DYNAMIC VALVE PLATE DESIGN FOR AN AXIAL PISTON PUMP (SERVO-LESS PUMP)

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ABSTRACT

In times with a need to reduce CO2 emissions we are focusing on reducing fuel with improving the power-losses of hydrostatic pumps and motors. Key areas of high losses in typical designs are the cross-port at the valve plate and leakages in the servo system and at control spools. The elimination of just the cross-port is discussed in [1]. The proposed concept is a new solution using an active special valve plate porting to reduce the cross-port losses, which also controls the displacement of hydrostatic unit. The active porting strategy has in fact direct influence on the servo moments of the hydrostatic unit. With special control software, which controls the porting at the valve plate, it is possible to increase the efficiency, influence the noise and control the displacement, respectively.

Keywords: Valve plate, Efficiency, Optimized noise, Servo-less axial hydrostatic unit, Digital control, Multimode control

1. STATE OF THE ART

Today's valve plate porting design (Figure 1) uses cross-port technology to make longer time for the pressure change compared to no cross-port. With this the noise is improved while the efficiency is degraded. Typical cross-port values are between 10° to 25°. The cross-porting areas/profiles are controlling the pressure change. [2]

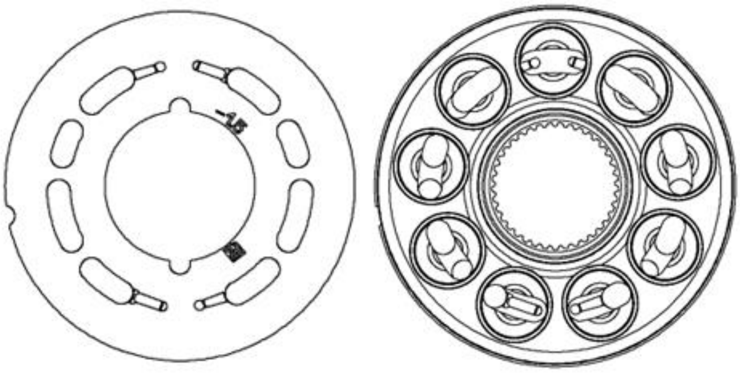

Figure 1, valve plate and cylinder block

The swash plate angle and shaft speed drive the pump flow. There are two designs of the swash plate and servo system. The servo system moves the swash plate into max stroke against the neutral return mechanism (Figure 2) or the servo system moves the swash plate from the max stroke against the maximum stroking feature (Figure 3), [6].

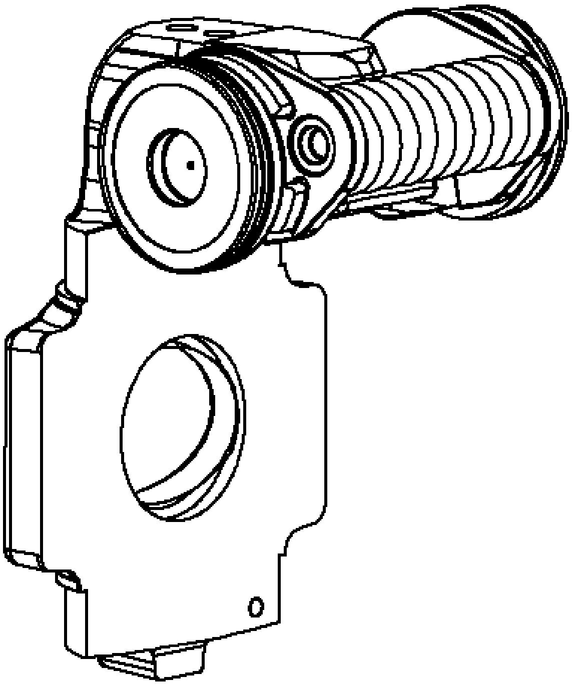

Figure 2, Neutral return mechanism

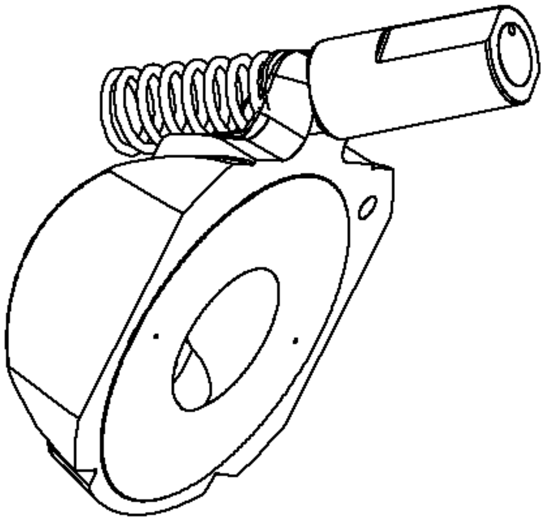

Figure 3, Max stroke feature

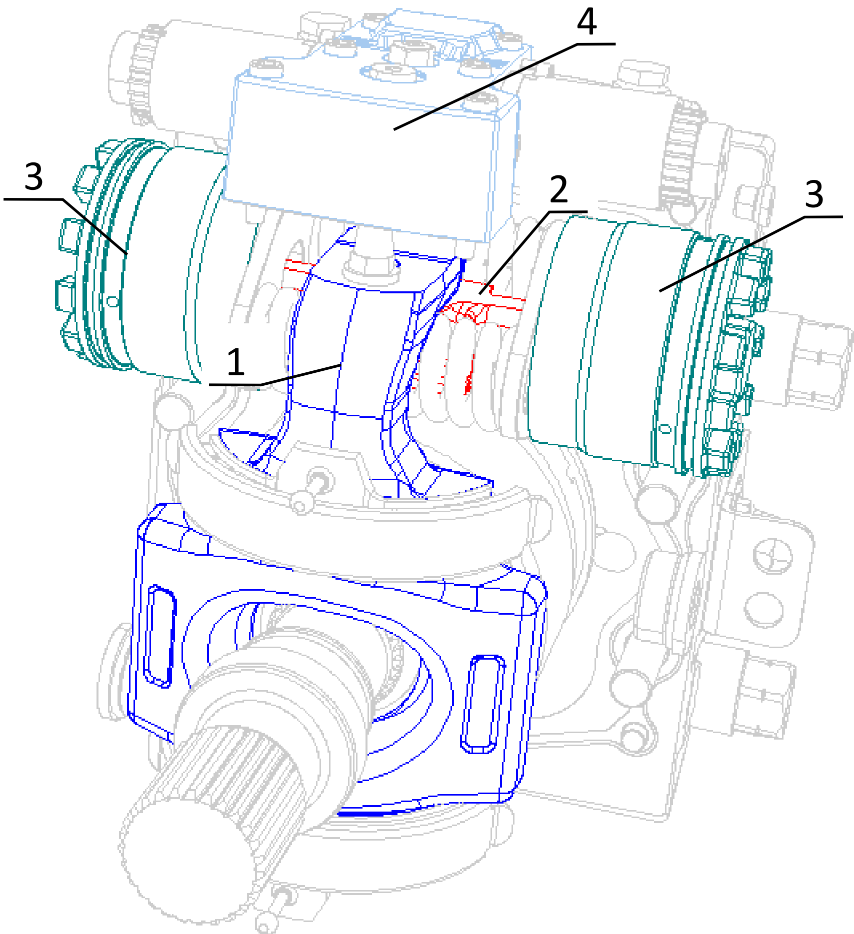

Figure 4, Close circuit servo pump

In typical closed circuit designs, the input, electric current of electronic displacement control (4), H1P service guide [5], is transferred into spool position including the mechanical feedback system. The control flow goes in and out servo cans (3). Servo piston (2) holds the swash at commanded position using servo arm (1).

2. DYNAMIC VALVE PLATE DESIGN

2.1. Concept

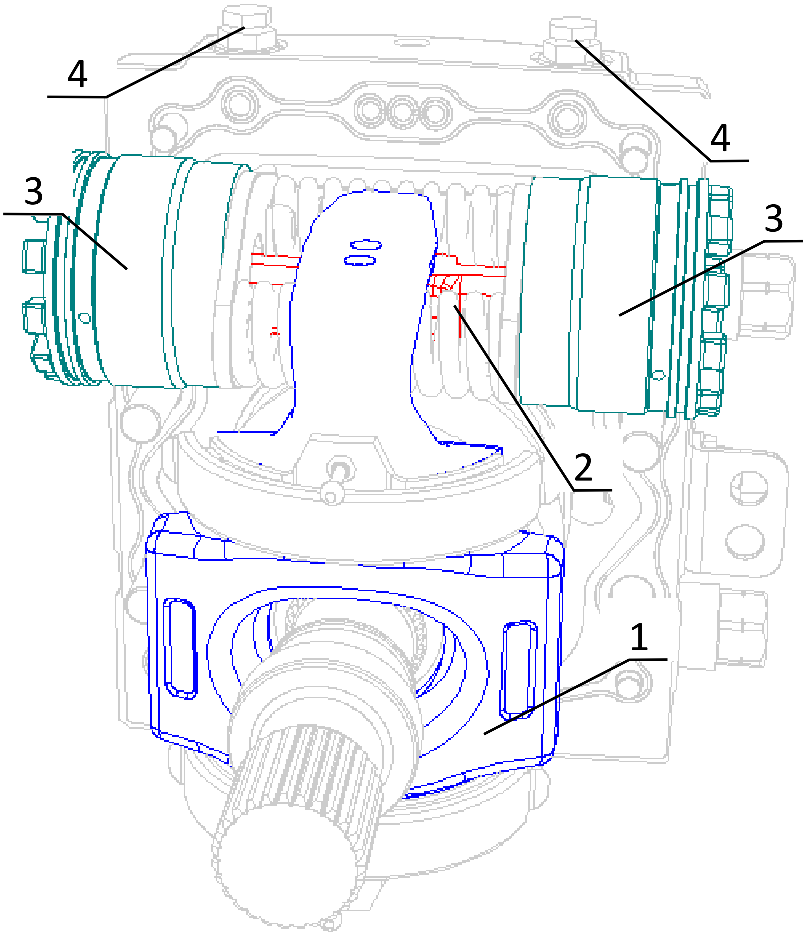

Figure 5, Dynamic (servo-less) valve plate pump

A standard close circuit pump is modified to verify the concept of the dynamic valve plate design. The control is removed. Servo cans (3) are drained to a housing. The servo piston assembly (2) with the springs has the function of the neutral return mechanism. Two rotary valves (4) are added into the end cap.

The rotary valves have a function of the variable orifices controlling the cross-porting flow, which has impact on the kit moments. The kit moments are capable to hold the required swash plate position at any operating conditions. More details and description in the chapter 6.

3. EFFICIENCY, NOISE AND KIT MOMENTS

The focus here is the axial hydrostatic pump efficiency. There are two group of losses: the kit losses and the control losses. The expectation is to make a significant change of the Kit losses and a step change of the control losses. The hydrostatic unit efficiency is closely connected to the noise creation, kit moments and cavitation in the rotating group.

It means that the goal of the design is to create a solution, which is the best point for all these four phenomena. [2]

3.1. Adjustable-adaptive porting design

Current designs are using a valve plate and a cylinder block kidney design, which is optimized for a specific operating conditions, such as high pressure, high rpm and max. displacement (all together). Not every unit operates in those high conditions and on vehicle base, we see high amount of time of middle to low conditions. Here the porting then is not at optimum, which means, that efficiency could be improved, and noise could be reduced.

The specific valve plate operated at max speed and mid pressure can make unit efficient and quiet, but the same valve plate operated at the low speed and high pressure is not capable to be efficient due to cross-porting leakages. Our intent is to design a valve plate, which is capable to adapt or to adjust to any operating conditions to keep the high efficiency in the whole range of the operating conditions.

3.2. Valve plate transient areas

The valve plate has two valve areas. One valve area controls the transition from low pressure to high pressure and the second valve area controls the transition from high pressure to low pressure. The traditional valve plate has a rigid timing between these two areas. The adjustable-adaptive valve plate can control independently each of those valve areas. From the flow point of view these two valve areas are separated and independent, but from the swash plate vibration and noise point of view they are coupled. The independent controllability enables the optimization of the noise of the unit.

3.3. Servo-less unit

A conventional pump with servo system needs the energy to overcome the kit moments. In case of the servo-less unit this energy burnt in the control and servo system is not needed. At conditions when the servo unit is operated at the hard stop with no servo pressure there is no space for improvement but in the case of the partial stroke or fully active control and max servo pressure the step efficiency improvement is possible.

4. PORTING DESIGN AND KIT MOMENTS

The porting design is connected to the pump performance and is impacting the design of all parts involved in the pump flow control.

The fluid dynamics of the transitions impact the cavitation and generates fluid born noise. It also defines the swash plate moment and excites the swash plate vibration. The servo system needs to overcome the swash plate moments. It specifies the needs for the servo system sizing and charge pressure value. Swash plate vibration is causing the servo piston and the servo cans vibration. This vibration generates the mechanical born noise. The servo sizing specifies the control flow needs.

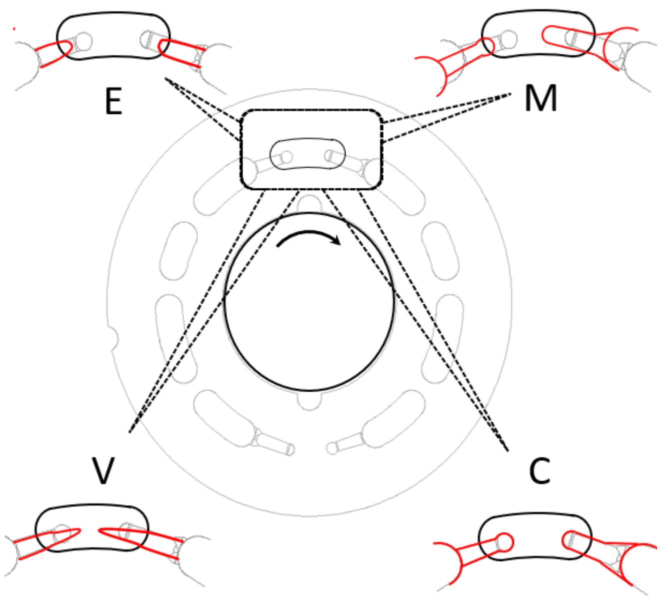

Figure 6, impact of porting design

The porting design is compromising four different areas: efficiency, noise and stability, servo sizing with charge pressure and cavitation (figure 6). In general, it is known how to make the porting design:

- (E) efficiency optimized
- (V) vibration and noise optimized
- (M) higher de-stroking (red) or lower de-stroking (black) moments
- (C) cavitation optimized

An adjustable-adaptive porting design allows to remove the servo system and at the same time enables to operate the pump at the mode optimized for the efficiency or for the noise and stability.

4.1. Kit moments – general description and terms

Kit and swash plate are shown in Figure 7. In case of the swash plate (2) design of an axial piston pump the rotating kit boundaries are the swash plate running surface (3), the valve plate running surface (4) and the cylinder block hub (6). The cylinder block hub is heavily loaded by torque – moment around the shaft axis. To meet a cylinder block (1) life expectation; any moment perpendicular to the shaft axis and transferred by the cylinder block hub (6) must be close to zero. It is achieved by having sweet point (13) aligned with the swash plate rotational axis. It means that the kit moments are balanced just by valve plate running surface (4) and swash plate running surface (3). The kit moment is the moment (7) applied on the swash plate (2) and it is equal to the moment (8) applied on the valve plate (5). Assuming there is a neutral return mechanism de-stroking swash plate (2) to the zero position by the moment (9). If the moments (9) and (7) are balanced, the swash plate is staying in the given angle and the pump provides the flow given by the kit geometrical volume and shaft speed. The moment of the neutral return mechanism (9) is balanced by the valve plate, so the final valve plate moment is the summation of the moments (8) and (10).

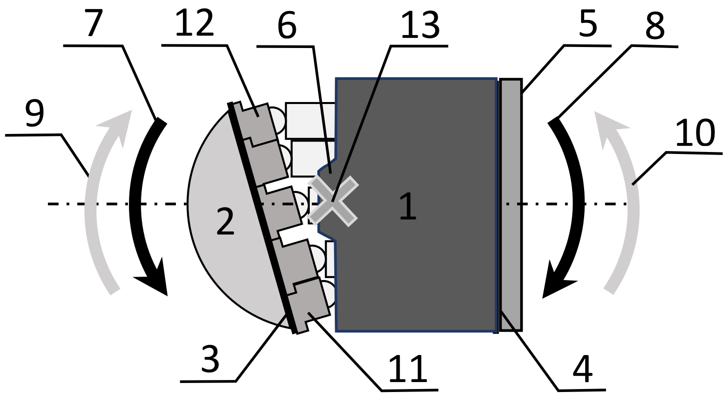

Figure 7, Kit moments

4.2. Valve plate indexing and cross-porting

There are inlet or low pressure kidneys and system or high pressure kidneys. So, there are two transient areas. In case of pumping mode, when piston is in the most inserted dead centre position IDC (11), it is transferring from the system/high pressure to the inlet/low pressure and when piston is in the most outer dead centre position ODC (12) it is transferring from the inlet/low pressure to the system/high pressure.

The indexing and cross-porting of the valve plate are two basic parameters influencing the kit moments. The figure 8 represents indexing of the valve plate. The figure 9 represents cross porting of the valve plate. The graphs are simplified to show the fundamental pressure behaviour. The overshoots and the undershoots are not shown.

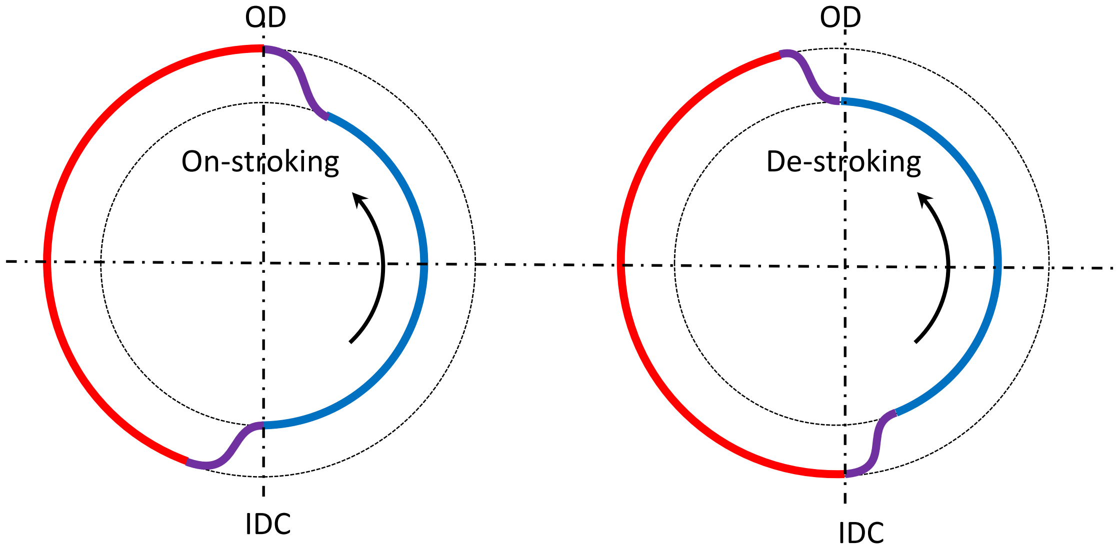

Figure 8, Indexing

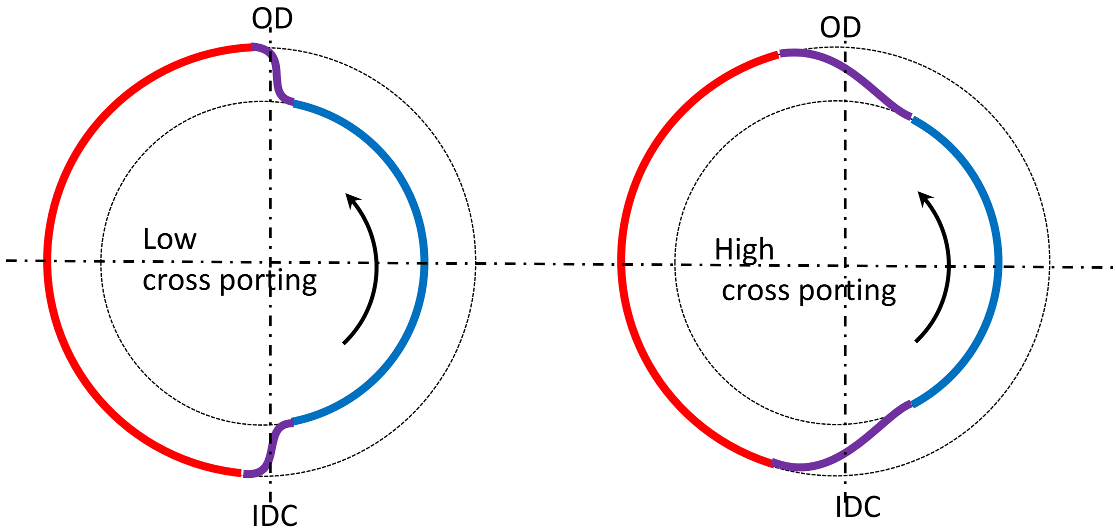

Figure 9, Cross porting

Indexing and cross porting is a result of the flow from the piston bore close to the dead centre to the coming kidney. These flows at the dead centres drive the pressure profile of each piston bore, where summation of all piston/slipper forces determines the moment applied on the swash plate.

The moments driven by pressure profile can be named the **valve plate moments**. The moment applied on the swash plate is the summation of the valve plate moments and moments due to inertia forces and piston bore frictions.

4.3. Default swash plate position

There are two options of the pump default position, the zero stroke (using the neutral return mechanism) and the full stroke (using the maximum stroke feature). Let's focus on the pump with the zero-stroke default position.

The sweet point, figure 7 (13) is well aligned with the swash plate axis. To have zero stroke as default position there is a neutral return mechanism, figure 2, which is pushing the swash plate to the zero position plus there is a threshold moment, which needs to be overcome to push the swash plate from the zero position. The neutral return mechanism is providing default de-stroking moments. This moment can be named the **default kit moment**. It means there are in general two options of the default moment: on-stroking or de-stroking.

5. VALVE PLATE FUNCTION

A valve plate has multiple functions. From the efficiency point of view the thrust bearing function has impact on the mechanical efficiency, the seal function has impact on the volumetric efficiency. The pressure profile control function has impact on both efficiencies, the mechanical and the volumetric efficiency.

5.1. Thrust bearing and seal land

The valve plate is the thrust bearing carrying the kit axial force. The cylinder block is the rotating part, and the valve plate is a non-moving part. Each piston bore must be sealed. The size, the shape and the tribology of the seal land is designed to generate an oil film capable to carry the axial kit force and to minimize the leakages.

5.2. Pressure profile control

The position of the valve plate kidneys has the function of timing. Timing means that the cylinder block kidney is connected to the high- or low-pressure port. In addition, in the traditional valve plate, there are control grooves and or porting holes.

Usually there are two valve plate parameters, the indexing and the cross-porting. Indexing is the timing of the ODC transition from the low pressure to high pressure and of the IDC transition from the high pressure to low pressure. The valve plate is typically indexed (figure 8) in the rotation direction, which is causing bigger de-stroking kit moments, leading to a larger servo system and a safe stroke to neutral. This is a very simplified statement. In the details it is more complex. The kit moments are functions of the five independent operating variables (5D operating space) like shaft speed, inlet - and outlet- pressure, swash plate stroke and oil viscosity.

Cross-porting (figure 9) is a short cut connection between both pressures at IDC and ODC. In general, the bigger cross-porting is smoothening the pressure transition, which is reducing pressure oscillations, noise and increasing the life of the unit. The downside of bigger cross-port is increased internal leakage and lower volumetric efficiency. So, from the efficiency point of view, a smaller cross-port is better.

The complexity is, that the valve plate including control grooves is optimized at 5D operating space.

6. DYNAMIC VALVE PLATE COMPONENTS

The new valve plate porting design has the capability to modify the indexing and cross-porting according to the operating conditions to optimize the noise and the efficiency. It contains two parts: static and active.

6.1. Valve plate static parts

The static part has all functions, like a traditional valve plate but the pressure profile control is modified by added control ports (at ODC and IDC, figure 10).

- The transition part of the pressure profile is bounded by four edges.
- The ODC transient area is starting when the cylinder block piston bore kidney leaves LP ODC Edge
- The ODC transient area is finishing when cylinder block piston bore kidney hits HP ODC Edge
- The IDC transient area is starting when cylinder block piston bore kidney leaves HP IDC Edge
- The IDC transient area is finishing when cylinder block piston bore kidney hits LP IDC Edge

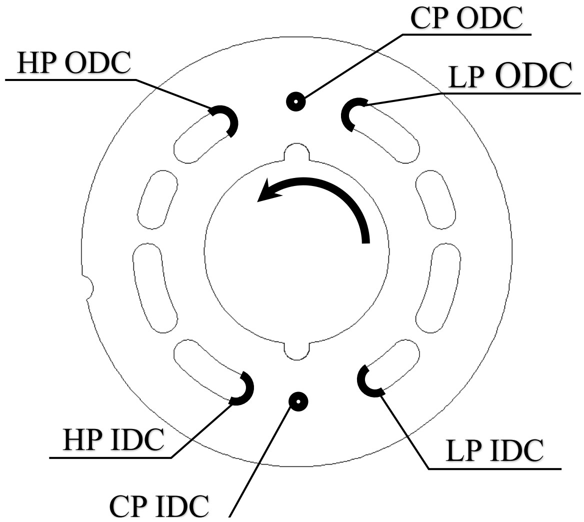

Figure 10,
Passive part of the dynamic valve plate

6.2. Valve plate active part

The active part has two control valves, which are controlling indexing and cross-porting. (figure 11)

- Control port CP ODC is connected to the high-pressure port via the flow valve CV ODC.
- Control port CP IDC is connected to the low-pressure port via the flow valve CV IDC.

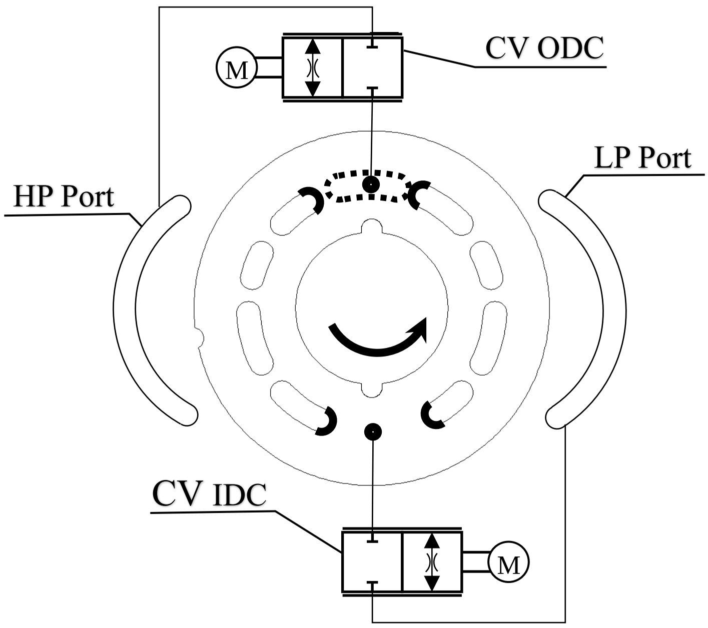

Figure 11, Active parts of the valve plate

7. THREE TRANSITIONING PHASES

At both dead centres there are three transitioning phases.

7.1. Phase A

The cylinder block kidney moves from low pressure and then connects to the CP ODC (figure 12). The piston is close to its dead centre and makes only very little axial movement / stroke.

When it comes to control port CP ODC the oil flows in the bore from the HP port through flow valve CV ODC (figure 12). The cylinder block kidney can be connected to the low-pressure kidney. In that case there is a cross-porting between the low pressure and high pressure controlled by the CV ODC valve. The second option is that the space between the control port CP ODC and low-pressure kidney is bigger than the size of the cylinder block kidney. In that case there is no cross-porting, and the oil is trapped in the cylinder block bore.

Phase A, cylinder block kidney is coming over the control port CP ODC

The angular space between Low Pressure Edge and control port is:

- bigger than cylinder block kidney, then oil is trapped in the bore for a short moment.
- smaller than cylinder block kidney, (figure 12), then there is a cross-porting controlled by control valve CV ODC.

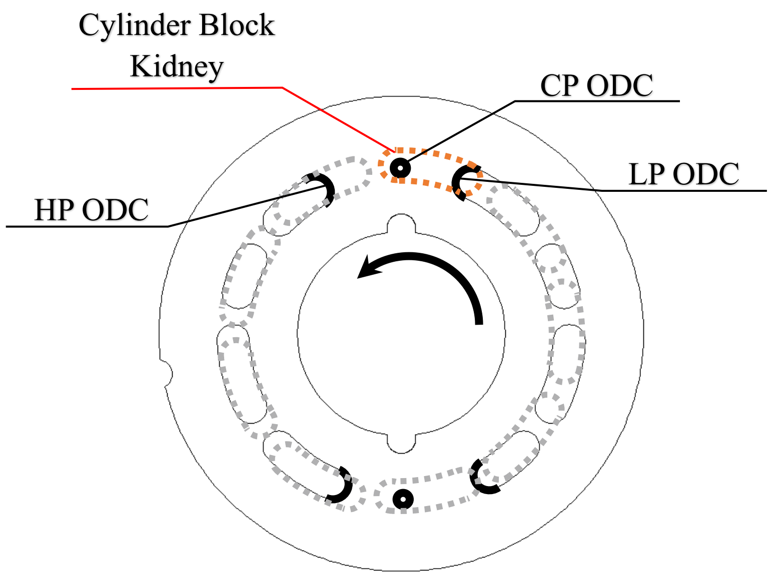

Figure 12, Phase A

7.2. Phase B

After leaving the LP ODC edge and hitting the control port CP ODC the flow in and out of the cylinder block bore is fully controlled by the CV ODC valve (figure 13).

Phase B, cylinder block kidney is going just over the control port CP ODC

The bore pressure **increase** is fully controlled by the Control valve CV ODC; there is a flow from the high-pressure port through the valve to the control port CP ODC to the piston bore.

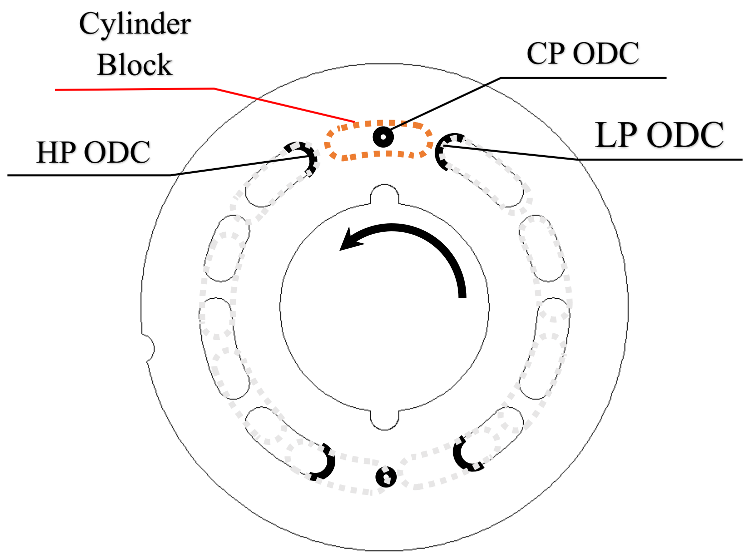

Figure 13, Phase B

7.3. Phase C

The last phase starts by hitting of the HP ODC edge. If the piston bore pressure is still lower than the system pressure, it is quicky balanced by the direct overlap with high pressure kidney.

Phase C, cylinder block kidney is coming over the edge HP ODC

The angular space between Low Pressure Edge and control port is:

- bigger than cylinder block kidney, then oil is trapped in the bore for a short moment.
- smaller than cylinder block kidney (figure 14), then there is an accelerated pressure balance if not already equal to the high pressure.

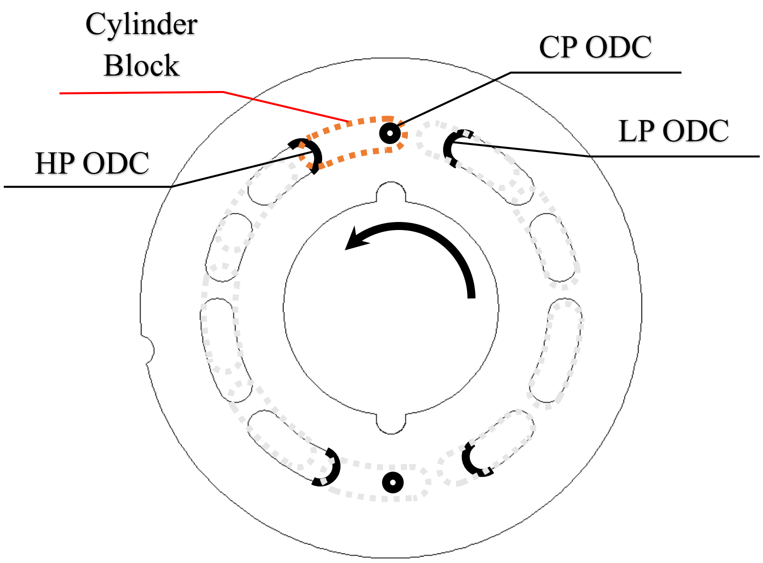

Figure 14, Phase C

At the IDC transition area there are the similar A, B and C phases like in ODC.

7.4. Relevance of the phase A, B and C

The capability to simulate and to understand the flow and pressure changes in the bore located at the dead centre are critical for the dynamic valve plate concept. There are a few milliseconds available to control the pressure profile during these three phases. Is it possible? At first this theory was tested using the digital twin of a 130cc axial piston servo pump.

The simulations were leading to the following conclusions:

- The variable orifice is capable to control the pressure profile to achieve the balance of the Kit moments and default kit moments, so to control the displacement of the pump. This means that the servo-less pump can be developed.
- The removing of the servo system leads to the unit efficiency improvement.
- The cross-porting can be optimized for all operating conditions including the variable pump displacement to optimize the efficiency.
- The non-synchronous/individual IDC and ODC valve opening is influencing the dynamics of the kit moments, which has impact on the pressure oscillations and noise.

8. DYNAMIC VALVE PLATE TESTING

The first feasibility study was done by a modified serial production closed circuit 130 cc pump.

8.1. Breadboard unit

Modified pump:

- Close circuit pump (1) with modifications described at chapter 2.1 and shown on fig 5.
- Two valves (CV IDC and CV ODC) are operated using 4 bar mechanism (2).
- The couple of 4 bar mechanisms is operated by Lego servo motors (3).
- The Lego micro-controller (4) is controlled by code created in the Lego application in IOS.
- 3D printed 4 bar mechanism is used to achieve an acceptable precision of valve position and to overcome the flow force by low torque Lego servo motors.

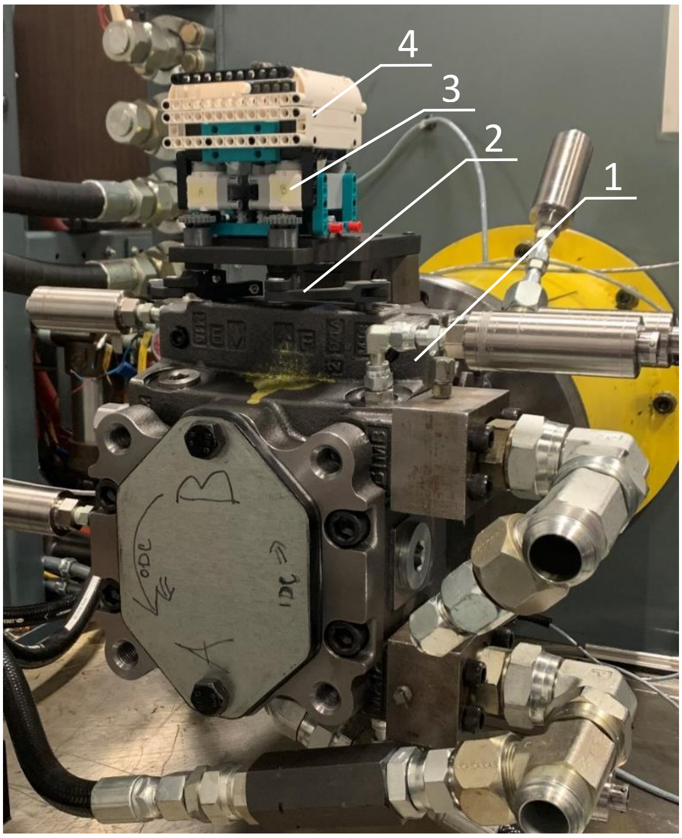

Figure 15, Modified pump

8.2. The LEGO benefit - repeatability

The active part of the dynamic valve plate consists of the two simple rotary valves and the servo motors with 4 bar linkage mechanism (figure 16). Gear (2a) is bounded with bar (2b). The rotary valve (6) angle is driven by the rotation of the gear (5). Each valve has its own 4 bar linkage mechanism and servo motor.

Using the LEGO battery and servo motors show the new concept capability to replace the servo system powered by a 26cc charge pump.

Using of LEGO app GUI allowed us to run multiple tests with high repeatability of the commands. It was fast, easy, and straight forward.

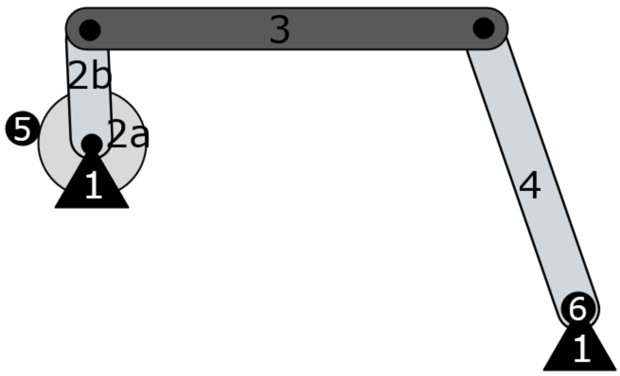

Figure 16, 4 bar mechanism

8.3. Example of the test results

There were done multiple types of the tests to study the controllability of the pump.

For example, the Lego servo motors were commanded to make six steps to close the rotary valves and six steps to open them to the original position.

The LEGO application set on the iPad was simple.

The servo motors are linear, but the 3D printed 4 bar mechanism is not.

Figure 17 shows the table of the commanded steps. Each step the servo motors turned 50 degrees. The last row shows the calculated orifice diameter corresponding to the ODC and IDC valve opening at each step. At the shaft speed 2000 rpm and delta pressure 100 bar, the swash plate starts to de-stroke at about 2.37mm orifice size. At 20% displacement the corresponding orifice size is only 1.06mm. For the delta pressure 200 bar the swash plate starts to de-stroke at about 1.84mm. The standard valve plate of this pump has over 3mm fixed corresponding orifice size. The result of the smaller cross-porting is volumetric efficiency improvement.

	step 1	step 2	step 3	step 4	step 5	step 6	step 7	step 8	step 9	step 10	step 11	step 12	step 13
position [degrees]	0	50	100	150	200	250	300	250	200	150	100	50	0
Orifice diameter [mm]	2.6	2.37	2.12	1.84	1.5	1.06	0	1.06	1.5	1.84	2.12	2.37	2.6

Figure 17, commanded steps

Figure 19 shows the flow of the pump. There are shown three load pressure setting (figure 18).

Figure 18, pressure levels

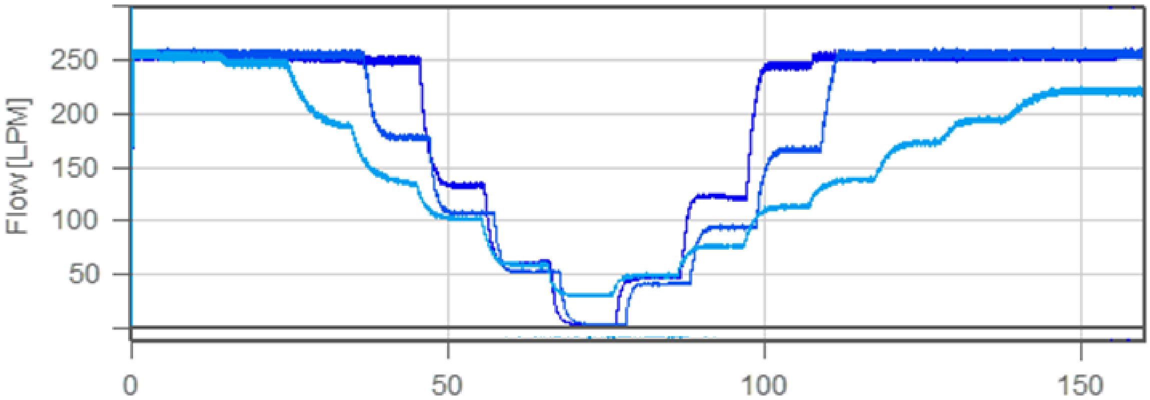

Figure 19, Pump flow at 2000 rpm

To present the smooth behavior of the pump, the low-pressure and the high-pressure in time domain is shown with the 5 kHz sampling frequency and not filtered (figure 20). The low system pressure oscillation is good indicator of the low swash plate vibration. With these results the controllability of the servo-less pump is basically proven.

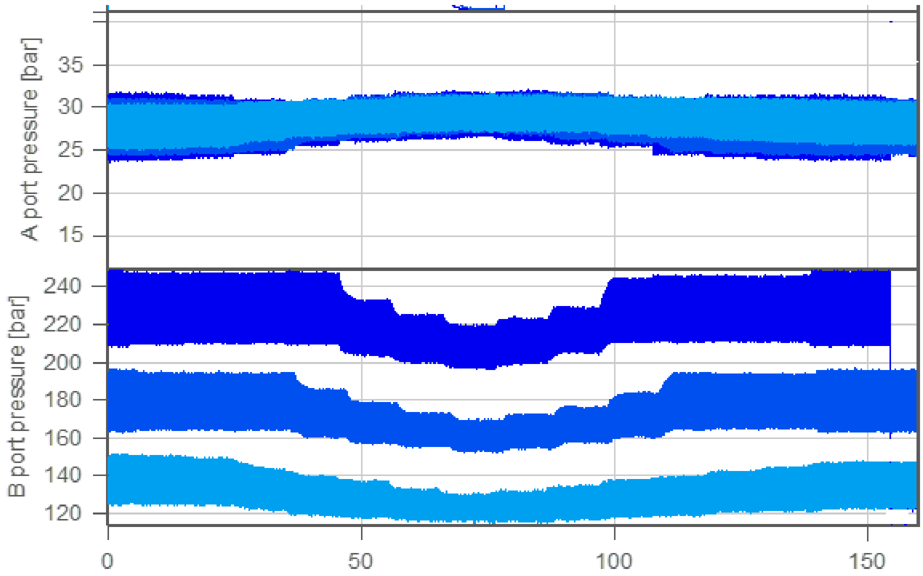

Figure 20, System pressure

9. SUMMARY AND CONCLUSION

- There is high potential and customer value propositions for developing of servo-less pumps.
  - Faster flow requirements response.
  - More compact unit, less components, lower weight.
- There is a good potential to reduce the cross-port losses of today's pumps especially at partial strokes and at higher pressures.
  - At lower stroke the ODC and IDC smaller orifice is reducing cross-porting losses.
  - At higher pressure and lower speed, the CV ODC and the CV IDC smaller orifice is needed, higher efficiency.
- The individual control of the valves has a significant impact on the system pressure oscillations, and it can be used to optimize the noise.
  - By holding of the CV IDC (or CV ODC) and varying the CV ODC (or CV IDC) have significant impact on the noise and sound quality.
- The results of the testing are especially convincing to use the dynamic valve plate concept by applying PLUS+1® software.
  - The vision is to use inputs from multiple sensors. The code will process inputs from sensors and command from the machine operator to run the CV IDC and CV ODC. The dynamic valve plate enables the pump to operate at optimized noise, efficiency and stability conditions.
  - Using of the pressure and the swash plate angle sensor allows to run the pump at the displacement or pressure or power control mode based on the needs of the machine.
- It is already a significant innovative result that it was possible to replace the servo system powered by charge pressure and flow at about 2-4 kW just by a LEGO battery. This concept enables the advantage of the reduced cross-porting flow at lower stroke, to have significant impact on the improved kit efficiency. In addition, together with the smart hydraulic system

utilizing multiple sensors it has in fact the potential to be a market game changer. The last but not least important point is that this technology is using existing series production pump hardware.

10. ABBREVIATIONS

- ODC – the kit piston position at the dead center with the biggest oil volume in the cylinder block bore
- IDC - the kit piston position at the dead center with the smallest oil volume in the cylinder block bore
- CP ODC – the control port near ODC position
- CP IDC - the control port near IDC position
- CV ODC – the control valve for the kit piston at ODC position
- CV IDC– the control valve for the kit piston at IDC position
- EDC – electronic displacement
- B_EDC – electronic displacement pump running with high pressure at B port
- IOS -apple operating system
- GUI – graphic user interface
- HP IDC – high pressure near the IDC position
- HP ODC – high pressure near the ODC position
- LP IDC – low pressure near the IDC position
- LP ODC – low pressure near the ODC position

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