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Development of direct driven servo hydraulic actuator

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Abstract Direct control of hydraulic cylinders - without use of control valve, represents a newer concept of energy-saving control of cylinders, without damping losses. In order to study this type of drive, it is necessary to design and manufacture a compact model of such device to study the control concepts and to check the operation of the system. We will study the existing implementations of such drives and create our own direct driven servo-hydraulic actuator (hereinafter DD SHA), with which we will move different loads. A servomotor must be attached to a suiTable hydrostatic unit (pump-motor). All the missing components need to be designed and manufactured for completed hydraulic circuit.

Keywords: • hydraulic cylinder • hydraulic actuator • direct driven • servo actuator • PLC control •

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1 Introduction

Direct driven servo hydraulic actuators consist a servo motor directly coupled to a hydraulic pump. The positioning of the hydraulic piston, the adjustment of the pressing speed, as well as the force control are accomplished without the use of a directional or proportional valve.

Contrary to this concept the conventional press drive is normally effected via an asynchronous motor running at constant speed and a pump with variable delivery rate that can be adjusted mechanically, and it is controlled by directional or proportional valves.

But still, the new technology cannot be utilised completely without valves. Different valves are required e.g. for safety functions, or for the filling of large cylinder chambers for quick movements. In addition, the maximum pressure in the system is also usually limited by pressure relief valves.

Due to their small size, capacity and versatility, pump-controlled hydraulic systems are very useful in various applications such as bending, moving, compressing, lifting, closing, and steering.

The advantages of such systems are [1]:

- increased productivity,
- robustness – long service intervals,
- overload safety – safety pressure valves,
- high accuracy and dynamics of the servomotor,
- possibility of connection – industry 4.0,
- less necessary components and space,
- easier maintenance,
- less hydraulic oil used,
- mobile system – easy connection and start-up.

There are also very large versions of direct driven (DD) electro hydraulic actuator (EHA) devices used to move turbine gates and flaps in hydropower plants. Such devices are purpose-built and custom-made. The hydraulic cylinders of such devices can reach up to 27 m of working stroke and up to 10,000 kN of working power.

2 Different possibilities of direct driven hydraulic cylinder

There are various systems that use one or two pumps to drive hydraulic cylinders, either through piston rod or differential cylinders. There are also a few different system configurations that use multiple hydraulic pumps to control the differential cylinder.

2.1 Versions with more than one hydraulic pump

Cleasby in Plummer [2] developed and built a prototype of a hydraulic system directly controlled by a pump. It was designed using special one-way hydraulic cylinder with a plane ratio of 1:2 for an aircraft simulator. Each cylinder was connected to a pair of identical constant flow pumps acting as a tandem pump and was connected to an electric servomotor. System also used a hydraulic accumulator which compensated energy of the weight of the load and provides a difference in flow due to the different volumes of the cylinder. This restores some energy and improves the efficiency of the entire hydraulic system.

There are a lot of roller ratios available on the market that are not 1:2, as this ratio is rarely used in practice. In addition, a system that requires two pumps makes the drive assembly heavy, complex, and expensive. Therefore, such systems are not popular in practice.

2.2 Versions with through piston rod and identical areas

Hydraulic cylinders with a through piston rod were developed primarily for the aerospace industry.

In hydraulic systems, hydraulic fluid typically circulates continuously throughout the cycle, including the tank, pump, accumulator, valve, and actuators. In circuits as shown in Figure 1, the hydraulic fluid does not leave the pump and actuator circuit; therefore, it is known as the hydrostatic circuit. However, such a hydraulic cylinder system with a through piston rod is not suiTable for a hydraulic system with a differential cylinder.

Compared to a hydraulic cylinder with a through piston rod, differential cylinders require less space to operate and are therefore more popular in the industry.

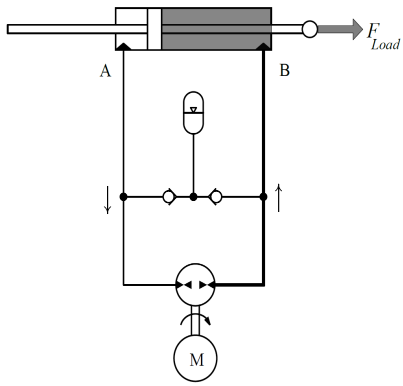

Figure 1: System with through piston rod [1]**.**

2.2 Versions with differential hydraulic cylinders

Allan J. Hewett [3] was the first to patent a single-pump hydraulic system that controlled a single differential hydraulic cylinder. He used a 3/2-way solenoid valve to divert the differential flow of the hydraulic cylinder. The valve directs the differential flow from both sides of the cylinder into the tank. Two non-return valves protect the pump against cavitation.

The force of the load helps to pump to the internal position of the final actuator and calms the uncontrolled movement. Until the solenoid valve changes position, the load will fall uncontrollably. From the moment the solenoid valve changes position, the pump acts as a hydraulic motor.

The hydraulic pump in this circuit operates in four hydraulic quadrants and is able to recover some energy when the load helps operation. The system has been used for some forestry machinery, and the results have shown evidence of uncontrollable load vibrations. Because one side of the cylinder is always connected to the low-pressure side of the hydraulic circuit through the solenoid valve, the circuit is uncontrollable under conditions of sudden load switching.

Rahmfeld and Ivantysynova [4] used a similar idea when they replaced the solenoid valve with two pilot non-return valves. As shown in Figure 2, when the load is resisted, the pump supplies the cylinder terminal B and the piston rod moves outwards. The high pressure at the cylinder connection B is maintained by the closed control valve PCVb and the non-return valve PCVa remains open. The pump sucks the oil from port A, the excess liquid from port A to pump I is directed to the tank with the open line of the PCVa pilot check valve, and thus pump I operates in pump mode. Because of the support load, the pressure in terminal A rises, the pilot check valve PCVb opens its line, and the piston rod begins to retract. From this point on, the pump works like a hydraulic motor.

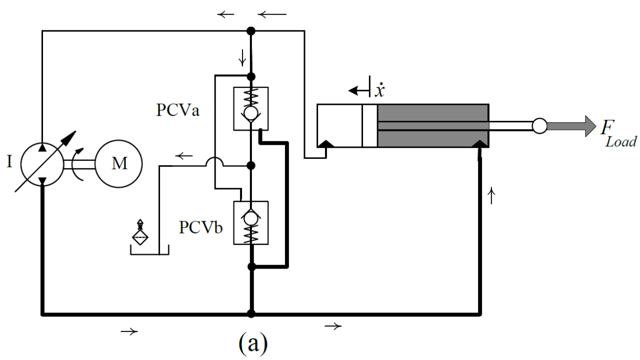

Figure 2: Direct driven differential hydraulic cylinder with two pilot non-return valves [1].

In the systems discussed so far, using a single pump to control the flow of differential hydraulic cylinders, one side of the cylinder is always connected to the low-pressure side of the hydraulic circuit. In the event of a sudden change in load, transient pressures occur, creating unwanted vibrations at the final actuator.

The improved system (Figure 3) consists of a DC electric motor connected to a two-way constant flow hydraulic pump. AdjusTable non-return valves CV1 and CV2 (with the possibility of adjusting the opening pressure) improve the rigidity of the hydraulic cylinder against small support loads by raising the low pressure. The non-return valves PCV1 and PCV2 hold the actuator in its position when the system is idle. Closing the non-return valves PCV3 and PCV4 causes the differential currents of the differential cylinder to be diverted to the tank. The system turns out to be very inefficient due to the use of two adjusTable non-return valves CV1 and CV2 to improve the response of the final actuator to loads that resist movement.

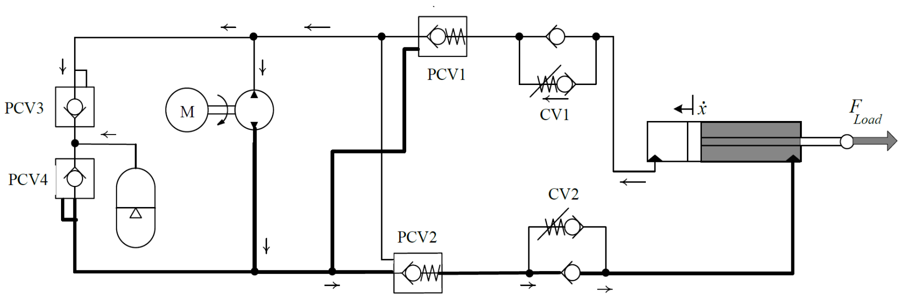

Figure 3: The improved design of direct driven differential hydraulic cylinder [1].

3 Design of our direct driven servo hydraulic actuator

Our goal was to construct and manufacture as simple DD SHA device as possible, which can be loaded as desired. A servomotor and all other hydraulic components had to be attached to a suiTable hydrostatic unit (pump-motor). We decided to choose the already proposed hydraulic scheme for the basic model (Figure 2). It had to be rearranged according to our needs and the shape of the device.

Given that the device will be used in the laboratory for the needs of studies and familiarization with such devices, it was necessary to add connection points for pressure monitoring, safety valves and filters for hydraulic fluid to the existing scheme. We also used a hydraulic accumulator to mitigate or prevent current and pressure peaks (similar to Figure 3). The final hydraulic scheme of designed direct driven servo hydraulic actuator is shown in Figure 4.

DD EHA devices are compact and based on efficiency in terms of device size. Since a lot of hydraulic components are used for our device, the device would be too large if we used classic components and connected them in a classic way - pipes, connections. Therefore, it was necessary to make a hydraulic block in which to install our components. We made a 3D model of the block and the hydraulic block itself, in which we installed the hydraulic components. Figure 5 shows a 3D model of the block with flow channels and connections.

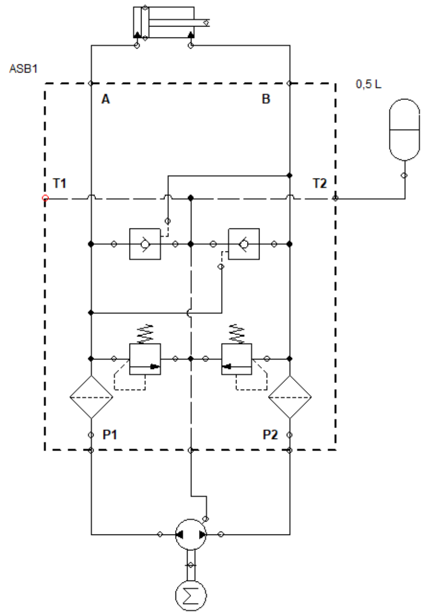

Figure 4: Hydraulic scheme of designed direct driven servo hydraulic actuator.

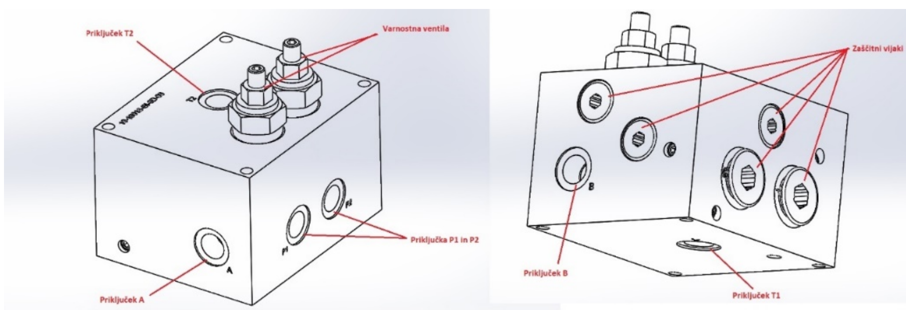

Figure 5: 3D model of the block with flow channels and connections.

3.1 Determination of hydraulic components

Based on the 3D model of the block, we were able to proceed with the construction of the layout of other components of the device and the layout of the device itself.

After the completion of the hydraulic scheme, it was necessary to precisely determine the hydraulic components. Depending on the method of component installation, we used 2-way screw-in hydraulic valves. Two controlled non-return valves type RHC 21/1 were used. Such valves are characterized by opening with a pressure at the opening connection, which is determined by the ratio of the surfaces inside the valve.

To protect the system against overpressure, we used two safety valves, which are adjusTable from 0 bar to 250 bar.

Because such hydraulic system operate in a closed hydraulic fluid circulation circuit, we used coarse screw-in hydraulic fluid filters. In our case, this is a built-in mesh with the appropriate density of loops (knits).

The final actuator of our device is a differential hydraulic cylinder. The diameter of the piston (d) is 22 mm, and the diameter of the cylinder (D) is 32 mm. The stroke of the cylinder (L) is 315 mm.

The size of the tank was determined according to the difference in chamber volumes in the hydraulic cylinder. The volume of the hydraulic accumulator is also determined. We used a 1-liter hydraulic fluid tank and a 0.75-liter hydraulic accumulator.

The main component of our DD SHA device is the hydraulic pump. A Bosch-Rexroth pump model AZMB-32-4.0UHO02PL was used. The external gear motor/pump, for both directions of rotation, can be used in four-quadrant operation. The size of the pump is 4 cm^3 and the maximum working pressure is 220 bar. The pump has a leakage port on which the maximum permissible pressure can be 3 bar. The pump is driven by a Rexroth Indramat, model MKD071B-061-KG1-KN with built-in absolute encoder, which gives us information about the position of the servomotor. The motor allows us a maximum speed of 4000 min-1 and a maximum torque of 32 Nm.

3.2 Modeling of device and final layout

Modeling of our device began with the connection of a servomotor and a pump. The shafts of both components are connected to the clutch, so it was necessary to make a suiTable flange, which connects the motor and the pump.
This was followed by planning the installation of the hydraulic block and other components.

Considering the fact that the air in the liquids always appears at the highest point of the system, it made sense to place the hydraulic accumulator in the highest position. Due to gravity, we ensured a constant pressure of the hydraulic fluid to the pump. To facilitate the connection of the components to the pipes, the servomotor with the pump was placed transversely to the direction of the hydraulic cylinder.

We have adjusted the mounting plate of our device so that it can be easily fixed to the laboratory workbench. If necessary, our device can be easily and quickly dismantled and moved to another location. Final layout of device with all components is presented in Figure 6.

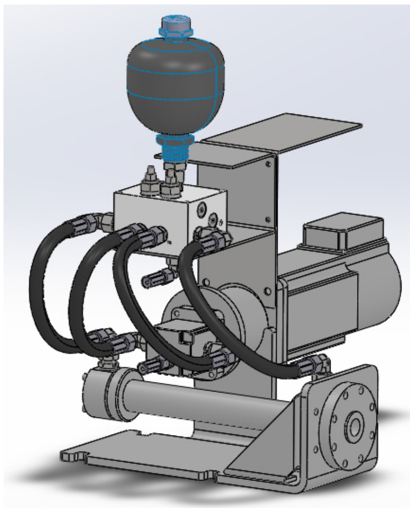

Figure 6: Final 3D model of the device with all components.

4 Performance and capabilities of direct driven servo hydraulic actuator

Based on the selected hydraulic cylinder, which has a piston diameter of 32 mm, a piston rod diameter of 22 mm and a working stroke of 315 mm, we calculated that the cylinder has 17.7 kN of working power and in the retracting direction 0.93 kN of power. The speed of moving outwards at full pump speed is 0.25 m/s and inwards 0.47 m/s.

4.1 Manual and closed-loop control

We first ran the system manually to check the correct operation and eliminate any errors. In doing so, we confirmed the assumption that the hydraulic cylinder moves outwards and inwards at different speeds. This results in different sizes of hydraulic cylinder chambers. This can be seen from Figure 7, as on the left the green curve rises with a smaller slope.

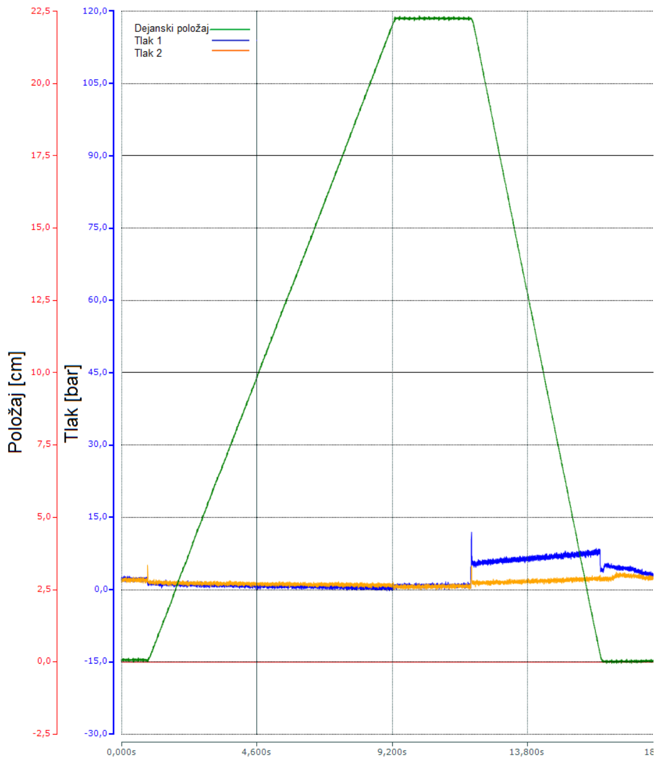

Figure 7: Results of manual system control.

When the system in manual mode worked properly without errors, we ran the system in automatic mode. The problem that occurred when starting in automatic mode was setting the PID controller. The problem arose due to the different speed of movement of the cylinder. We used the Ziegler-Nichols method to set the PID controller correctly. After setting the PID controller, the response of the system is extremely fast, as the hydraulic cylinder is controlled directly via the hydraulic pump, consequently via the servo motor.

The red line in Figure 8 represents the desired position and the green line the actual position of the hydraulic cylinder. The slope of the green line rise also depends on the set maximum permissible revolutions of the servo motor.

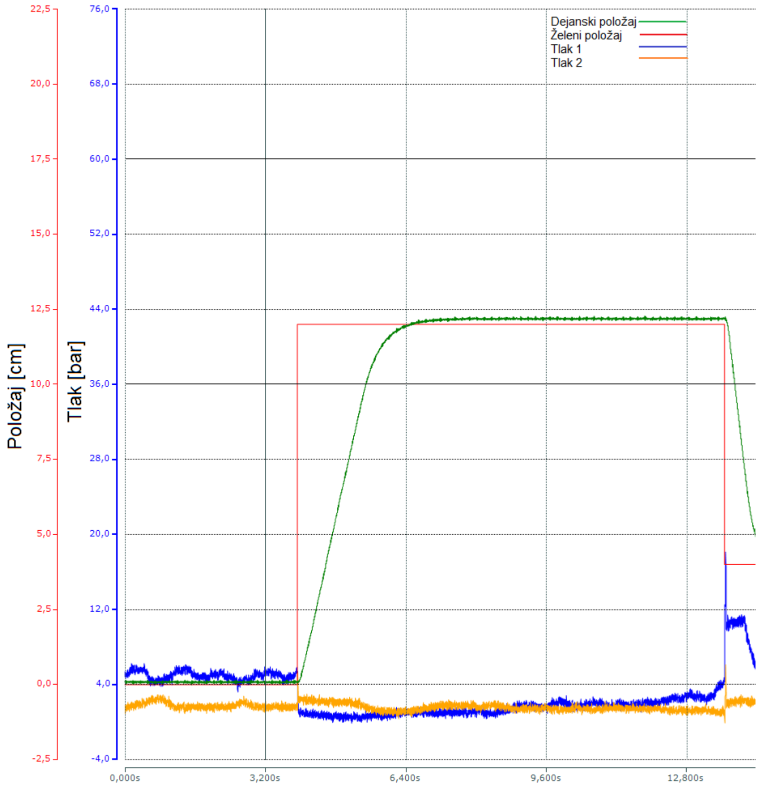

Figure 8: Results of position closed loop system control.

4 Conclusion

In the design and manufacture of the device, we limited ourselves to the size of the device and its usability for the purposes of a laboratory study.

When designing the device, it was necessary to think about how to vent the system later, to place the device in the laboratory so that it does not pose a danger to those present, and to consider all the necessary quantities that we had to calculate. We found our device to be powerful and rigid. The operation and behaviour of the device is smooth. There are no large pressure peaks in the system that would be observed as a nonlinear change in the position of the hydraulic cylinder.

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