A four-quadrant hydraulic transformer for hybrid vehicles

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ABSTRACT

The application of hydraulic transformers in hydraulic hybrid vehicles doesn't seem to be obvious. The transformer creates an extra conversion step, adding losses, weight and costs, which could be easily avoided by means of variable displacement machines. Yet, transformers offer the advantage of pressure amplification, thereby creating a boost torque with small, simple and robust constant displacement machines. The constant displacement machines have a much higher efficiency at average part load driving conditions than the variable machines. The improved average cycle efficiency of the constant displacement machines more than compensates the extra losses of the hydraulic transformer.

This paper describes the design of a hydraulic transformer for series hydraulic hybrid drive trains. The transformer is designed for a wide range of operating conditions, allowing both pressure amplification and four-quadrant operation. Directional valves are implemented for specifying the mode of operation of the transformer, thereby avoiding inadvertent driving conditions. The design is based on the principle of the Innas Hydraulic Transformer and the Floating Cup design.

KEYWORDS: hydraulic hybrid, floating cup, hydraulic transformer

1 NEW TRANSMISSIONS FOR PASSENGER CARS

Hydraulic transmissions are more or less banned from passenger cars. The simple, but equally strong reasoning behind this banishment is based on the believe, that in the future the majority of vehicles will be all-electric. In this vision the battery will finally break the crude oil dependency of the transport sector and create an utopia in which all batteries are charged by means of renewable energy. In addition, fuel cells running on 'clean' hydrogen will give the vehicle the same performance and drive range as current vehicles.

However, the paradigm of the clean electric drive train is more a wish than a reality. Recent studies [1…5] have concluded that electric systems, even as an add-on in hybrid electric vehicles, are too vulnerable, too heavy, too expensive and too inefficient to be applied in passenger cars. Hydraulic systems and components could offer an alternative. Hydraulic pumps, motors and accumulators have a much higher power density than their electric counterparts and the (limited) energy density of hydraulic accumulators is not an issue for most vehicular applications. But current hydraulic motors and pumps are not adequate for application in passenger cars, having too high noise levels, too high torque variations, and a poor efficiency especially at part load operating conditions. The new floating cup principle and the hydraulic transformer offer an alternative approach that could well overcome these disadvantages:

- the high number of pistons strongly reduces the torque variations
- the noise level of the floating cup hydraulic motors is below the contact noise between the wheel and the pavement
- the floating cup principle has a high efficiency in the field of operation
- the hydraulic transformer allows pressure amplification and the application of relatively small constant displacement motors

Figure 1 shows a lay-out of the new hydraulic hybrid or 'HYDRID' drive train. Together with the Institute of Fluid Power Drives and Controls (IFAS) of the RWTH Aachen University, the specific fuel consumption of the HYDRID-transmission has been calculated [6, 7, 8]. The analysis was performed for a mid-size sedan having a diesel engine and an all-wheel drive. The outcome of the study is that the fuel consumption is reduced by more than 50%, both for the New European Driving Cycle (NEDC) and the US FTP75 cycle, . The CO_2-emission is reduced to 82 gr/km, well below the limit of 120 gr/km set by the European Commission for the year 2012.

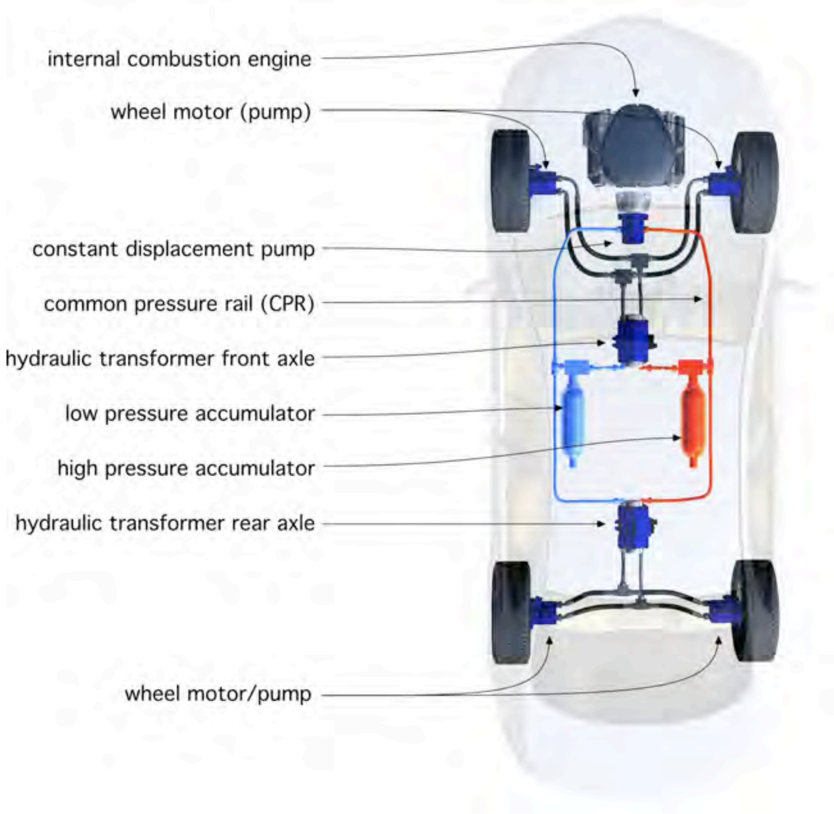


Figure 1: Layout of the HYDRID: a series hydraulic hybrid transmission.

The HYDRID transmission is not an add-on to the existing mechanical transmission: it is a complete substitution of the original transmission. All energy produced by the internal combustion engine is now converted to hydraulic power and supplied to the high pressure accumulator. The common pressure rail (or CPR) is the grid that distributes the energy throughout the vehicle, but also separates the power supply from the loads. Whereas in current passenger cars, the fuel metering of the engine (i.e. the gas pedal) determines the wheel torque, in the new drive train the engine-pump-combination is nothing more but a power station that has to fulfil a simple task: to supply energy with the highest efficiency and the lowest emissions at the lowest cost.

The hydraulic transformer is the core of the new transmission. The wheel torque created by the wheel motors (during propulsion) annex wheel pumps (during braking) is completely determined by the pressure output generated by the hydraulic transformers. The transformers are based on the principles designed by the Dutch company Innas B.V. [9, 10]. The ratio between the pressure differential at the input Δp_A and the pressure differential created at the output of the transformer Δp_B is set by the rotational angle δ of the port plate relatively to the top dead centre position of the piston movement. Whereas in conventional vehicles there is a clear separation between propulsion (via the gas pedal or accelerator) and braking (via the friction brakes), these two functions are now combined in the transformer.

2 TRANSFORMERS VERSUS VARIABLE DISPLACEMENT MACHINES

Hydraulic hybrid drive trains generally apply variable displacement machines to control the drive torque. In series hybrid transmissions the wheel torque is completely dependent on the torque of the hydraulic motors and the size of these motors has to be chosen as such that the maximum torque requirement T_{max} of the vehicle can be fulfilled, also when the pressure in the high-pressure accumulator is low:

$$V_{\max} = \frac{T_{\max} \cdot 2\pi}{\Delta p_{\min} \cdot \eta_T} \qquad [1]$$

The size $V_{\max}$ also has to be compensated for the torque efficiency η_T, representing the friction losses as well as the torque variations due to the kinematic principle and commutation effects. Especially at low rotational speeds and start-up conditions the torque generated by a hydraulic motor can be much lower than the theoretical maximum ($\eta_T = 1$). Figure 2 shows a comparison of the measured torque efficiency at low rotational speeds (< 1 rpm) for three different types of motors.

It could be argued that the pressure level in the high pressure accumulator varies between a certain minimum and maximum pressure level, and that therefore the maximum torque could be realized at the maximum pressure level. However, since energy can only be recuperated if the accumulator is not yet filled, the pressure level of the high-pressure accumulator has to be kept rather low during normal driving conditions. In case of variable displacement motors, the relatively low supply pressure can only be compensated by means of applying motors having a large maximum displacement V_{max}. Aside from being heavier and more expensive, the larger motors are forced to be driven at small displacements during average driving conditions. At these small displacements the efficiency of most hydraulic motors is very poor. In a recent study about hydraulic hybrids, Van de Ven, Olson and Li [11] have concluded that this is one of the most important areas for further research and development.

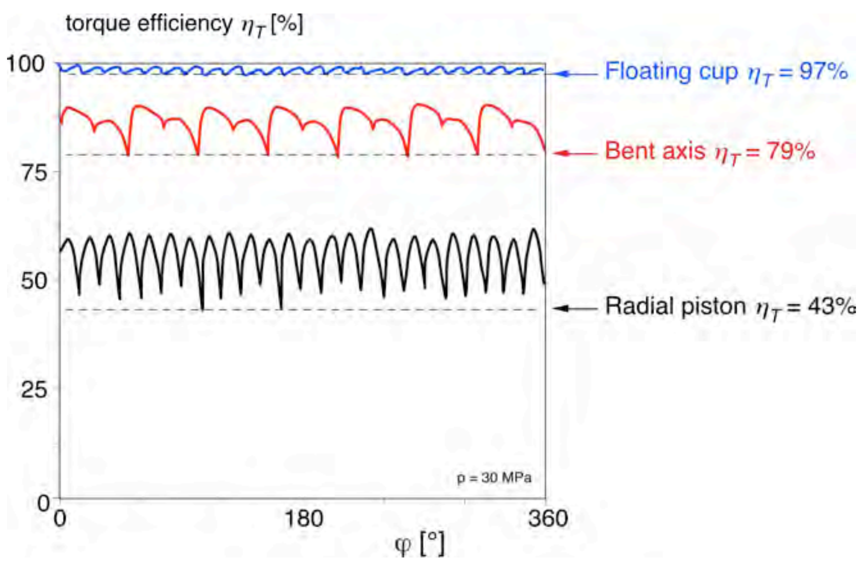


Figure 2: Ratio between the measured torque at low rotational speeds and the theoretical maximum torque at a supply pressure of 30 MPa.

The use of variable displacement motors can however be avoided. Instead of controlling the torque of a hydraulic motor by changing the displacement, it is also possible to use constant displacement motors and change the output torque of the hydraulic motors by means of the pressure differential Δp:

$$T = \frac{V \cdot \eta_T}{2\pi} \cdot \Delta p \qquad [2]$$

For this option, hydraulic transformers are needed to convert the pressure level in the accumulator to the pressure needed for creating the required torque and traction. A hydraulic transformer can be realised by means of a constant displacement machine having three ports instead of the regular two ports applied in pumps and motors [9, 10]. The transformer is controlled by changing the rotational position δ of the port plate relative to the sinusoidal movement of the pistons (see figure 3). Assuming three equal ports the pressure ratio between the in- and output is depicted in the diagram of Figure 3. A strong advantage of the transformer is that it can amplify the pressure of the input to a higher pressure at the output. It is for instance possible to create a pressure level of 400 bar at the wheel motor, even if the pressure in the high-pressure accumulator is only 200 bar. Therefore, having a transformer as a pressure amplifier, the constant displacement motors only need to have half the displacement of the variable displacement motors without the hydraulic transformer.

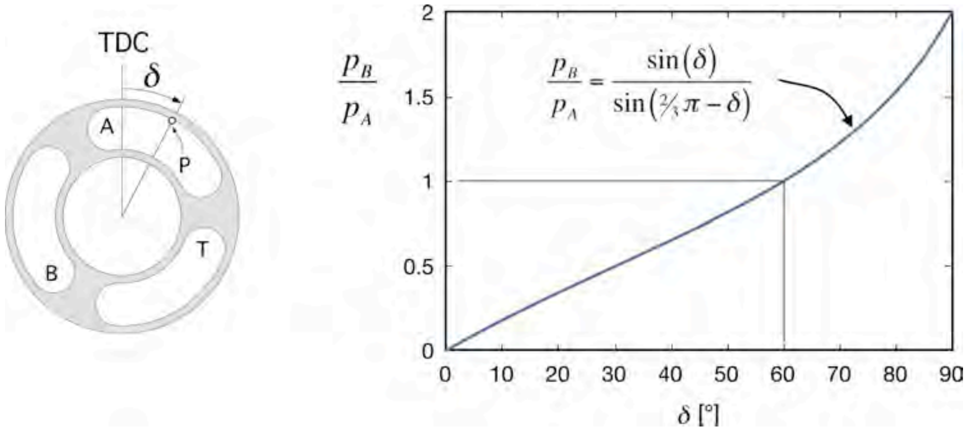


Figure 3: Hydraulic transformer principle.

A	port connected to the high-pressure accumulator
T	port connected to the low-pressure accumulator
B	port connected to the load
P	reference point on the port plate
TDC	top dead centre position of the piston movement
δ	control angle of the transformer

The use of simple, robust and efficient constant displacement motors is a clear advantage of the transformer. The small, light and robust constant displacement machines are also better for a direct mount in the hub of the wheel, thereby avoiding an excessive increase of the unsprung weight of the wheel. A final advantage of the transformer is that it can be disengaged while cruising on the highway. The vehicle can than be operated as a normal drive train having the pump directly coupled to the wheel motors.

3 PERFORMANCE AND SAFETY REQUIREMENTS

The HYDRID creates a fundamental change in the operating principle of the vehicle. Unlike normal drive trains, in which the engine and the brakes control the traction of the vehicle, most of the traction control is realised in the HYDRID by means of the transformers, both during propulsion and braking. Aside from emergency brake actions (for which the foundation brakes will remain in the vehicle), the braking is no longer relying on friction and dissipation. Instead the wheel motors act as pumps during braking, thereby recuperating the kinetic energy of the vehicle. A positive wheel torque, creating a propulsion torque at the wheels, is generated by means of supplying high pressure oil at the supply port of the wheel unit. A negative wheel torque on the other hand is realised by means of switching the high and low pressure port. The switching must be performed fast and efficient.

A new situation occurs when the vehicle comes to a stand-still at the end of a brake action. If this is realized by means of the normal foundation brakes nothing happens: the vehicle will just stand still as long as the brakes are activated. This is quite convenient when the vehicle stops while being on a slope: no matter whether the vehicle is standing up- or downhill, the brakes will prevent the vehicle from rolling in either direction. However, in case of the HYDRID the wheel motors just create a wheel torque that is opposite to the propulsion torque. If the vehicle now comes to a standstill the negative traction will make the vehicle move in the opposite direction.

These in-adverted operating conditions have to be avoided, and the driver needs a clear way to define the mode of operation of the vehicle: forward propulsion, forward braking, reverse propulsion and reverse braking. These conditions are realised by:

- allowing the transformer to be operated ‘over-centre’, for instance between -90° < δ < 90°
- adding valves to define the forward and reverse propulsion modes

The hydraulic diagram of the new transformer is shown in figure 4 (only one of the two wheel motors is shown). The four modes of operation are shown in figures 5a to 5d. In the diagrams the control angle δ is set (as an example) at a value of 30°. At this value the wheel motor requires twice the flow and halve the pressure level of the flow and pressure difference at the CPR-side of the circuit.

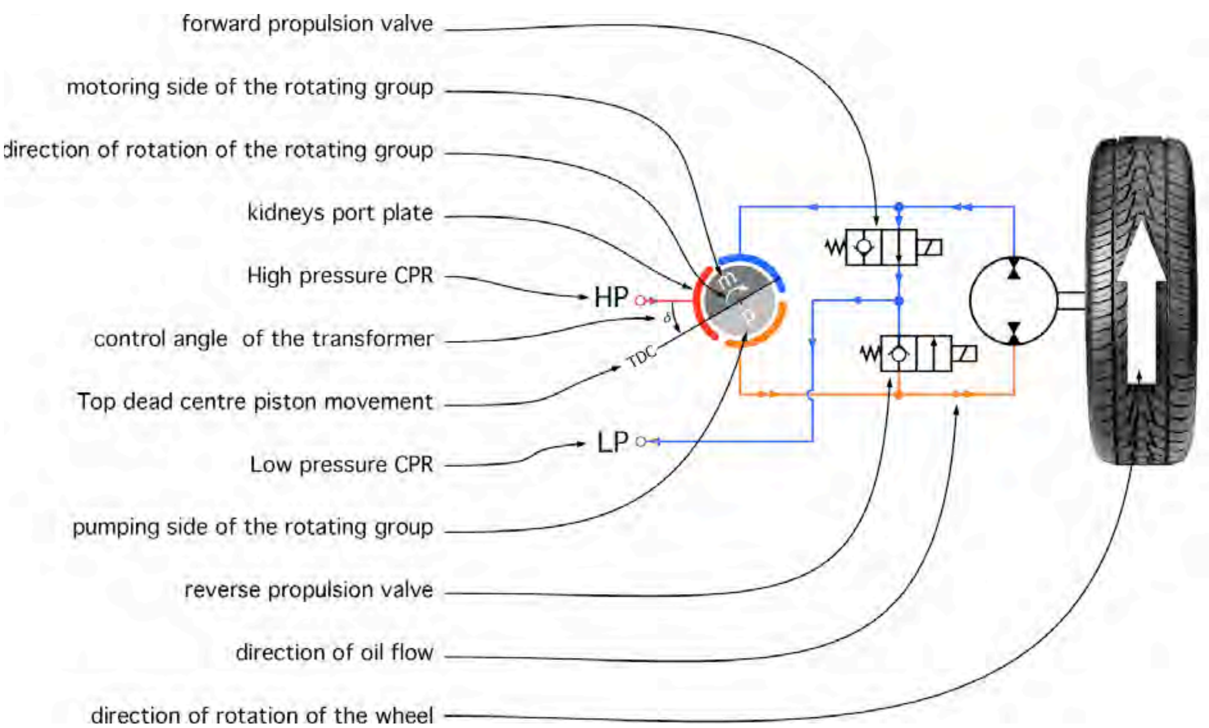
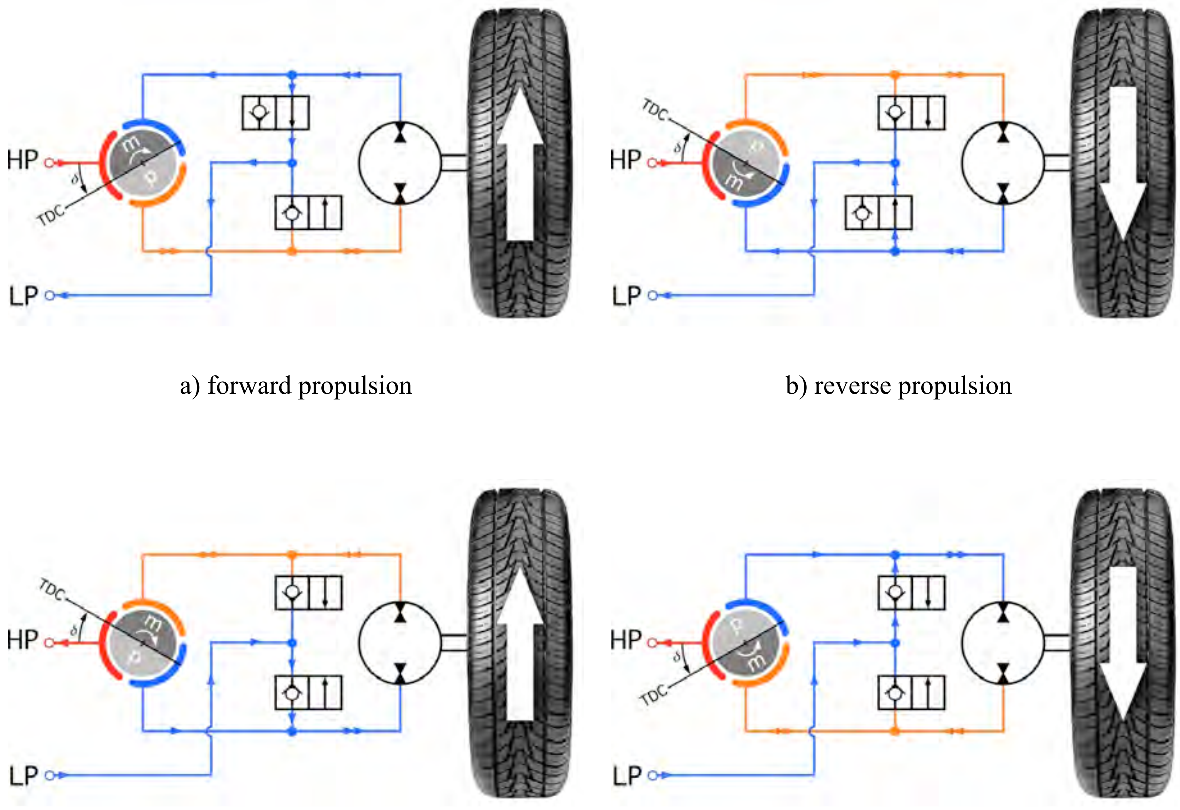


Figure 4: Hydraulic system schematics of the hydraulic transformer and wheel motor.

The new design has a number of important advantages:

- At the end of a brake action the vehicle will not start rolling in either direction. In order to start the vehicle moving again, either the forward propulsion or the reverse propulsion valve has to be operated.
- The neutral position of the two valves always defines the brake mode (both in forward and reverse propulsion mode).

- The rotating group of the transformer keeps its direction of rotation when switching from propulsion to brake mode. The speed of the transformer is coupled to the speed of the vehicle.
- The control valves are switched when the control angle δ of the transformer is 0° at which condition there is no flow going through the valve.
- The control valves only take part of the flow, which reduces the flow losses of these valves. The remaining oil is flowing in a direct connection between the transformer and the wheel motor.



a) forward propulsion

b) reverse propulsion

c) forward braking
(energy recuperation)

d) reverse braking
(energy recuperation)

Figure 5: Four modes of operation for the hydraulic transformer. The modes are shown for a transformer with three equally sized ports and a control angle of 30°. At these settings the oil flow going through the wheel motor is twice the flow at the CPR side of the transformer.

It is obvious that it is possible to have more than one motor connected to the output of the transformer. It is also possible to create a free running mode by having both valves activated and setting the transformer at a neutral control angle (δ = 0°).

4 DESIGN OF THE 4-QUADRANT TRANSFORMER

In theory it is possible to build the hydraulic transformer described above with any hydrostatic principle that features commutation by means of some kind of a port plate. But the transformer requires an efficient hydrostatic principle to become successful. It is also essential that, for the application in hydraulic hybrid drive trains, the transformer can deliver pressure levels up to 500 bar. Furthermore, the controllability of the transformer is greatly improved if the number of pistons is increased. All these requirements are best met with the floating cup principle.

The hydraulic transformer is controlled by changing the angle between the rotational position of the port plate and a reference position of the piston movement. In this paper the top dead centre (TDC) position of the pistons is taken as a reference point for the rotating group rotation. This leaves 2 different ways for controlling the transformer:

- to rotate the port plate and have a fixed TDC position
- to rotate the TDC-position and have a fixed port plate position

The first design of the floating cup hydraulic transformer applied a rotating port plate (see Figure 6). It is however difficult to get a proper hydrostatic balance of the port plate, which is necessary to reduce the actuator force required to rotate the port plate [12]. Furthermore, the rotating port plate requires a connection to the stationary ports of the housing, which is quite challenging for the 4-quadrant transformer considering the wide operating range of the control angle (-90° < δ < 90°).

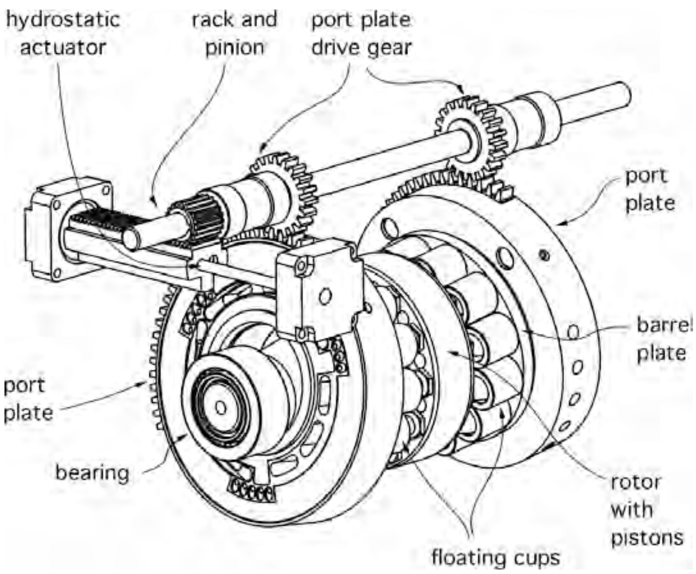


Figure 6: Floating cup hydraulic transformer with rotating port plates.

In the new 4-quadrant transformer the indexing port plate design has been abandoned and the port plate position has been locked. Instead the transformer is controlled by means of changing the rotational position of a swash block, i.e. of the TDC reference point of the piston movement. Figure 7 shows an exploded view of the main parts of the 4-quadrant hydraulic transformer, excluding the housing.

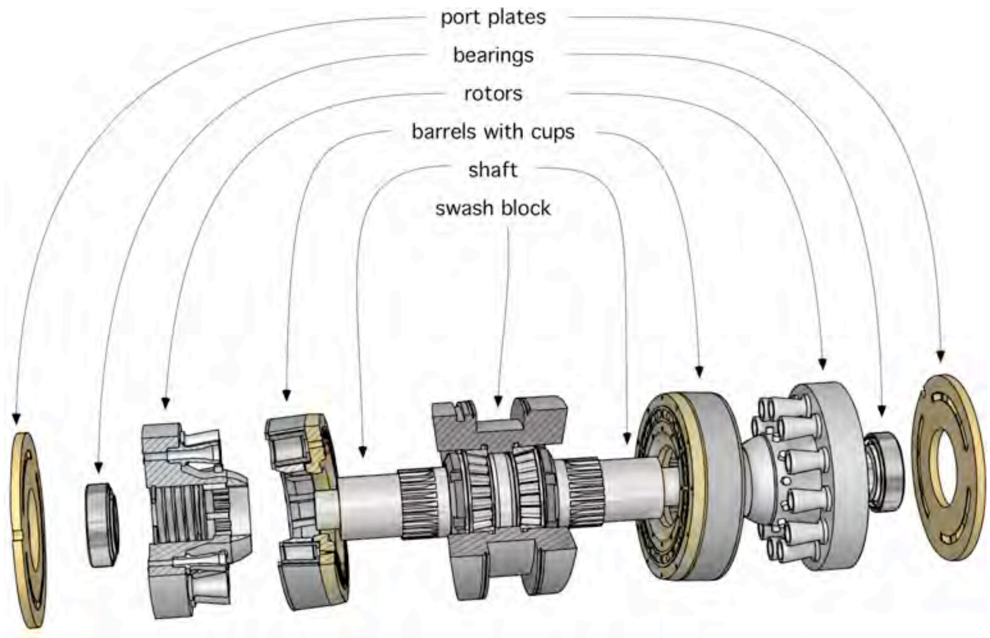


Figure 7: Exploded view of the main parts of the transformer, excluding the housing.

The port plates are located on both ends. The commutation is realised by the rotors –not by the barrels– and the oil is supplied via hollow pistons. The hollow pistons increase the dead volume, which is most welcome in the transformer for eliminating pressure spikes and cavitation during commutation. The barrels run on the central tapered swash block. The angle between the tilted surfaces of the swash block and the shaft axis creates a relative movement between the piston and the cup, thereby generating a positive displacement. The rotational position of the swash block can be changed, thereby changing the angle between the fixed port plate position and the TDC reference point of the piston movement.

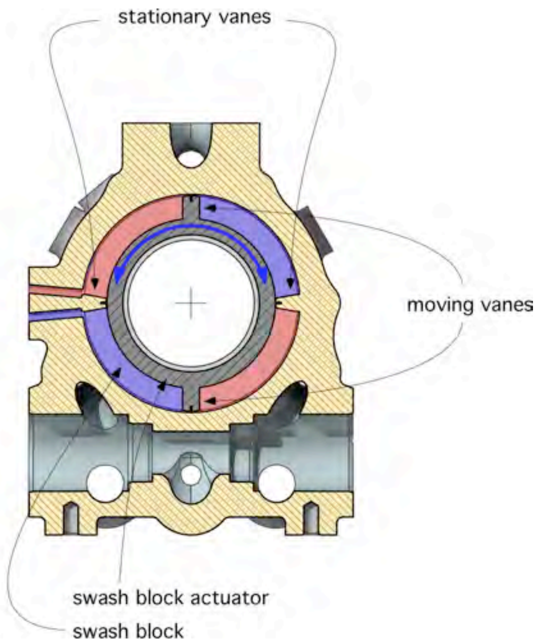


Figure 8: Cross section of the hydraulic transformer showing the swash block actuator.

The rotation of the swash block is realised by means of a rotating cylinder (Figure 8). In order to balance the hydraulic forces of the actuator, a design with 2 moving vanes, 2 stationary vanes and 4 pressure chambers has been chosen. The actuator is controlled by means of the low pressure of the CPR system, being 10 - 20 bar above the pressure in the reservoir. Due to the width of the vanes, the swivel range of the actuator is limited to 166°. This does not need to be a serious limitation since the division between negative and positive control angles does not need to be symmetrical (-83° < δ < 83°). For the HYDRID an asymmetrical division has been chosen having a control angle between -69° and +97° (see figure 9). This limits the maximum pressure amplification ratio during reverse propulsion and forward braking to about 1:1.20. On the other hand it increases the amplification ratio during forward propulsion (and reverse braking) to 1:2.54. The advantage of the chosen control range is that, even when the pressure level in the high-pressure accumulator is at a minimum value of 200 bar, the output pressure can still be increased to 500 bar. This is for instance the situation when the car requires a maximum torque, for instance for overtaking another vehicle on the road, at a moment when the high-pressure accumulator is almost empty.

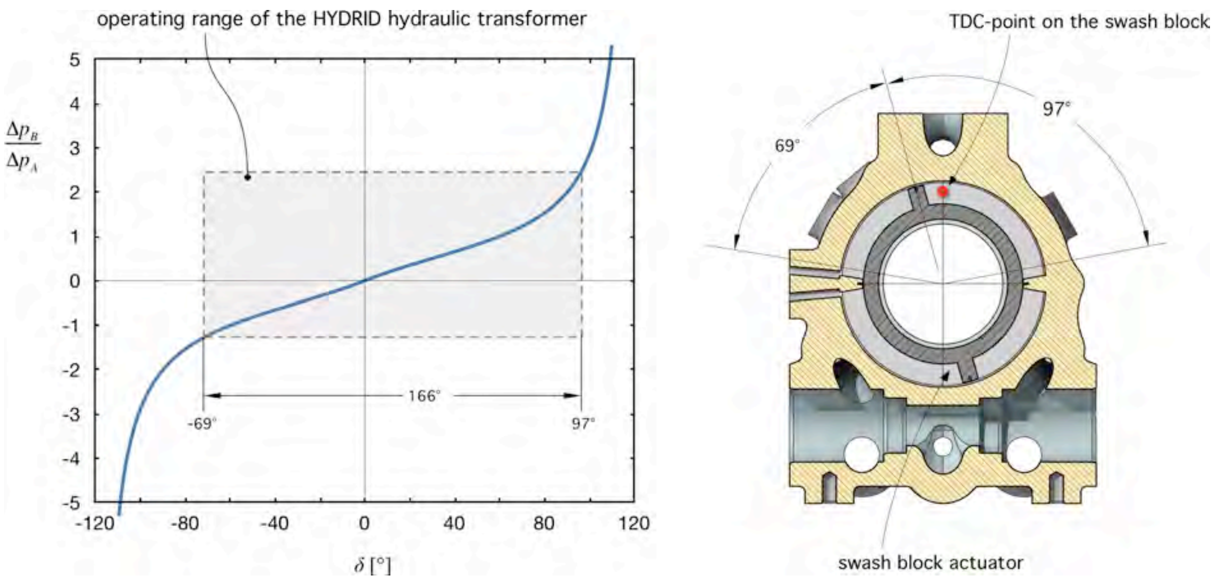


Figure 9: Ratio between the pressure differential Δp_B at the load side and the pressure differential Δp_A at the CPR-side of the 4Q-transformer. The rectangle in the middle shows the chosen range of control angles of the swash block actuator and the corresponding pressure ratios.

5 NUMBER OF PISTONS

One of the most important differences between the floating cup principle and other positive displacement principles is the number of individual displacement chambers i.e. cylinders and pistons. Instead of the regular 7 to 9 pistons, the floating cup principle features 20 or more pistons. The number of pistons has a large influence on the flow and pressure pulsations, the bearing load and the torque variation of the hydraulic transformer. Unlike hydrostatic pumps and motors, the transformer has three instead of two commutations from one pressure level to another during each revolution. Most of the time, the commutations occur outside the top and bottom dead centre regions where the pistons have a considerable speed and arm length for generating a torque. This results in stronger flow and torque variations.

The graph below shows the influence of the total number of pistons on the peak-to-peak torque variations of a 60 cc hydraulic transformer (the size of the transformer is defined as the total geometrical swept volume of the transformer – as if it were a pump or motor). The torque variations are shown for four different control angles of the transformer, at a supply pressure of 400 bar.

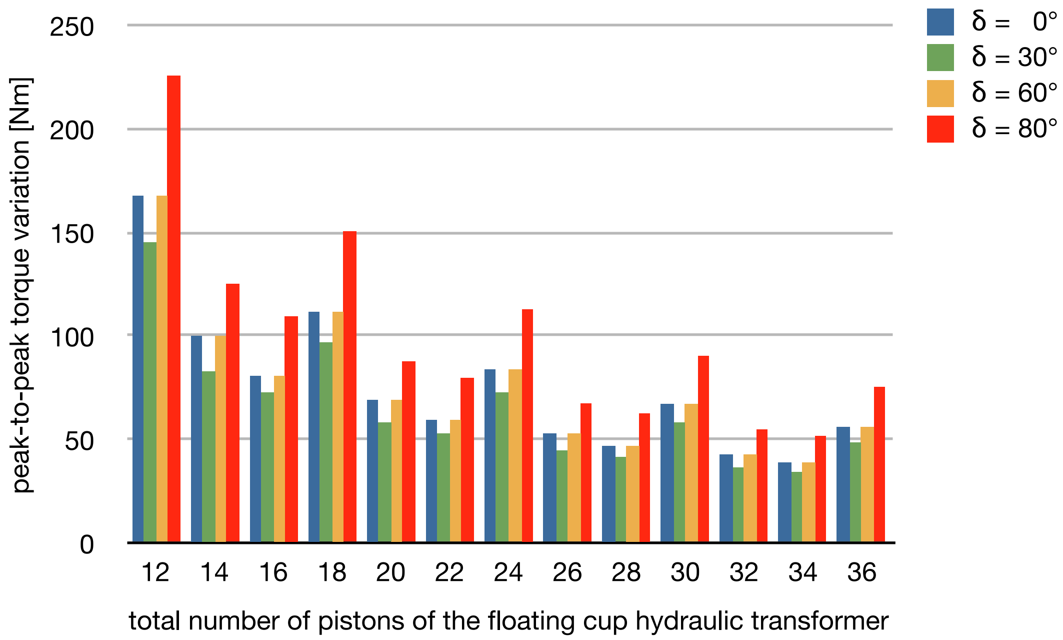


Figure 10: The influence of the total number of pistons and the control angle δ on the variation of the internal shaft torque at a supply pressure p_A of 400 bar. The transformer has three equal ports and a total geometrical displacement of 60 cc/rev.

The torque variation strongly influences the controllability of a transformer operated hydraulic system, especially at low operating speeds, and the variation should be reduced as much as possible. The torque variation is dependent on:

- The control angle δ: the torque variation is smallest for $\delta = 30°$
- The supply pressure i.e. the pressure levels in the high- and low-pressure accumulator: a higher pressure difference results in larger torque variations
- The number of pistons: in general the torque variations are halved for each doubling of the number of pistons.

The torque variations are also strongly influenced by the timing of the commutation of the three ports: the torque variation shown in the diagram of figure 10 is highest for 12, 18, 24 and 36 pistons. A simultaneous commutation (which means that for three equal ports and two barrels the total number of pistons should be dividable by 6) results in a higher torque variation. This raises the question whether it would not be better to have for instance 26 pistons (2x13) in stead of 24 pistons (2x12). The choice also influences the flow and pressure variations as well as the bearing load. To answer this question a more detailed model of the transformer has been made in AMESim. The diagram of figure 10 assumes instantaneous pressure changes during commutation and the torque variations are governed by the kinematics of the transformer mechanism. The new model also takes into account the compressibility and restriction effects that occur during port opening and closing.

Figure 11 shows the ratio of the torque variation amplitude for a transformer having 2x12 pistons versus 2x13 pistons. The ratio is calculated for various operating speeds and control angles. According to these simulation results, the transformer having 2x13 pistons clearly has an advantage, having a torque variation that is up to 3 times smaller than with 2x12 pistons. For low operating speeds, when the torque variation is most aggravating, the difference in torque variation is limited to a factor of 2.

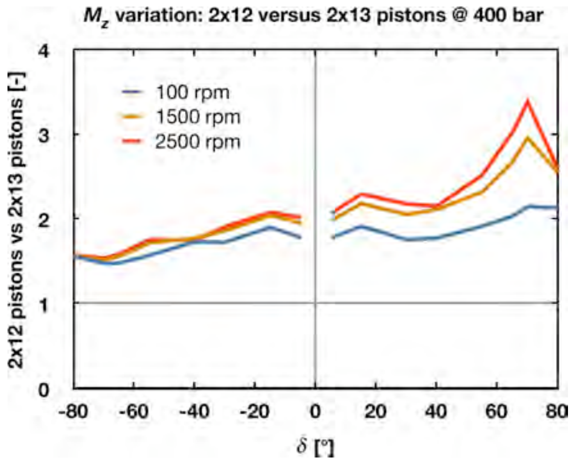


Figure 11: Ratio of the torque variation (peak-to-peak amplitude) for a transformer having 2x12 pistons versus a transformer having 2x13 pistons.

The choice between 2x12 and 2x13 pistons does not have a large effect on the flow variation (see figure 12). The flow variations are most and for all influenced by dynamic effects, caused by the expansion and compression of oil volumes, and to a lesser extend by kinematic phenomena.

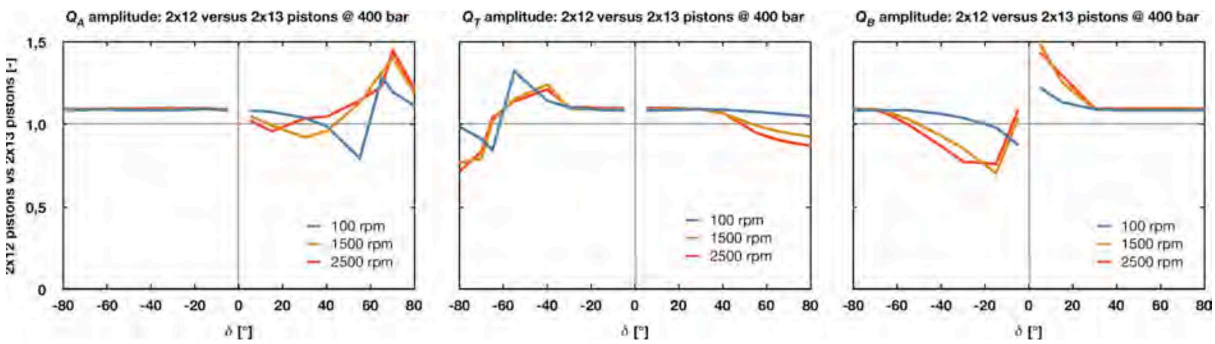


Figure 12: Ratio of the flow variations (peak-to-peak amplitude) for a transformer having 2x12 pistons versus a transformer having 2x13 pistons. Q_A is the flow to and from the high-pressure accumulator. Q_T is the flow to and from the low-pressure accumulator. Q_B is the load flow to and from the wheel motors.

Finally, the number of pistons has a large effect on the bearing load. The diagrams below show the amplitude ratio of the bearing load (in three directions) for a transformer with 2x12 pistons versus a transformer with 2x13 pistons. The diagrams are about the same for both sets of bearings: the central swash block bearings and the end bearings of the shaft. The amplitude is largest for the transformer having 2x13 pistons. Especially in the axial direction of the transformer (the z-axis) the bearing load is much higher and can amount to 10 kN.

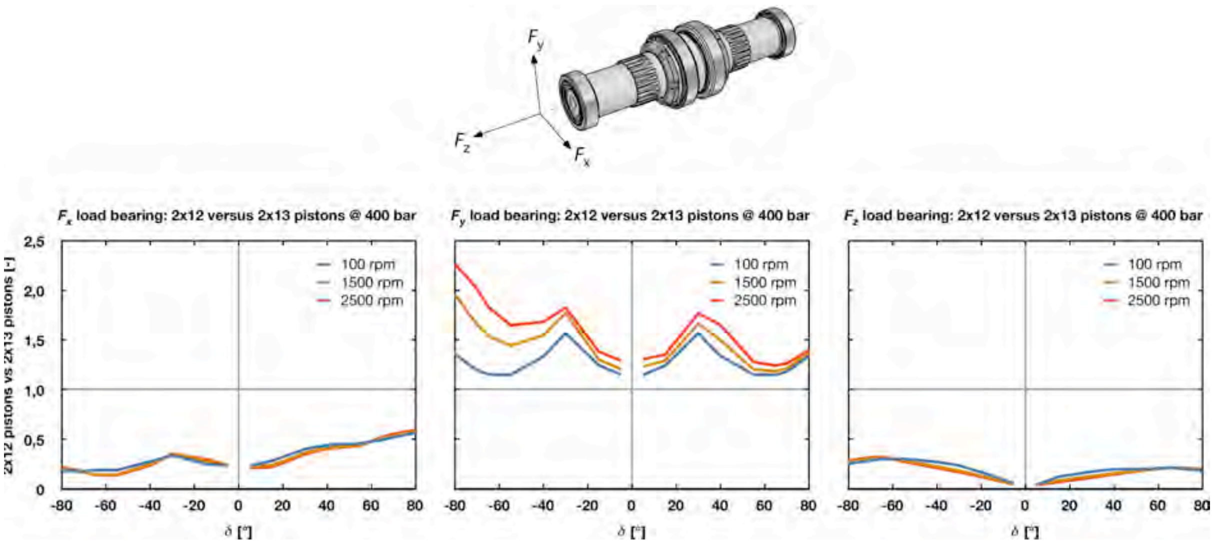


Figure 13: Ratio of the bearing load variations for a transformer having 2x12 pistons versus a transformer with 2x13 pistons. The y-direction is parallel to the TDC-BDC-axis of the swash block.

The selection of the number of pistons is therefore not obvious. A design with 2x13 pistons certainly strongly increases the bearing load. But the simulation also seems to indicate that the torque variations are halved when going from 2x12 pistons to 2x13 pistons. However, in the simulation a constant rotational speed of the transformer and a fixed rotational position of the swash block was assumed. In reality, the torque of the rotating group is counteracted by an equal torque of the swash block, and the torque variations of the rotating group will therefore also result in a torque variation of the swash block. Since the rotational position of the swash block is also influenced by these torque variations, the control angle varies, especially at low rotating speeds. This will not have much effect on the bearing load but it will strongly affect the torque variations. More research is needed to investigate this relationship.

6 CONCLUSION

More than 10 years of development of hydraulic transformers and floating cup machines have culminated in the design of a new hydraulic transformer (figure 14), especially designed for hydraulic hybrid drive trains.

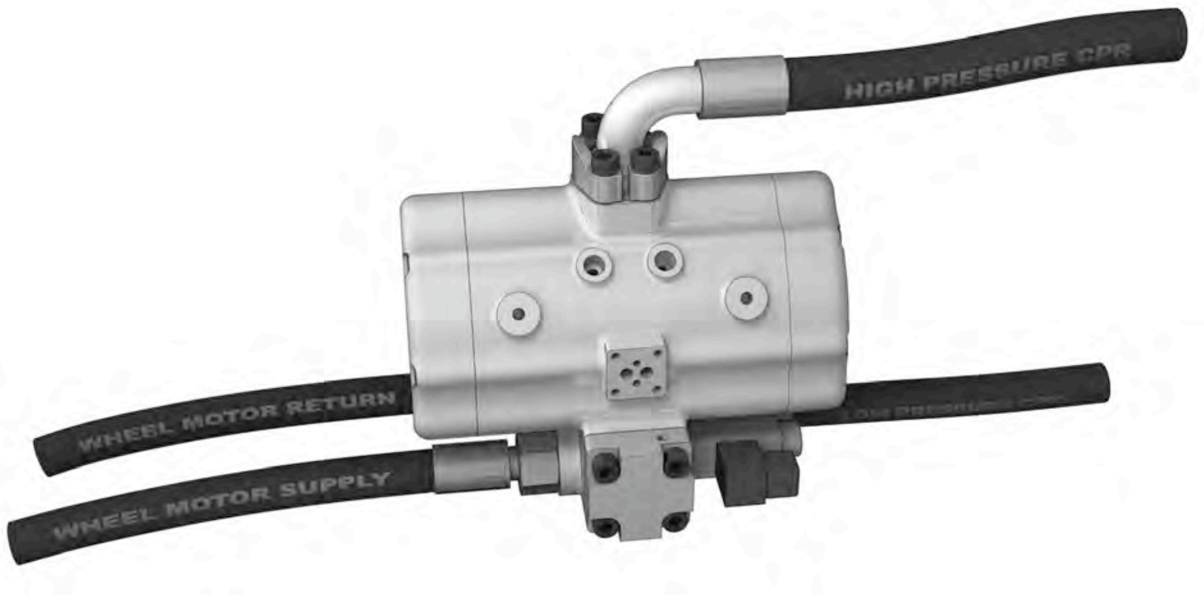


Figure 14: The HYDRID 4-quadrant hydraulic transformer

The design features a full 4-quadrant operation, as is required for a drive train with brake energy recuperation. Furthermore the transformer has two valves for defining the driving mode of the vehicle: forward propulsion, forward braking, reverse propulsion and reverse braking. The valves also prevent inadverted vehicle movements, like driving in reverse at the end of full stop. More research is needed to get a better understanding of the dynamic behaviour of the transformer, the response of the torque variations on the swash block position and the integration in a drive train.

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