ZE2100 – tilting left/right (A) and front/rear (B) /6/

The ram’s tilting control always works together with the velocity and position control. That means the servo valve’s sum signal consists of 3 different control outputs. As a consequence of converting the position differences into cylinder forces, an interaction between parallelism control and position/velocity control is prevented. Figure 14 shows results for ram’s parallelism at 8 strokes/minute and with an eccentric drawing cushion force of 2000.0 kN. The measurements were recorded for forming stroke and return stroke, but the parallelism control is active during forming stroke only. During the forming stroke, the tilting around the x-axis has a maximum of 0.1 mm/m and the tilting
around the y-axis is not bigger than 0.2 mm/m. The distances between the left and right cylinders are 3800.0 mm, while the distances between front and rear cylinders are 1700.0 mm. The drawing cushion adopts the ram’s tilting movement in all directions very good.

![Figure 14: ZE2100 – parallelism control](image)

left: tilting front/rear, right: tilting left/right

In conclusion, the retrofit has led to an enormous enhancement of the quality of the closed loop control. Especially the drawing cushion’s pressure control reached a new level of stability. This is due on one hand to the changes in hardware (new servo valves, high resolution modules, real-time control system), and on the other hand, to the model based control algorithms.
4. References

/1/ Arisa S.A.: S-4-1600-450-230-LDE technical documentation, Logrono, Spain, 2002


/3/ Müller-Weingarten: hydraulic diagram 9098_64 - ZE2100-45.2.2 technical documentation, Esslingen, Germany, August 1998

/4/ Presswerkverbund Marke Volkswagen: Pressenvermessung Abschlussbericht, Werkzeugbau Wolfsburg, Germany, November 2013

/5/ Presswerkverbund Marke Volkswagen: Pressenvermessung Abschlussbericht, Werkzeugbau Wolfsburg, Germany, January 2015

/6/ Majer, Herbert: Vergleich zweier Regelungskonzepte für eine aktive Hydropneumatische Fahrzeugfederung, Stuttgart, Germany, 1989