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REALIZATION OF FAST 10-TON SERVO PRESS USING HYDRAULIC HYBRID SERVO BOOSTER

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Abstract. We report the development and control of a 10-ton servo press using our novel hydraulic circuit, called Hydraulic Hybrid Servo Booster (H2SB). The press is equipped with a massive 200 kg slide. In this paper, we describe the details of the hardware and present two experimental results: 1) EHA positioning control, 2) Fast approach and press control using boosting mode. The former shows that precise 10 µm positioning is easily achievable with the small servo pump even in the high load. The latter demonstrates that high-speed slide motion is possible with the properly chosen accumulator and meter-out circuit, and smooth transition from the high-speed motion to the high load press motion is possible.

Keywords: Hydraulic servo, Press machine, Hybrid drive, Boosting, Precision drive

1. INTRODUCTION

Manufacturing industry has long been expecting to develop advanced technologies for molding difficult-to-process materials, to greatly reduce the number of processes and processing loads, and to enable adaptation for multi-product production. Servo press machines are able to improve slide down dead point accuracy, slide stop during processing, arbitrary setting of motion shape, etc., which was difficult to control in the past [1]. Among the servo press, *hydraulic* servo press is suitable for extrusion of long objects and especially useful for heavy load operation.

Recently, in hydraulic industry servomotor controlled EHA or HST attracted interest by its advantage in energy-efficiency and flexibility over conventional servo-valves. Actually, there exit commercially available EHA-type servo presses. However, as the required power becomes higher, the size of the servomotor must be larger accordingly. Consequently, not only the cost increases, but also the precision and dynamic response decrease: Large servo-pumps cannot outperform smaller servo-pumps in dynamic response and flow control resolution at the most important stage: press, where the speed of the motion is relatively low. Variable displacement pumps or twin pumps can achieve the continuous or multi-stage *gear shift*, its resolution is limited due to the pump size, or the co-axis servo motors.

To overcome this problem, we have invented a new type of hydraulic hybrid circuit, called *hydraulic hybrid servo booster* (H2SB) [2]. As shown in Figure 1, the basic circuit consists of a small servo pump embedded in conventional valve driven open-loop circuits. This circuit works not only as a conventional metering circuit or an EHA unit, but also as a boosting circuit. Thanks to this multi-function, heavy-load and high-precision servo drive are possible without using large servomotors at the expense of addition of small servo-motors.

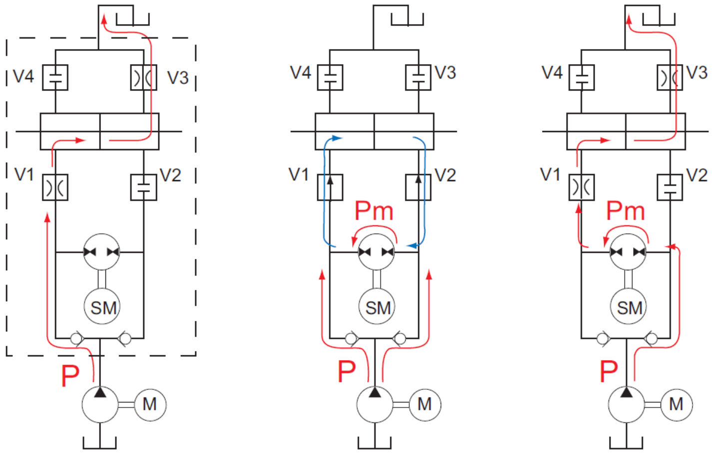

FIGURE 1. Hydraulic Hybrid Servo Booster (H2SB) consists of the main pressure source, valve bridges and servo-pump. The boxed section is duplicated for multi-degrees-of-freedom applications. The circuit has thee functions: Open circuit mode (left), Closed circuit mode (center), and Boost mode (right).

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In Reference [2] we presented the application to small-sized servo press where the four valves are implemented as on/off valves. The on/off valves allow the cylinder rod move fast up to the maximum orifice area. When the rod passed the prescribed position just above the target work, the outlet valve is closed to stop the rod motion. This instantaneous valve closing results in undesired surge pressure. If the rod mass is small enough so that mechanical shock is negligible, there is no problem with this naïve method. On the other hand, if the rod is connected to massive slider, as in this study, the speed must be smoothly decreased.

In this paper, we show another realization where the valve V3 in Fig.1 is replaced by a proportional valve to achieve smooth speed control. Moreover, we introduce an accumulator so that the slide moves fast over the maximum flow of the main pump. The special focus here is that how we can smoothly make transition from high speed motion to precise positioning or pressing using the unique characteristics of H2SB. As the initial trial, we conducted some experiments where hand-tuned simple controllers are combined. Below we present the experimental system of the press machine, then present the press control method and discuss the experimentally obtained results.

2. A 10-TON SERVO PRESS

Figure 2, left shows the outlook of the press machine. This is a 10-ton press composed of 200 kg slide that moves vertically with four ball joints. The slide is connected with a double-rod cylinder with the piston diameter 100 mm and rod diameter 56 mm. The maximum force is 112 kN at 21 MPa pressure. The stroke of the cylinder is 500 mm and the open height is 600mm.

Figure 2, right shows the hydraulic circuit. This is one of the realization of the H2BS circuits (Fig. 1) , where we employed conventional two-way solenoid (On/Off) cartridge valves for V1, V2 and V3, and a two-way proportional cartridge valve for V4 (the outlet orifice of the cylinder chamber). Note that in our previous small press in [2], V3 and V4 is combined into a single four-way solenoid valve. In the current study, we cannot use only solenoid valves because the moving mass is 200 kg.

The H2BS unit is connected to the main pressure source. We use an IPM motor-driven gear pump with the volume 40 cm^3/rev. In addition, we introduced an accumulator to the pump to make the slider approach fast to a target position. As a small servo-pump, we use a 0.8 cm^3/rev micro piston pump coupled with a 800 W AC servomotor. For the servo-pump control, we use the built-in speed control mode of the servo driver with some parameter tuning. If there is no volumetric loss, the single rotation of the micro pump results in 0.15 mm cylinder displacement. The rated torque of the motor is 2.4 Nm, that is, the pump can generate 16.9 MPa differential pressure theoretically, which results in 90.4 kN. Although the motor size seems too large, it is convenient for initial testing. The cylinder is connected to the H2BS circuit by 4 m hoses.

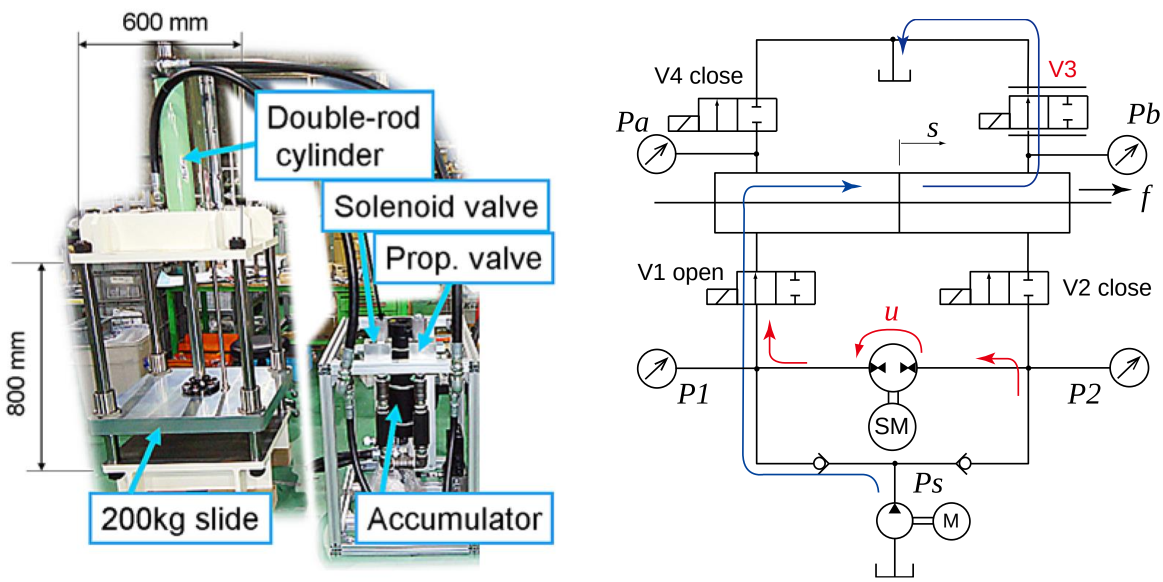

FIGURE 2. (Left) Outlook of the 10-ton servo press composed of 200 kg slide, double rod cylinder, accumulator, and H2SB circuit. (Right) The hydraulic circuit diagram for the open circuit mode and boost modes.

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The servo press is installed with two kinds of digital positon sensors: one is 500 mm stroke with 10 µm resolution, the other is 30 mm stroke with 0.1 µm resolution. Pressure sensors are installed to the each chamber of the cylinder, inlet/outlet of the servo-pump, outlet of the main pump, and the tank port. For the real-time control system, we employed dSPACE DS1104 controller board and the software toolkit, where our control algorithm runs at exactly 1 ms sampling time. All the analog signals are passed to 16-bit AD converter, then filtered using forth-order Butterworth filters with the cut-off frequency 30 Hz.

Table 1 summarizes the main specification of the system.

TABLE 1. Components and specifications of the 10 ton H2SB servo press

Component	Specification	Value
Main pump (Daikin / Sumitomo Precision)	Maximum Pressure	7 [MPa]
	Displacement	41.5 [cm^3]
Servo motor (Panasonic)	Rated torque	2.4 [N.m]
	Rated rev	3000 [r/min]
Micro Pump (Takako)	Displacement	0.8 [cm^3]
	Maximum flow rate	2.4 [L/min]
Accumulator (Hydac)	Charged pressure	2 [MPa]
	Gas volume	5 [L]
Position sensor (Magnescal)	Resolution	10 [µm]
Pressure sensor (Trafag)	Range	25 [MPa]
	Precision at 25[°C]	0.3 % FS
Cylinder	Pressure receiving area	53.91 [cm^2]
Slide	Weight	200 [kg]
	Range of motion	500 [mm]

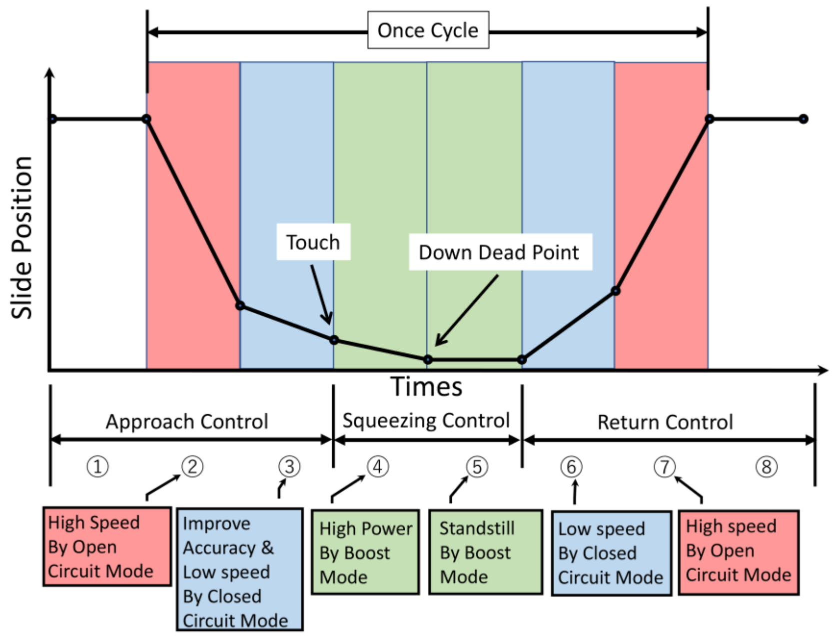

FIGURE 3. One cycle of H2SB servo press motion

4. EXPERIMENTS

Figure 3 shows a typical slide motion of the servo press machine and the proposed control modes in this study. The slide moves down to the target positon as fast as possible, then carefully approaches to the work piece (metal stock covered with a 5mm thick rubber sheet in this study). Then, as soon as the slide contacts to the work, it starts push at some desired pressure (or keep the desired load) for a prescribed period. Then, it returns to

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the original position (at maximum speed). Minimizing the cycle time while achieving the precision is crucial to make the productivity high, hence, make the servo press machine useful.

To evaluate the basic performance of the press, we conducted the following two experiments:

1) Positon control with the EHA (closed-circuit) mode (step response of the position control)
2) Fast approach and positioning using a combination of the meter-out and EHA mode, press with the boost mode, and fast return.

In all these experiments we employed a simple PID controller with different parameters (auto-tuning or introducing some model-based controllers are left for future work). The results are presented below. Although not shown here, it is easy to set various motion patterns (trapezoidal trajectory or so) as necessary.

4-1. Position Control with EHA Mode

To check the positon control resolution, we conducted a step response experiment with the EHA mode (see Fig. 1, center) at unloaded condition. In this experiment, the slide is allowed to move within the range of the precise sensor with 0.1 μm resolution, which is used for the position feedback.

The experimental results is shown in Fig. 4, where each data is captured at 10 ms sampling time. The magnitude of the position step is set to 750 μm. The position feedback gain is tuned to a relatively high value. The position error is converged to 1 μm within 5 s, and 0.1 μm in 7 s. There can be seen overshoot and vibration, but negligible. The steady-state output flow from the micro-pump, measured from the actual motor speed, is 0.2 LPM. This is a drain flow. The higher the pressure is, the more the drain flows.

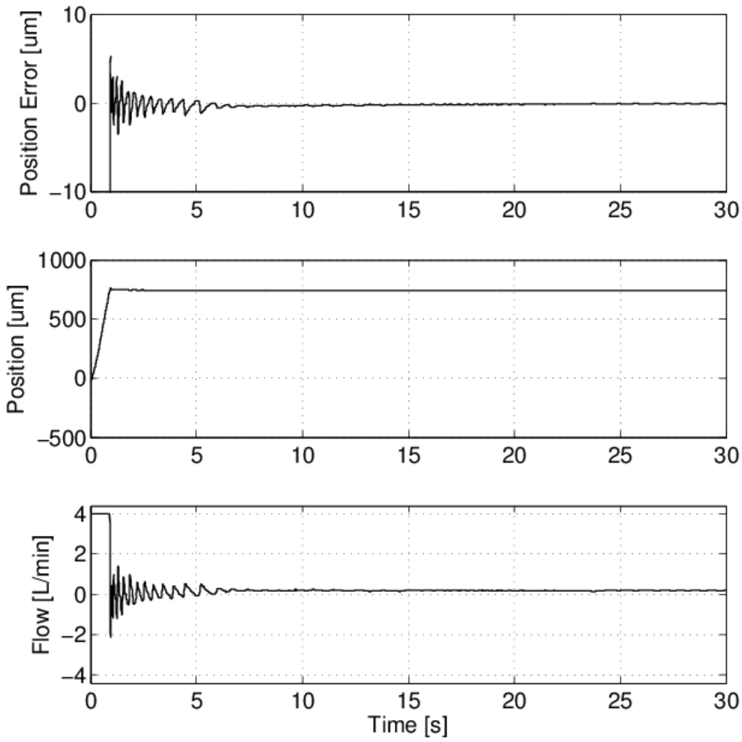

FIGURE 4. Step response of position control by closed circuit (EHA) mode. The step is given by 750 μm. The position feedback gain is set relatively high. This results in a small overshoot and vibration, which are negligible. The position error is converged to 1 micrometer within 5 s, and 0.2 micrometer in 7 s.

4-2. Fast Approach, Press and Return

Figure 5 shows the experimental result on the typical press motion explained in the beginning of this section. The first panel shows the slider position. The first target slide position is set to 469 mm (200 μm above the work). A simple PD control with a phase lag compensation is adopted for the meter-out control (V1 is opened, V2 and V4 are closed, and V3 is throttled). The maximum velocity is around 500 mm/s as shown in the second panel. For the switching from open circuit to closed circuit, we simply used the position event in this experiment. Specifically, if the slider passes the prescribed position (1500 μm in this experiment), then it switches the mode. Then, V2 is fully opened, and servo-pump is position controlled. With hand-tuned

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parameters, we could make the slider reach the first target position within 100 μm error in about 1.2 s. After keeping the EHA position control mode for 0.1 s, then it closes V2. After waiting another 0.1 s, it gradually opens V3 to make the rod-side chamber pressure Pb reaches to the tank pressure (0.5 MPa approx. in this case). This enables the slide to touch downs to the work piece and makes the controller transit smoothly to the boosting mode. This process completes 1.649 s in this experiment.

Then, the servo-pump restarts to control the pressure Pa of the head-side chamber. The bottom graph shows the servomotor command u hits the maximum (1 means the 100% rotation speed). It took some time (2.2 s, approximately) for the servo-pump to reach the high pressure due to its small displacement. We made the controller hold the pressure around 14 MPa (with 0.5 MPa tolerance) for 0.5 s. Then, V3 is fully closed. Finally, it opened valve V2 and V4 and closed V1 to make the slide return to the original upper position from.

Although we did not evaluate the precision of the pressure control in this experiment, another experimental result on force step response shown in Fig. 6 demonstrates that the pressure control error is below 3% of the full scale (100 kN) at boosting mode while the supply pressure is kept 7 MPa.

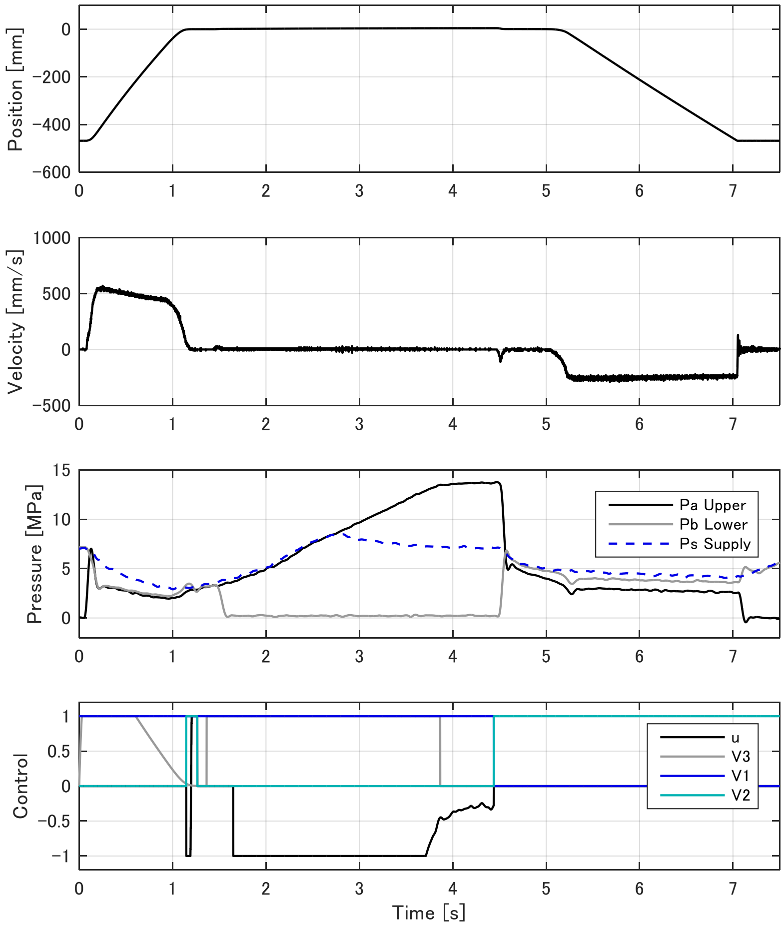

FIGURE 5. Experimental result of full stroke press control using all the three control modes.

5. CONCLUSION

We developed a 10-ton servo press using our novel hydraulic circuit, called Hydraulic Hybrid Servo Booster (H2SB). Since the H2SB was successfully applied to a small-sized servo press, in this paper, we showed another realization where the outlet valve of the cylinder was replaced by a proportional valve to achieve smooth speed control of the massive 200kg slide. Moreover, we introduced an accumulator so that the slider move fast over the maximum flow of the main pump. Therefore, the special focus here was that how we can smoothly make transition from high speed motion to precise positioning or pressing using the unique characteristics of H2SB.

As the first trial, we implemented hand-tuned simple controllers and tested them independently. Then combined them effectively. In this paper, we presented two experimental results: 1) EHA positioning control, 2)

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Fast approach and press control. The former showed that precise 10 µm positioning is easily achievable with the small servo pump even in the high load. The latter showed that high-speed motion is possible with the properly chosen accumulator and meter-out circuit, and smooth transition to press motion is possible. We also confirmed in Reference [3] that transition from boosting mode to open-circuit mode is automatically achieved without switching the valves. The transition depends on the load; the large flow from the main pump or accumulator (blue arrow in Fig. 2) can flow into the cylinder once the inlet pressure (P1 in Fig. 2) is lowered due to the absence of the load.

Overall, the experimental results proved that H2SB is actually promising hydraulic circuit for servo press machines. Our ongoing work focuses on model-based control algorithms for this system and compare the performance with the existing system.

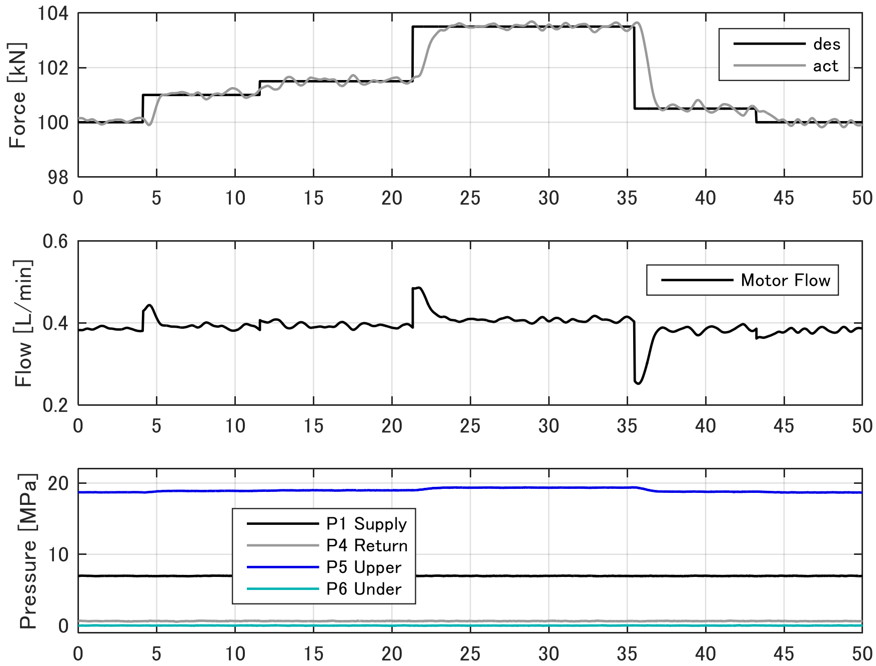

FIGURE 6. Force (pressure) control performance around 100 kN at boosting mode where the supply pressure is 7 MPa. Top panel shows that the steady-state errors are below 3 %, although there are transient error due to the small servo pump. The second panel shows the theoretical output flow of the servo pump. The bottom panel shows the pressure of the cap-side chamber almost reached 20 MPa, and the servo boost is successful.

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