# A hydraulic transformer with a swash block control around three axis of rotation

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## Abstract

A new design of a hydraulic transformer is presented. The design combines the floating cup principle and the three-port hydraulic transformer concept of Innas. The design resembles the design of the variable displacement, floating cup pump. An important difference is the bearing of the swash block. In the variable displacement pump, the swash block has a cylindrical bearing, and has only one degree of freedom. In the new transformer design, the swash block is supported by a spherical bearing, which results in three rotational degrees of freedom.

This paper describes the fundamental design principle of the new 'Oiler' transformer, its design constraints and the most important design solutions. The new design allows an unlimited control range of the hydraulic transformer, combined with large, unrestricted oil passages for all operating conditions.

KEYWORDS: hydraulic transformer, floating cup principle, oiler transformer, design

## 1. Introduction

In a recent study /1/ the fuel consumption of a large, 30 tonnes wheel loader was investigated. A state-of-the-art loader, with a mechanical drive train and load-sensing system for the implements, was compared to a loader with a new hydraulic system for both the wheel drive and the hydraulic cylinders. The new hydraulic system featured hydraulic transformers for power control and efficient floating cup pumps and motors. The transformers not only replaced the valve control of the main cylinders, but also the torque converter and the gearshift box of the wheel drive. The outcome of the study was a reduction of the fuel consumption by as much as 50%, without compromising the performance of the loader. The losses of controlling the hydraulic cylinders were reduced by almost 90%. Part of this reduction was due to energy recuperation, but most of the effect was simply due to the elimination of the valve control.

Hydraulic transformers are power control components, converting hydraulic power from a common pressure rail to a hydraulic cylinder or motor and vice versa. Transformers can also amplify pressures, supplying high pressures to the load if needed, even when the accumulators are not fully charged and the pressure level in the common pressure rail is not at a maximum. Transformers can also work in four quadrants, thereby offering a large range of operating conditions, including energy recuperation.

However, the large operating range can only be realised if the construction of the hydraulic transformer allows this. Furthermore, it is required that the energy losses of the transformer are reduced to a minimum, especially at ‘average’ operating conditions. To fulfil these demands, the design of the Innas Hydraulic Transformer (IHT) /2, 3/ and the floating cup principle have been combined. The principle of the IHT is based on a constant displacement machine. The transformer output is controlled by means of changing the angular position of the port plate, relative to sinusoidal movement of the pistons. The floating cup principle is a relatively new axial piston design for pumps, motors and hydraulic transformers. The principle is characterised by extremely low friction and leakage losses. Total efficiencies of 97% and higher have been measured /5/.

This paper describes the next generation of the hydraulic transformer. The new transformer has swash blocks, which are supported by a spherical bearing. As a result the swash block can be rotated around three axes. These degrees of freedom are used to enable a large operating range of the transformer. Furthermore, the efficiency is expected to be higher than of previous designs, especially at high operating speeds. This allows an increase of the maximum operating speed, which reduces the size of the transformer while maintaining the output power of the transformer.

## 2. Principle design choices

Unlike pumps and motors, the Innas Hydraulic Transformer (IHT) does not have two but three ports in the valve plate. Also different from pumps and motors, the commutation does not always occur in the top dead centre (TDC) and bottom dead centre (BDC) of the piston movement. Instead, the relationship between commutation and piston movement has been made variable by means of rotating the port plate, or, alternatively rotating the mechanism that determines the TDC-BDC-axis (see Figure 1).

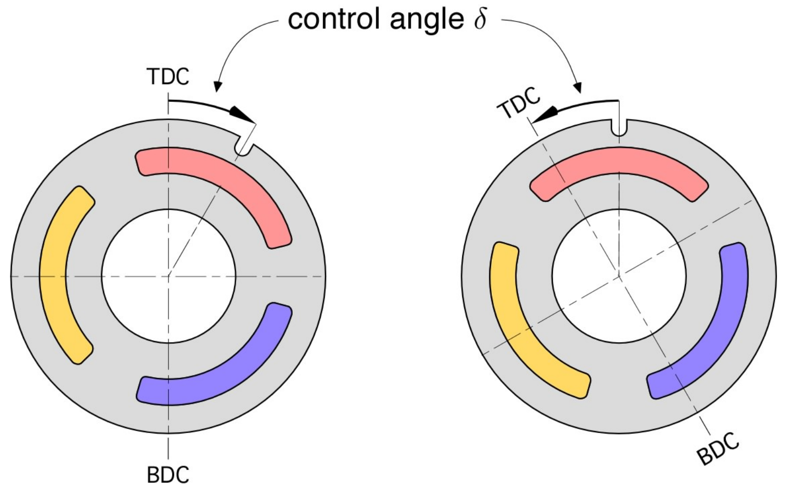



**Figure 1:** Control of the Innas Hydraulic Transformer by means of rotating the port plate (left) or rotating the TDC-BDC-axis (right)

The first designs of the hydraulic transformer were based on a rotation of the port plate /2/. This was an obvious choice since these first prototypes were adaptations of existing, constant displacement, bent axis motors. However, the friction and tribology aspects of the rotating port plate are extremely difficult to solve. Also, the rotation of the port plate results in a strong limitation of the operating and control range of the transformer. In the example shown in Figure 2, the port plate can only be rotated in a range between 0° and 60°. Beyond this range, the valve lands of the port plate would move on top of the stationary ports. This would result in high flow losses. Furthermore the hydrostatic force balance would be disturbed if the valve lands of port plate would cover the stationary ports. Finally, if the port plate would be rotated much further, a short circuit would be established from one port to the other.

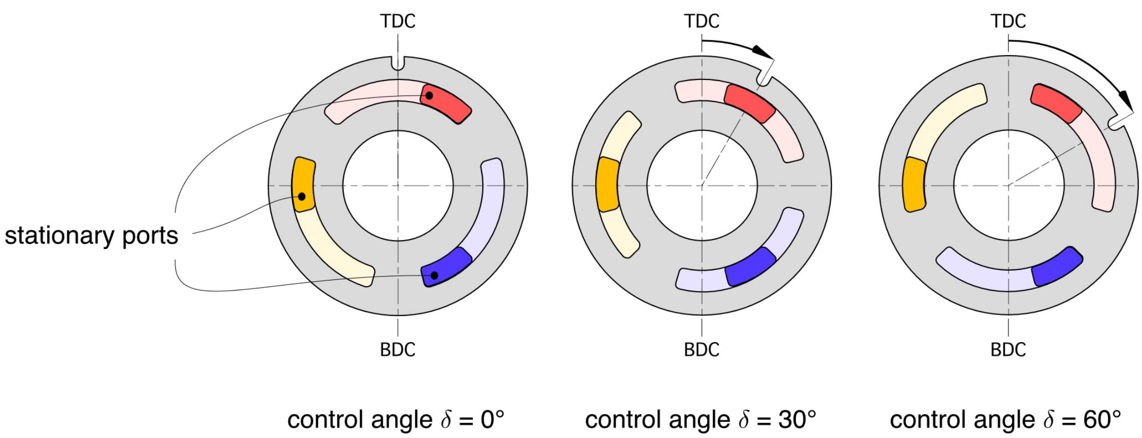



**Figure 2:** Size of the stationary ports of the housing in case of a rotating port plate.

To overcome these disadvantages, a design was made in which the transformer was controlled by means of rotating the TDC-BDC-axis /3/. Figure 3 shows an exploded view of this transformer. The commutation is realised at the left and right side of the transformer. In this design, the valve plates don't rotate but are kept at a fixed position. Because of this, the connection between the ports of the valve plate and the housing can be large and unrestricted. The control angle of the transformer is varied by means of the swash block in the middle of the transformer. A rotation of this tapered swash block results in a rotation of the TDC-BDC-axis relative to the rotational position of the valve plate. In theory, this allows a variation of the control angle between -180° and +180°. For most applications a variation between -110° and +110° is sufficient.

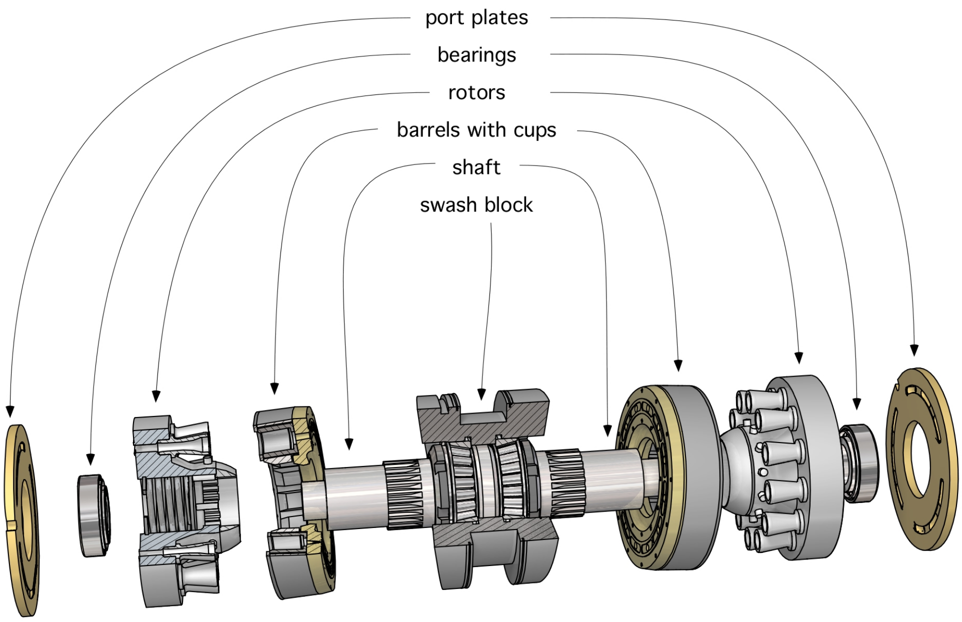



**Figure 3:** Exploded view of the main parts of the transformer, excluding the housing

However, also this design has a number of disadvantages:

- The oil flow has to go through the pistons, which increases the flow losses.
- The hollow pistons limit the swash angle of the barrels. This increases the size of the transformer. Also the pitch circle of the rotors and the barrels is enlarged, which increases the friction and leakage losses of the machine.
- The design has four rotating, hydrostatic thrust bearings annex face seals: two between the rotors and the valve plates, and two between the barrels and the swash block. The high number of these interfaces increases both leakage and friction losses.

The floating cup principle can be extremely efficient. In pumps and motors, total efficiencies of more than 97% have been measured /5/. Most losses are caused by the rotating hydrostatic thrust bearings. In floating cup pumps and motors there are two of these interfaces: the gaps between the rotating barrels and the stationary port plates.

The design of the transformer, with the rotating swash block in the middle, doubles these critical interfaces and the losses associated with these interfaces. In theory, these losses are only a few percent in the best point. But the transformer is often used in operating points far away of this best point, and the extra two rotating interfaces can have a substantial detrimental effect on the average efficiency of the transformer.

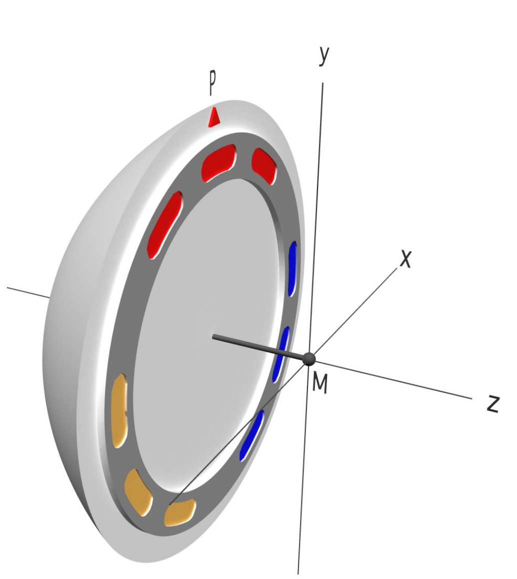
In order to avoid these losses, a new design of the Innas Hydraulic Transformer has been made. The design is much like the design of the variable displacement pump /4/. An important difference however is the bearing of the swash block. In the variable displacement pump, the swash block bearing is cylindrical, leaving only one rotational degree of freedom. In the new hydraulic transformer the swash block bearing is ball shaped, which results in three rotational degrees of freedom. The movement of the swash block can be described by means of Euler angles. This has led to the working title of the new hydraulic transformer: the 'Oiler transformer'.

## 3. The Oiler Transformer

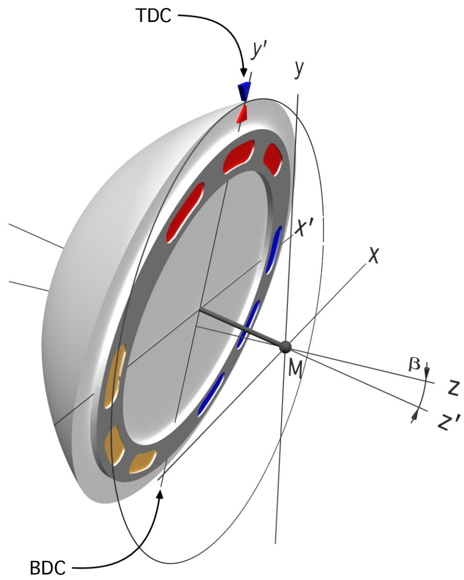
The starting point of the Oiler transformer is a segment of a ball with point *M* as the centre point (see figure 4). On top of the flat surface of the ball segment is a port plate with three ports: one port connected to the high-pressure rail, one to the low-pressure rail and the third port to the load. The middle of the high-pressure port is marked with the arrow at point *P*. The triangle pointing to *P* is a reference point, which is needed for the explanation further on.

The ball segment can only rotate; there are no translational degrees of freedom. This can be achieved by having the ball segment supported by and pushed into a spherical, bowl shaped bearing surface. The ball segment can rotate around axis *x*, *y* and *z*, having point *M* as the pivoting point.

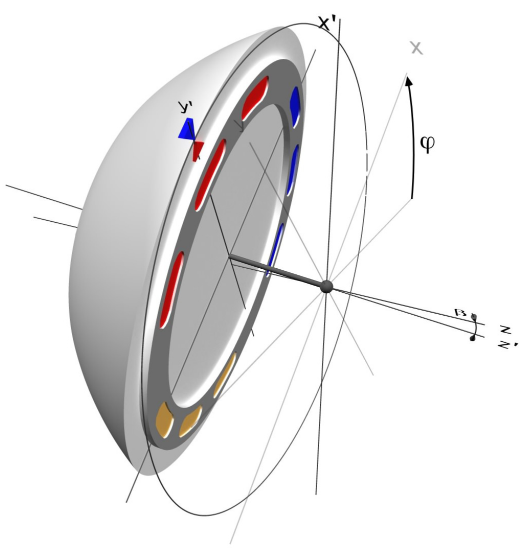
A rotation around the *x*-axis (figure 4b) creates a displacement of the barrel-pistons-cups-assembly, which is running on top of the port plate. This rotation is necessary since the hydraulic transformer can only transform hydraulic power if there is a positive displacement. The top dead centre (TDC, marked with a blue triangle) and bottom dead centre (BDC) are located on the *y'*-axis, which is moving with the ball segment, together with the other two axis *x'* and *z'* of the ball segment.



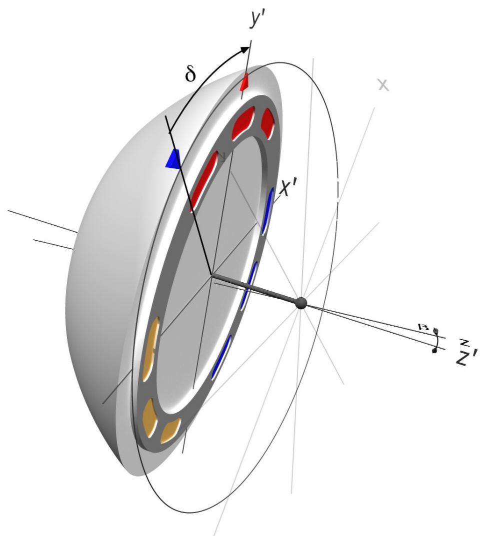

a. Initial position of the swash block




b. Rotation *β* around the *x*-axis




c. Rotation *φ* around the *z*-axis



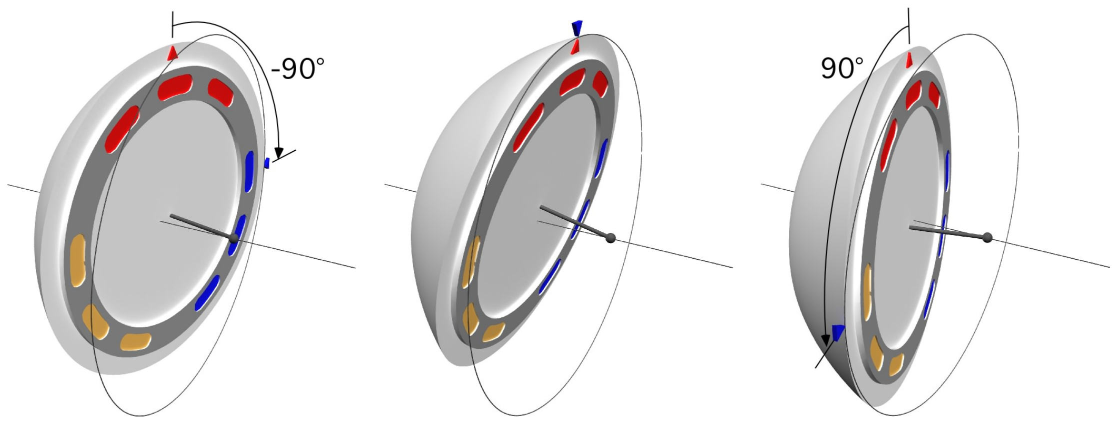

d. Rotation *δ* around the *z'*-axis

**Figure 4:** Rotation of the swash block around three axes

Combined with the first rotation around the *x*-axis, the tilted swash block is furthermore rotated over an angle *φ* around the z-axis of the machine (figure 4c). The *z*-axis is the main axis of the transformer, being the axis of the shaft and the rotor of the transformer. As a result of this rotation, the TDC-BDC-line will rotate as well.

The third rotation *δ* is around the *z'*-axis (figure 4d). The *z'*-axis is standing perpendicular at the port plate surface. The angle between the *z'*-axis and the *z*-axis equals the displacement angle *β*. The rotation *δ* around the *z*-axis will rotate the ports of the port plate almost back to the original position shown in figure 4a. But the *δ*-rotation will have no effect on the position of the TDC-BDC-axis (see the blue arrow in figures 4c and 4d). The *δ*-angle is the control angle of the transformer, offsetting the ports of the valve plate to the TDC-BDC-axis as was illustrated in figure 1.

The combined rotation around the *z*-axis ($\varphi$) and the *z'*-axis ($\delta$) allows a large operating and control range of the transformer while minimising the movement of the swash block. Figure 5 shows three positions for control angles of -90°, 0° and 90°. The spherical swash block bearing also allows a variation of the displacement angle $\beta$. A reduction of $\beta$ can reduce the torque variation of the transformer axis, thus improving the controllability of the transformer at low operating speeds. In this paper, however, $\beta$ is considered to be constant.




$\delta$ = -90°; $\varphi$ = 90° $\delta$ = 0°; $\varphi$ = 0° $\delta$ = 90°; $\varphi$ = -90°

**Figure 5:** Position of the swash block for three control angles

**4. Movement of the back ports**

In order to allow oil transport to and from the rotating group, ports are needed at the spherical back side of the swash block. These ports are connected to the ports at the front side of the swash block. But the back ports also require a connection to the stationary ports of the housing. The combination of the rotation $\varphi$ around the *z*-axis and the rotation $\delta$ around the *z'*-axis can be chosen as such that the movement of the back ports is kept as small as possible. The rotation $\varphi$ more or less compensates the movement of the swash block caused by the setting of the control angle $\delta$.

There are several mechanical solutions to define the relationship between $\delta$ and $\varphi$. One solution is illustrated in figure 6. The swash block has a semi-circular crown gear (the light grey gear ring), which is running on a stationary counterpart (the dark grey gear ring).

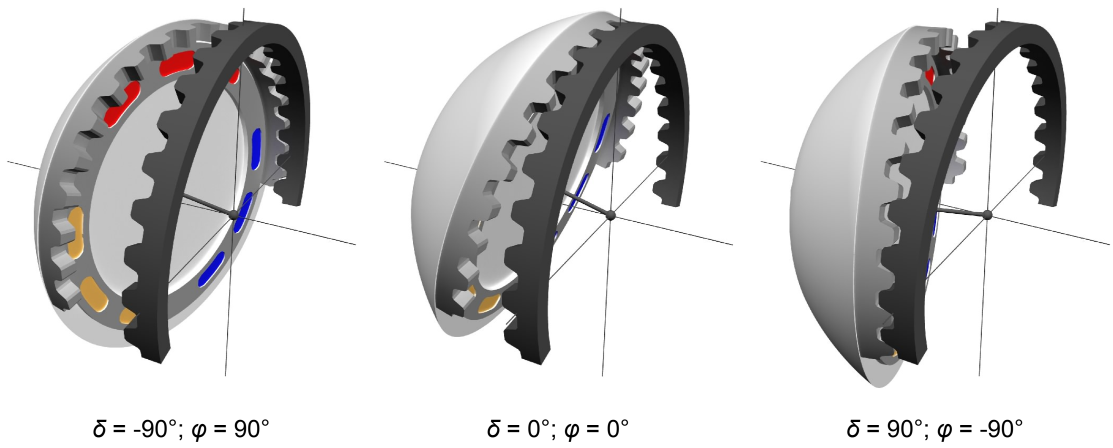



**Figure 6:** Defining the relationship between $\delta$ and $\varphi$ by means of a gear transmission

The ratio between $\delta$ and $\varphi$ defines the movement of the swash block and therefore also the movement of the back ports relative to the stationary ports of the housing. Figure 7 shows the position of the swash block and its back ports assuming that $\varphi = -0{,}92 \cdot \delta$. The green circles indicate the position of the stationary ports. While moving between $\delta$ = -90° and $\delta$ = 90°, the back ports will move on the bearing surface of the housing. These swept areas are indicated by the red broken lines. The blue broken lines show the swept area of the back ports, including a sealing rim around the ports.

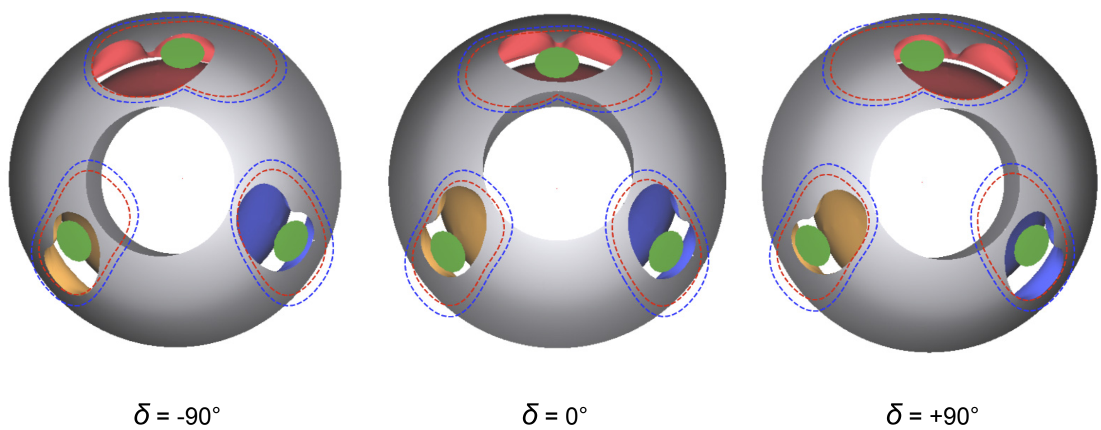



**Figure 7:** Position of the swash block at three different control angles for $\varphi = -0{,}92\ \delta$. The green circles represent the positions of the stationary ports of the housing.

The size of the back ports of the swash block needs to be large enough to balance the axial forces on the front side of the swash block. Furthermore, the size and the shape of the back ports determine the opening area of the stationary ports of the housing. The new swash block control around three axes allows a good compromise between all these design requirements.

## 5. Force and torque balance

Like in a variable displacement pump, the hydrostatic forces of the rotating group create large loads on the swash block. The pressure field of the back ports and the sealing lands can counteract the axial forces acting on the port plate. However, due to the spherical bearing, the back ports will not only make an axial force (which counteracts the axial force generated by the corresponding port of the valve plate) but will also create a radial force on the swash block. Without counteracting this force, the swash block will tip. Consequently, each back port needs a bias piston to counteract this radial force.

For two extreme positions, figure 8 shows a schematic cross section of the swash block. Force $F_1$ is generated by one of the three ports at the front side of the swash block. This force is counteracted by another hydrostatic force $F_2$ which is created by the corresponding back port. The size of the back port is dimensioned as such that the magnitude of the axial component $F_{21}$ of $F_2$ is about equal to the load $F_1$.

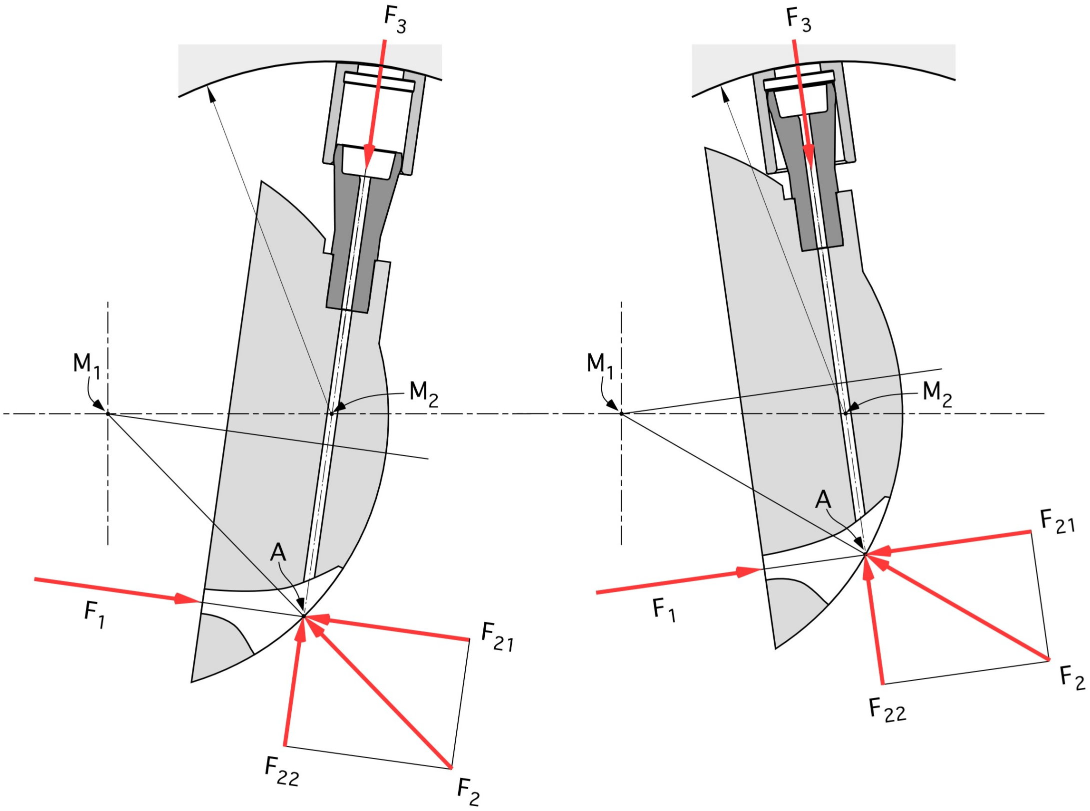



**Figure 8:** Cross section of the spherical swash block at two extreme angular positions, showing the loads of one of the ports on the front and backside and the corresponding bias piston.

Due to the spherical orientation, the pressurised back port also results in a radial force $F_{22}$. This force is counteracted by a force $F_3$ which is created by the bias piston. The drawing of Figure 8 shows a bias piston and cup, similar to the pistons and cups of the rotating group. The bias piston is connected to the back port by means of a connecting line. Oil is supplied to the cup via the piston. In order to obtain a static force and torque balance, the bias force $F_3$ needs to follow the rotation of the swash block. In the example of Figure 8, the force $F_3$ needs to go through point A, independent of the angular position of the swash block. In order to fulfil these demands:

- the bias cup needs to be supported by a cylindrical surface
- the centre line of this cylindrical support surface has to go through point $M_2$ (see Figure 8)
- the rotation $\varphi$ of the swash block around the $z$-axis needs to be equal to minus the rotation $\delta$ around the $z'$-axis ($\varphi = -\delta$)

Since the hydraulic transformer has three ports at different pressure levels, there are three bias pistons, one for each port. Figure 9 shows the swash block from the front and the backside. Each back port is connected to a bias piston at the opposite side of the swash block. Each bias piston has a cup-like cylinder. The end face of these cups is not flat but cylindrical, which allows them to run on the cylindrical support surfaces of the housing.

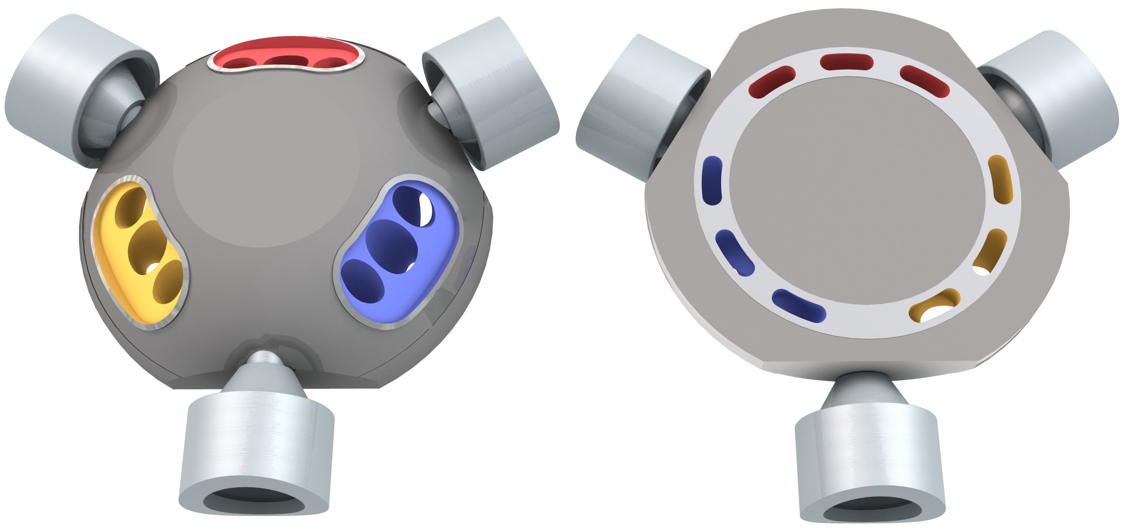


**Figure 9:** Top and bottom view of the swash block including the three bias pistons and cups.

The total concept of the new transformer is illustrated in Figure 10. Only one half of the transformer is shown. The cross section of the housing shows the spherical bearing (which supports the swash block) and one of the hydraulic ports supplying oil to and from the swash block. Only one bias piston is shown, including its cylindrical support surface.

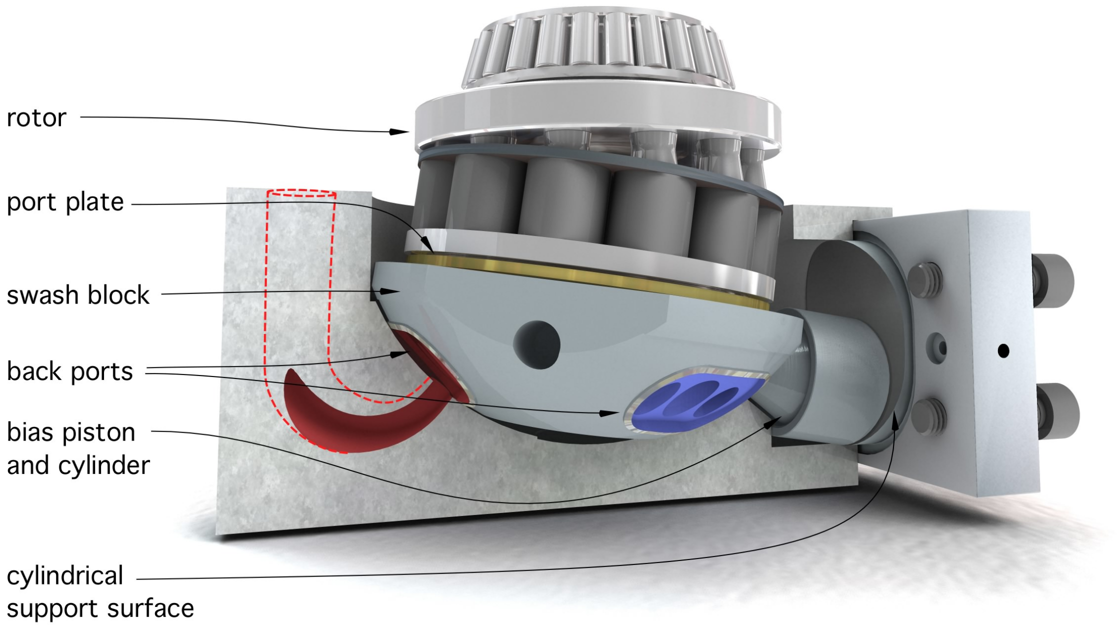



**Figure 10:** Drawing and partial cross section of half of the 'Oiler' transformer showing only one of the three bias pistons and cups and one of the stationary ports of the housing.

## 6. Conclusion

There is an urgent need for increasing the efficiency of excavators, loaders, lift trucks and other hydraulically operated machines. Most important is the reduction of throttle losses of proportional control valves. Hydraulic transformers could completely eliminate these losses. However, in order to be effective, these transformers:

- need to have a high efficiency, also in part load conditions,
- have a large operating range, including 4-quadrant operation and pressure amplification
- offer a dynamic and stable control of (often) dynamic hydraulic loads

The new 'Oiler' transformer utilises the efficient floating cup principle. The design of the rotating group is almost identical to previous designs of floating cup pumps and motors for which already peak efficiencies of 97% and higher have been measured. In order to achieve a large operating range, a new swash block with a spherical bearing is introduced. The extra rotational degrees of freedom are used to allow for a large operating range of the transformer, whilst maintaining the back ports of the swash block at about the same position. In order to balance the hydrostatic load, which is created by the rotating group, each back port is combined with a bias piston.

## 7. References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## 8. Nomenclature

| | |
|---|---|
| *x, y, z* | cartesian coordinates of the transformer |
| *x’, y’, z’* | cartesian coordinates of the swash block |
| *F* | Force |
| $\beta$ | rotating angle, defining the maximum displacement of the machine |
| $\delta$ | control angle of the transformer |
| $\varphi$ | off-set angle |