Model and Simulation Analysis of a High Speed Hydraulic System in a Fineblanking Press

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Abstract. As a key component of a hydraulic fineblanking press, a high speed hydraulic system is used to achieve the rapid movement of the slider in the noncutting stage, which is important for improving the processing efficiency. It is important to study the various properties of a high speed hydraulic system as the rapid movement affects the precision of the machine as well as the quality of the stamping parts. In this paper, a high speed hydraulic system model was established, and the static and dynamic characteristics of the key components in the system were simulated and analyzed. The system control logic was designed according to the blanking process, and the changes in the speed, displacement, pressure and flow of the high speed cylinder in the blanking process were analyzed. A strategy using PID feedback control of the system was proposed to improve the blanking precision and provide a reliable basis for the control system design.

1 Introduction

The hydraulic fineblanking press is a type of high-efficiency machining device that is mainly used for the mass production of stamping parts, and it has high precision and surface quality. A high speed hydraulic system is a key component of the machine and has an important impact on processing efficiency and quality.

As shown in Figure 1, a blanking cycle of the punching slider is divided into the following four movement stages: feed, detection, blanking and return. To improve the processing efficiency, the slider moves quickly in the feed and return stages. Due to the high quality and rapid reciprocating motion, the inertial impact of the slider affects the processing stability and quality. To ensure that the displacement, speed and acceleration of the slider meet design requirements, it is necessary to generate a system model and perform a simulation analysis according to the processing parameters in the design of the high speed hydraulic system.

Scholars around the world have conducted extensive research regarding the important technology of hydraulic systems. Adeoye et al. analyzed a characteristic curve using values obtained from various adjustments of the stroke working speed [1]. Dasgupta et al. studied the dynamic performance of a closed-loop servo-valve controlled system using a bond graph model [2]. Valdés et al. performed parametric modeling of the flow rate using CFD simulations [3]. Ylinen et al. presented a hydraulic cylinder model for flexible multibody simulations using monolithic coupling [4]. Chalupa et al. studied the modelling and optimal PID control in the MATLAB/Simulink environment [5]. Gradl et al. presented a linear hydraulic stepper drive for sensorless positioning tasks [6]. Ding et al. studied the trajectory-tracking problem and proposed a novel nonlinear control algorithm [7]. Wang et al. described a coupling between the 1D method of characteristics and the 3D finite volume method in the transient flow [8]. Huang et al. carried out a simulation analysis of the hydraulic system under different working conditions using AMESim software [9]. Lan et al. proposed an induction method to establish the dynamical mathematical model for accurate positioning, fast response and real-time tracing [10]. Gong et al. constructed an integrated simulation model based on power bond graphs [11]. Lei et al. established a dynamic simulation model and analyzed the dynamic characteristics [12]. Li et al. focused on the modeling, simulation and optimization using Modelica [13]. Lisowski et al. investigated the reduction in flow resistance of a valve using CFD and ANSYS/FLUENT analysis [14]. Sun et al. studied the transient flow and analyzed time-history curves [15]. Xu et al. proposed a

Figure 1. Four stages of a blanking cycle.

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multiobjective optimization model to evaluate and improve the safety brake performance [16]. Coelho et al. presented an adaptive cascade controller using differential evolution optimization [17]. Ye et al. developed an improved particle swarm optimization algorithm for a PID controller [18]. Guo et al. proposed a state feedback control based on a disturbance observer coupled with backstepping [19]. Li et al. studied the PID correction with MATLAB in a simulation analysis of the electrohydraulic proportional control system [20]. Kilic et al. proposed a structured neural network model to predict the chamber pressures in the hydraulic cylinder [21]. Forental et al. investigated the dynamic characteristics using experimental and modeling approaches [22]. Based on the abovementioned literature, this paper presents the simulation and analysis of a high speed hydraulic system in a B630T fineblanking press (rated load of 6.3 MN). First, working models of the key valves were established, and the characteristics of flow, pressure and transient response were analyzed. Second, the changes in the flow and pressure of the high speed hydraulic cylinder and the changes in the displacement, velocity and acceleration of the piston rod in a blanking cycle were analyzed using typical processing parameters. Finally, the effects of displacement feedback control with a variable control current of the high speed hydraulic system on the accuracy of the displacement were studied.

2 Modeling Of the High Speed Hydraulic System and the Key Valves

As mentioned above, there are four stages in a blanking cycle with rapid slider movement in the feed and return stages; accordingly, a high speed hydraulic system model was established, as shown in Figure 2, with a constant system pressure source of 90 bars.

The electrohydraulic directional valves V8 and V2, the proportional directional valve V3 and the pilot operated check valve V6 in the model control the system pressure and flow, which drive the high speed cylinder. Therefore, it was necessary to set up a working model of these key valves and analyze their static and dynamic characteristics, mainly flow, pressure drop, and opening and closing. The specifications of the key valves used in the model and the analysis are shown in Table 1.

### Table 1. Specifications of the key valves

<table>
<thead>
<tr>
<th>Valves</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>V8</td>
<td>Flow diameter: 16 mm; maximum pressure: 28 MPa; opening time: 0.55 s; closing time: 0.35 s; orifice diameter in port A: 1 mm; two-position four-way; internal supply and drainage.</td>
</tr>
<tr>
<td>V2</td>
<td>Flow diameter: 16 mm; maximum pressure: 28 MPa; switch time: 0.55 s from right to left and 0.35 s from left to right; two-position four-way; external supply and internal drainage.</td>
</tr>
<tr>
<td>V3</td>
<td>Flow diameter: 10 mm; maximum pressure: 31.5 MPa; switch time: right to left: 0.50 s; switch time: left to right: 0.60 s; three-position four-way.</td>
</tr>
<tr>
<td>V6</td>
<td>Flow diameter: 30 mm; maximum pressure: 31.5 MPa; maximum flow: 400 L/min.</td>
</tr>
</tbody>
</table>

The working model of the electrohydraulic directional valve V8 is shown in Figure 3, and the simulation result is shown in Figure 4. The curves demonstrate the relationships between the pressure drop and flow rate of V8. The opening and closing characteristics of the four ports of V8 were consistent. As seen in Figure 5, the flow varies with time for port A of V8 under the constant differential pressure and step signal (valve is opened or closed); the opening time from 0 s to fully open is 0.55s, and the closing time from 0.1 s to complete close is 0.35s.

### Figure 3. Working model of valve V8.

### Figure 4. Relationships between the pressure drop and flow rate of valve V8.
Figure 5. Transient response characteristics of port A of valve V8 under the effect of step signal.

Similar to valve V8, the working model of the electrohydraulic directional valve V2 is shown in Figure 6, the relationships between the pressure drop and the flow rate are shown in Figure 7, and the opening and closing characteristics are shown in Figure 8.

Figure 6. Working model of valve V2.

Figure 7. Relationships between the pressure drop and flow rate of valve V2.

Figure 8. Transient response characteristics of port P of valve V2 under the effect of step signal.

The working model of the proportional directional valve V3 is shown in Figure 9. To accurately obtain the relationships between the pressure drop, flow rate and input current of valve V3, the transfer function $f(x)$ with first-order inertia was used to process the control current in the model, as shown in Figure 10, and the opening and closing characteristics are shown in Figure 11.

Figure 9. Working model of valve V3.

Figure 10. Relationships between the pressure drop, flow rate and control current of valve V3.

Figure 11. Transient response of port B of valve V3 under a pressure difference of 1 MPa and step signal.

The working model of the pilot operated check valve V6 is shown in Figure 12, the relationships between the
pressure drop and the flow rate are shown in Figure 13, and the flow varying with time when valve V6 is opened suddenly under a differential pressure of 0.65 MPa is shown in Figure 14.

3 Control Process of the High Speed Hydraulic System

3.1 Control of the Electrohydraulic Directional Valves

The action of the electromagnets Y1, Y3 and Y10 of valves V8, V2, and V4 were consistent, which were controlled by the displacement sensor of the main cylinder. The control logic of valve V8, V2 and V4 with four option switches is shown in Figure 15. Each switch had four ports, three inputs and one output, and port 1 was used for the control signal. The switch had a set threshold value; when the value of port 1 was greater than the threshold value, port 4 outputs the value of port 3 and otherwise outputs the value of port 2. The letter k was a constant, indicating the control signals of the electromagnet of the four stages separately.

3.2 Control of the Proportional Directional Valves

The control of the electromagnets Y7 and Y8 of valve V3 are shown in Figure 16, which demonstrates the closed-loop control of each stage of the high speed cylinder. The control strategy was as follows: first, the displacement difference was obtained by comparing the actual displacement to the set displacement of the high speed cylinder, and the difference was then input to the PID controller to adjust the input current of the proportional directional valves; the displacement of the high speed cylinder was then controlled to precisely approximate the given displacement.
AD: Actual displacement; SD: Set displacement; MD: Main cylinder displacement; DSA: Difference between set and actual displacement; CC: Control current; HCP: High speed cylinder pressure; F: Feed; D: Detection; B: Blanking; R: Return; OR: Overpressure return; Y7, Y8: Electromagnets; RPID: Return PID control; FPID: Feed PID control; BPID: Blanking PID control; DPID: Detection PID control.

Figure 16. Schematic diagram of PID control of proportional electromagnets.

4 Process Simulations and Performance Analysis of the High Speed Hydraulic System

4.1. Process Simulation

The working process of the high speed hydraulic system was simulated according to practical blanking process parameters, and the pressure and flow changes in the hydraulic system and the displacement, speed, and acceleration changes in the piston were analysed.

The specific blanking process parameters were as follows: the thickness of the plate to be punched was 8 mm, the total mass of the moving parts of the press pushed by the high speed cylinder was 6.43 tons, and the system friction damping was 50000 N/(m/s); additional parameters are shown in Table 2.

The changes in the displacement, velocity, acceleration, pressure, and flow of the high cylinder in a blanking cycle are shown in Figure 17 and Figure 18. Notably, the speed was exactly the set value when the control current value made the system reach a steady state.

Table 2. Blanking process parameters.

<table>
<thead>
<tr>
<th>Process stages</th>
<th>Feed</th>
<th>Detection</th>
<th>Blanking</th>
<th>Return</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (mm)</td>
<td>45</td>
<td>10</td>
<td>10</td>
<td>65</td>
</tr>
<tr>
<td>Velocity (mm/s)</td>
<td>120</td>
<td>50</td>
<td>25</td>
<td>135</td>
</tr>
</tbody>
</table>

As seen in Figure 17, the displacement changing process includes four stages, which meets the process requirement of fineblanking. Notably, the displacement curve indicates a transition at each turning point and stagnation at the highest position, which results in a blanking cycle of 1.65 s (punching 36 times per minute), while the blanking cycle should be 1.46 s (punching 41 times per minute). In a blanking cycle, the velocity changed smoothly; however, the acceleration fluctuated, mainly in the acceleration and deceleration between different stages.

As seen in Figure 18, the varying pressure trend of the high speed cylinder in a blanking cycle was consistent with the acceleration of the piston rod, except for the slight difference in pressure due to the different frictional resistance at different velocities, and the highest pressure was 84.15 bars. The flow of the high speed cylinder was proportional to the velocity of the piston; therefore, the varying flow trend was consistent with the velocity, both having no large fluctuation and oscillation. The maximum flow was 72.8 L/min during the feed stage and 81.8 L/min during the return stage.

The above simulation analysis reveals that the displacement and velocity of the piston in the high speed cylinder meet the practical process requirements, and there are no significant fluctuations and oscillations of pressure and flow in the process. Given the general process parameters, the design of the high speed...
hydraulic system is appropriate, and the flow and pressure of all hydraulic valves meet the requirements of the high speed hydraulic system.

5.2. Performance Analysis

The influence of the displacement feedback control on the displacement curve is shown in Figure 19, using the same simulation process parameters in Table 2; however, the control current used in the simulation was approximately 90% of the actual required value. For example, a control current of 93.5% of the maximum current was required for the velocity of the fast advance stage to reach 120 mm/s, and the control current used in the simulation was 84.5%. Additional current values are shown in Table 3.

![Figure 19. Influence of the PID feedback control on the displacement curve when control current was reduced by 10%.](image)

As seen in Figure 19, if there was no displacement feedback control, the displacement curve drastically deviated from the ideal curve when the control current was 90% of the required current, and the time of a blanking cycle was extended from 1.62 s (punching 37 times per minute) to 1.82 s (punching 33 times per minute). A PID controller using the displacement sensor in the main cylinder as the feedback device was adopted to adjust the control current of the proportional valve; the actual displacement curve was still precisely approximated to the ideal displacement curve, even if the control current was reduced to 90% of the required current, so there was considerable improvement in the control precision of the system. The PID parameters mentioned above were adjusted independently according to the fineblanking process; the control effect may have been different if the process parameters were different or the control current was not reduced by 10%.

### Table 3. Control current required and used in the simulation.

<table>
<thead>
<tr>
<th>Electromagnet Process stages</th>
<th>Y7 Required current (%)</th>
<th>Y7 Used current (%)</th>
<th>Y8 Required current (%)</th>
<th>Y8 Used current (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>93.5%</td>
<td>84.5%</td>
<td>61%</td>
<td>55%</td>
</tr>
<tr>
<td>Detection</td>
<td>45.4%</td>
<td>41.4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blanking</td>
<td>76.2%</td>
<td>69.2%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Conclusions

In this paper, a high speed hydraulic system for a 630T fineblanking press was established, and the static and dynamic characteristics of the key hydraulic valves as well as the control strategy and operation effect of the hydraulic system were analyzed. After analyzing the results, the following conclusions have been drawn:

The high speed hydraulic system proposed in this paper meets the process requirements of fast feed, slow blanking and fast return in fineblanking.

The control mode and the parameters greatly influence the characteristics of the high speed hydraulic system; improper modes and parameters may cause significant fluctuations in pressure and flow or severe oscillation.

Displacement feedback control significantly improves the tracking performance of the high speed hydraulic system for a given displacement, with high resistance to external interferences.

A high speed hydraulic system is a key component of the machine and has an important impact on processing efficiency and quality.

The research results of the paper will help to improve the design quality and efficiency of the hydraulic system in complex equipment.

### Acknowledgement

This research was financially supported by the National Natural Science Foundation of China under Grant 51375438.

### References