FUNCTIONAL PROOF OF A FLAT SLIDE VALVE AS A 4/3-WAY PROPORTIONAL VALVE

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ABSTRACT

With a flat slide valve concept, when compared to conventional piston spool valves, reduced leakage and increased service life could be achieved. In order to achieve a reduction of leakage flows and guarantee the adjustability of the valves at the same time, a correct design of the pressure compensation is essential. The magnitude of force depends on both the operating point of the valve and the position of the slider. Due to the design of the flat slide valve, it is possible to use ceramic semi-finished products for the main stage, which consist of control plates and a slide plate. The geometries are simple enough to be inexpensively manufactured with sufficient accuracy, using a ceramic pre-product using laser cutting technology. This article introduces the concept of the flat slide valve for a proportional 4/3-way valve. The design of the valve, including the design of the metallic main stage is presented. This includes the design of the flow channels, which have to be suitable for ceramic materials. Furthermore the design of the actuator and hydraulic circuit for testing is presented. With the shown design, the function of a 4/3-way valve, known from piston spool valves, can be implemented with a linear behavior between slide plate deflection and opening flow cross section.

Keywords: Flat Slide Valve, High-tech ceramics, Pressure Compensation, Reduction of Wear, Reduction of Leakage, Linear Control Behavior, Innovative Valve Design

1. INTRODUCTION

In hydraulic systems, directional control valves are often used to control fluid flows. In particular, piston spool valves consisting of cylindrical components are employed. In the case of piston spool valves, a rotationally symmetrical spool moves in axial direction within a housing or a sleeve [1]. In most cases, sleeve/housing and slider are made of a metallic material. Thereby, two weak points occur, the first weakness is erosion at the control edges as shown in **Figure 1** and leads to wear of the control edges [3]. This wear has a negative effect on the controllability

Figure 1: Wear (erosion) at the control edges [2]

of the valves and thus limits their service lifetime. The second weakness is the function-related gap between sleeve/housing and spool, which is necessary to be able to adjust the spool, as can be seen in **Figure 2**.

Figure 2: Function-related gap between sleeve/housing and spool

Through the application of a pressure difference, an unavoidable leakage occurs through the gap, leading to a reduced efficiency.

Ideas for a friction- or leakage-minimized design of flat slide valves have already been suggested in [4] and [5]. The patent mentioned in [4]

describes a valve disk package for sanitary applications. The pressures used in sanitary applications are very low compared to the pressures commonly used in standard hydraulics. In the patent applied for in [5], a sleeve is used as a spacer between the cover plate and the base plate. This is to ensure that the sliding plate is movable and no normal force is applied to it. The use of this sleeve however results in a gap between the individual plates, which also leads to leakage as with conventional piston spool valves.

In contrast to the work presented in [4] and [5], the concept of a flat slide valve described compresses plate-shaped components in such a way that theoretically there is no sealing gap between the individual plates. This minimizes the resulting leakage and improves the efficiency of the valves. In addition, this design enables cost-effective integration of ceramics. Ceramics have a higher abrasion resistance, which can contribute to an increase in the service life of the control edges. The investigation of some ceramics which could be used in the flat slide valve has already been investigated in [7]. However, pressing the plates together and hereby reducing the gap, increases friction between the plates, which counteracts an adjustment of the valve and thus must be overcome. The functionality of a ceramic flat slide valve has not yet been proven in hydraulics.

The use of a new, innovative flat slide valve, which is the subject of a multidisciplinary research project at ifas (Institute for Fluid Power Drives and Systems) and IWM (Institute for Material Applications in Mechanical Engineering), is intended to improve upon the weakness of conventional valves and to demonstrate the functionality of a ceramic flat slide valve for hydraulic applications. In a first step, a valve with a main stage made of a metallic material is designed and tested. This first demonstrator is presented in this paper.

2. PRINCIPLE OF THE FLAT SLIDE VALVE

To prove the functionality of the ceramic flat slide valve, a functional model of a flat slide valve is constructed, which is designed as a 4/3-way valve. **Figure 3** shows the basic conceptual design of a flat slide valve.

The main stage of the valve is formed by three plates, which sit on top of one another. Together these plates form the flow channels of the valve.

Figure 3: Basic conceptual design of a flat slide valve

The two outer plates are the so-called control plates. The control plates are geometrically identical and fixed in position. The plate between the control plates is the slide plate, which is linearly movable. Depending on the position of the slide plate, the individual connections can be connected to each other, disconnected or partially connected.

Below the main stage is the pressure compensation, which is an elementary part of the concept. In order to prevent a gap between the plates of the main stage, five pressurized stamps are used. The force generated by these stamps is transferred to the main stage by a compensation plate and counteracts a gap formation.

The valve is sealed against the environment with a cover and a housing. In the concept shown, the locations of the hydraulic main connections of the valve are also indicated. These consist of the pump port, the two working ports A and B and the tank ports.

Figure 4 shows the main stage, the compensation plate and the compensation stamps. The compensation stamps press the main stage against the housing so that a normal force acts on the slider plate. On one hand, this normal force prevents a gap widening between the plates, on the other, the necessary actuator force also rises with increasing normal force. The necessary actuator force can be calculated using:

$$F_{\text{Fric}} = \mu \cdot (F_{\text{mech,t}} + F_{\text{mech,b}}) \quad (1)$$

In addition to the forces applied by the stamps, other forces also act on the main stage, such as the hydraulic pressures, which are present in the valve. In [6] the acting forces and correlations have been explained.

Figure 4: Forces acting on the slider

If the mechanical force is greater than zero, a gap is formed between the plates and the leakage increases. If the normal force is too high, large actuator forces are necessary to change the valve position. An exact calculation and design of the pressure compensation is therefore necessary.

3. THE METALLIC MAIN STAGE

The main stage, which will be made of metal for the first demonstrator, is shown in **Figure 5**.

Figure 5: Implemented steel main stage of flat slide valve

The design of this main stage was first presented in [6]. The design criterion for the flow behavior of the main stage was derived from valves of nominal size 6. In concrete terms, this means that at a flow rate of 30 l/min with HLP 46 (40°C) the valve should have a pressure drop of 10 bar at full deflection. In addition, the main stage should be able to withstand hydraulic pressures of up to 300 bar. The individual channels are arranged on one line, so that the compensation only has to balance the forces arising in the valve along this line. In

the center of the main stage, the channel connected to the pump port P is drawn in red. To the right and left of the pump port, the two working ports A and B are marked green. The two channels, which are connected to the tank are blue.

The maximum deflection of the main stage is ± 3 mm. Additionally, the main stage has a positive overlap of 1 mm in both directions. This can also be seen in **Figure 6**, which shows the main stage in neutral position (0 mm). In this position all ports are separated and there is no flow between each port. For the first test of the valve, aforementioned positive overlap was chosen in order to be able to investigate the behavior of the valve, in particular the leakage at low flow rates, and to be largely independent of manufacturing tolerances.

Figure 6: Neutral position of flat slider

Figure 7 shows the main stage at a maximum deflection to the left of -3 mm. This permits a flow from pump port P to working port A and a flow from working port B to tank port T.

Figure 7: Full deflection of flat slider to the left

When designing the main stage, it was possible to achieve a linear ratio between the valve stroke and the opening flow cross section in the simulations. The relationship between slider deflection and opening flow cross section for pump port P to working port A and pump port P and working port B can be seen in **Figure 8**.

Figure 8: Relationship between slider deflection and flow cross section for P-A and P-B

4. REALIZATION OF THE DEMONSTRATOR

In order not to have to manufacture a new demonstrator for each development stage of the valve, a demonstrator was developed which is able to measure different main stages. The plates of the main stage can have variable thicknesses and can be made of different materials. The special properties of ceramics, such as the comparatively high sensitivity to notch fracture, have also been considered. In addition, different channel geometries can be realized with relatively little effort.

Figure 9 shows the housing, which consists of three parts and the inner parts of the valve.

Figure 9: Demonstrator flat slide valve

The housing consists of a lid, a base and an intermediate housing. The lid and the base are aligned with each other via the intermediate housing using dowel pins. O-rings are used to seal the individual housing parts to the outside. The individual connections for supplying the stamps are located within the cover. In the final application, the flat slide valve should be supplied with the same pressures that are applied to the individual ports. The magnitude of the necessary

force is then defined by the size of the pressurized area. However, during function testing this would mean that for each new geometry of the main stage or for each pressure compensation to be tested; a new cover and stamps would have to be manufactured. For this reason, the individual stamps are supplied by pressure reducing valves for functional testing. Thereby a quick adjustment of the pressure compensation is possible.

The individual hydraulic ports (P, A, B, T), which supply the main stage of the valve, are located in the base of the housing. In addition to the hydraulic ports, there is also a leakage port. With this port, the leakage flow that would occur if a gap was formed can flow off to the tank. In addition, the connection can be used to detect the remaining leakage between the plates after finishing the testing of the pressure compensation and thus evaluate the concept.

A pressure sensor, which monitors the housing pressure, is also located in the base of the housing. This can be used to determine the force applied by the pressure to the inner parts of the valve and also allows the implementation of an emergency shutdown in case the housing pressure exceeds a critical level.

The actuator of the valve is attached to the intermediate housing. It is possible to connect actuators on both sides of the intermediate housing. For example, the main stage can be operated tensioned. Currently, one actuator is used to adjust the flat slide valve and the second side is sealed to the outside using a plug and an O-ring.

Figure 10 shows the inner parts of the valve.

Figure 10: Inner part of the flat slide valve

The pressure compensation is realized by the five compensation stamps and the compensation plate. The pressure compensation is guided by three guiding rods and slide bearings. The upper control plate is aligned with the compensation

plate via dowel pins and is fixed to it with screws. The slider plate is located between the two control plates and can be moved linearly, guided by the three guiding rods shown. The lower control plate is connected to the adapter plate by dowel pins and screws. This adapter plate supplies the main stage with fluid.

Figure 11 shows a sectional view of the inner parts of the valve from Figure 10 and the base of the body.

Figure 11: Sectional view of inner parts and base

The dowel pins for alignment of the control plates and the supply of the control plates through the adapter plate and the bottom are shown above. The seals between compensation plate and control plate, and between control plate and adapter plate, ensure that leakage can only occur between slider and control plates.

Figure 12 shows the metallic main stage, consisting of two control plates and a slide plate. Besides the parts shown in Figure 12, another slide plate is made of a special brass (CW713R), which is currently installed in the valve.

Figure 12: Metal main stage

Additional to the holes for the dowel pins and screw connections, the through-holes for the guiding rods are also shown in the figure. This guide rods are used to guide the compensation plate, and the slide plate linearly using the guide

surfaces shown. The flow channels correspond to the geometry shown in Figure 5. On both sides of the intermediate housing a connection geometry is located to attach an actuator.

In order to allow backlash-free adjustment of the slide, the design shown in **Figure 13** was implemented.

The connecting rod connects the actuator with the

Figure 13: Connection between slide plate and actuator

slider plate through the sleeve, which is shown on the left. The sleeve contains two guide bands, a dynamic seal and a wiper. After testing the pressure compensation, these can be removed in order to be able to measure the force required for adjustment without influencing it. The sleeve is sealed to the outside using an O-Ring by a static seal. The dovetail is secured with help of a notched pin in the connecting rod and can be tightened by the nut. The two pins serve as spacers so that the slide can move without collision.

5. ACTUATION

A stepper motor of size Nema 23 is used to adjust the valve. The motor has a resolution of 200 steps per revolution (1.8°) and the installed encoder can be used to evaluate the steps that have been carried out. **Figure 14** show the assembled actuator unit.

Figure 14: Actuator of flat slide valve

The rotary motion is converted into translatory motion by using a trapezoidal threaded rod and trapezoidal threaded nut. The trapezoidal rod has a pitch of 2 mm. A 64-fold microstepping can be realized with the used the stepper motor clamp. This results in a theoretical adjustability of the unit of:

$$\Delta x = \frac{\text{Pitch of trapezoidal rod}}{\text{Motor steps} \times \text{Micro stepping}} \quad (2)$$

$$= 0.00016 \text{ mm}$$

Axial needle roller bearings protect the stepper motor from axial overload. To measure the forces, which are required for an adjustment of the slide plate, a force sensor is mounted to the actuator, which can handle forces up to 1000 N. The maximum load capacity of the force sensor also represents the force limitation of the actuator. A combination of clevis joint and head joint has been installed in the actuator to ensure that the force measurement is almost completely free of transverse forces. A distance sensor measures the deflection directly before entering the valve. The actuator is guided by guiding rods and linear ball bearings. **Figure 15** shows the flat slide valve with attached actuator.

Figure 15: Valve with attached actuator

6. HYDRAULIC CIRCUIT FOR LOAD SIMULATION

In order to simulate a load, the hydraulic circuit shown in **Figure 16** is used for testing and measuring of the flat slide valve.

In addition to the pressure sensor shown, each hydraulic connection of the flat slide valve also has a temperature sensor to measure the fluid temperature. This allows a determination of the pressure drop between the individual valve ports and a determination of the viscosity of the fluid. Before the fluid enters pump port P and after the fluid leaves tank port T, a volumetric flow sensor is installed. A leakage or a gap widening between the plates of the main stage can be detected by

Figure 16: Hydraulic circuit for load simulation

determining the difference between the two measuring signals of the volume flow sensors. For a more precise evaluation of the leakage, the leakage port of the housing can also be used. Thereby the fluid outlet flow can be determined with the use of a scale and time recording. The leakage port is not shown in Figure 16.

With the help of the pressure relief valve (3) and the check valves (A1, A2, B1, B2), a load can be simulated between the working ports A and B. If the flat slide valve connects ports P and A and ports B and T, the pressure at working port A is higher than the pressure at working port B. Thereby check valve A1 is open and due to the lower pressure at working port B, the check valve B1 remains closed. The fluid exiting the pressure relief valve has a lower pressure than the fluid at working port A and a higher pressure than the fluid at working port B. As a result, the check valve B2 and A2 remain closed. The check valves are acting reverse for a connection from P to B and from A to T.

To simplify the control effort, a pressure sensor is located directly in front of the pressure relief valve (3).

The pressure relief valve (4) serves as a safety valve, since the used pressure relief valve (3) is limited to a pressure of 100 bar on the tank side.

Due to manufacturing tolerances, it may happen that one side of the control edges engages before the other. In this case, the high-pressure side would already be connected, and the low-pressure side would still be disconnected from the tank. The resulting overpressure can then flow via the pressure relief valve (4) to the tank and the pressure relief valve (3) is not getting damaged. With the pressure reducing valve (2) it is possible to use only one supplier to supply the flat slide valve and the stamps.

7. VOLUMETRIC MEASUREMENT

To compare the CFD simulations with reality, a measurement of the main stage was carried out. Figure 16 shows the results of this volumetric measurement for a flow from P to A. The volume flow was recorded for multiple positions. As fluid a HLP 46 was used, which had a temperature of 40 °C. The pressure difference between P and A was set to a constant level of 10 bar during the entire duration of the measurement. This also corresponds with the boundary conditions, which were used during the CFD simulations. The individual measuring points are shown as blue asterisks in the diagram. The black dotted line shows an ideal linear flow characteristic.

Figure 16: Volumetric flow measurement of main stage

As can be seen in Figure 16, an almost linear flow characteristic can be achieved with the presented channel geometry. The results show good correlation with the CFD simulations shown in [6]. Furthermore, the set target of a flow rate of 30 l/min; at a position of ± 3 mm and a pressure difference of 10 bar; could be achieved.

8. CONCLUSION AND OUTLOOK

In this paper, the advantages of flat slide valves in comparison to the currently used piston valves were presented. By using flat slide valves, a reduction of leakage could be achieved. Furthermore, the use of ceramic plates in the main stage can increase the service life of the valves, due to their better resistance to erosion.

The main stage of the valve consists of two fixed control plates and a linear moving sliding plate. These three plates form the flow channels of the valve. Depending on the position of the sliding plate, the individual ports are connected or disconnected.

In order to counteract the gap formation between the individual plates, a force is applied

to the main stage by compensation stamps. However, this applied force must be limited, otherwise movement of the sliding plate is not possible.

A metallic main stage was presented which has a pressure difference of 10 bar at 30 l/min at full deflection, as can be discerned from valves of nominal size 6. A positive overlap was initially provided for further investigation of the leakage behavior. The function of a 4/3-way valve known from piston spool valves can be realized with the shown geometry. During the design of the flow channels a linear behavior between sliding plate deflection and opening flow cross section was achieved. In addition to the metallic main stage, the detailed design of the valve and the actuators used to adjust the position of the main stage were also presented. The circuit diagram shown in Figure 15 allows the valve to be tested with values close to reality.

The valve is currently being tested at ifas. The volumetric measurement of the valve stage shows a good correlation with the CFD simulations presented in [6]. Also an almost linear flow behavior could be achieved. The testing of the pressure compensation will be published and carried out hereafter. After testing the metallic main stage, a second demonstrator will be set up in cooperation with the IWM, which will include a main stage made of ceramic plates. This demonstrator will be used to prove the function of the ceramic flat slide valve. In addition to the functional test of the flat slide valve, the general usability of ceramic materials in hydraulics will be tested with this test setup.

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NOMENCLATURE

A	Hydraulic working port A
B	Hydraulic working port B
P	Hydraulic pump port P
T	Hydraulic tank port T
h	Gap height
x	Deflection of slide plate
F_{actor}	Required actuator force
F_{fric}	Resulting friction force
$F_{mech,t}$	Mechanical force on top side of plate
$F_{mech,b}$	Mechanical force on bottom side of plate
Q_L	Leakage between ports
μ	Friction coefficient

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