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WHAT A DIFFERENCE A HOLE MAKES – THE COMMERCIAL VALUE OF THE INNAS HYDRAULIC TRANSFORMER

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ABSTRACT

Secondary controlled systems with a common pressure rail (CPR) are an alternative to current load sensing systems. These CPR-systems offer a combination of flexibility and efficiency that can never be attained with flow controlled systems. In other fields of technology, well-known examples of common rail systems are the electricity grid and the recently developed common rail injection systems for diesel engines. Nevertheless, despite the promising principle and the many advantages of secondary control, these systems have not become a success in the hydraulic field. Without doubt, the lack of hydraulic transformers on the market which have an acceptable performance and characteristics at an acceptable price level, has been a major obstacle.

In order to find a better solution, a hydraulic transformer has been developed which could be acceptable in terms of costs, controllability and efficiency. This paper discusses the state-of-the-art of the development of this so-called Innas Hydraulic Transformer (IHT), its commercial value and its applications. A direct comparison with current flow control components is not possible since the IHT is meant for CPR-systems. For this reason the evaluation will be performed on a system level, comparing current flow controlled systems with the new IHT based CPR-systems.

KEYWORDS: Hydraulic transformer, common pressure rail, commercial value

1 NEED FOR FLEXIBILITY

The strength of hydrostatic systems is their flexibility. The high power density and the ability to transport and switch energy flows by means of valves, hoses and lines make this technology very attractive for applications in which there is a relatively large number of motors and cylinders. Furthermore the power output can be controlled rather accurate with a high dynamic response.

Today, customer requirements differ much from the starting days of the hydraulic industry. The emphasis is on increased flexibility, more functions (i.e. more load points), better control possibilities, high efficiency, and reduced costs. Furthermore, in the mobile machinery market, there is a clear trend towards smaller machines and reduction of exhaust emissions.

Whether the hydraulic market will be able to face these customer demands, depends on the ability of the hydraulic market to innovate and to come up with new components and control strategies. In the competing fields of electric and mechanical drive lines the developments continue at a rapid pace. Already industrial hydraulics is loosing market share to advanced and flexible electric control technologies, and in the mobile market the continuously variable transmission offers an alternative for variable hydrostatic drive lines. In both cases the hydraulic industry loses both existing and potential new markets because of the increased flexibility of competing technologies.

A closer analysis of the hydraulic technology reveals two shortcomings:

1. The majority of today's hydraulic systems is flow controlled. These systems can be compared to kinematic mechanical drives where the movements of the various components are directly related to each other. In hydraulic systems the direct relation is established by means of oil columns which act as 'push rods'. Despite the flexible appearance of these oil columns, the underlying kinematic principle of hydraulic flow controlled systems is fundamentally inflexible.
2. The hydraulic industry does not offer an equivalent of electric converters like frequency controllers or a mechanical CVT. It does not provide a component that converts hydraulic energy into hydraulic energy with a variable transformation ratio without throttle losses (the hydraulic industry does not even offer a fixed transformer similar to the electric transformer or the mechanical gear transmission).

In flow controlled systems (in principle) every independently controlled load point needs a pump. This pump delivers a variable flow at a rate that is exactly equal to the flow rate required at the load side. In a network with a large number of load points this would in principle lead to a large number of pumps. Since this would be too expensive, load sensing systems have been developed as a compromise between the efficient but expensive flow control and the inefficient but also inexpensive throttle control. In addition, load sensing is often applied to avoid the load dependent behaviour of throttle control. But even these load sensing systems are –to some extend– inflexible kinematic systems.

Secondary controlled systems with a common pressure rail (CPR) form an alternative approach. These CPR-systems offer a combination of flexibility and efficiency that can never be attained with flow controlled systems. In other fields of technology, well-known examples of common rail systems are the electricity grid and the recently developed common rail injection systems for diesel engines. Nevertheless, despite the promising principle and the many advantages of secondary control, these systems have not become a success in the hydraulic field. The reason for this is without doubt that there are no hydraulic transformers on the market which have an acceptable performance and characteristics at an acceptable price.

At the last Scandinavian International Conference on Fluid Power, SICFP '97, the Dutch company’s Innas and NOAX presented a new design of a hydraulic transformer: the Innas Hydraulic Transformer or IHT [1, 2]. The principle of the IHT is based on the simple design of a constant displacement pump or motor, and is therefore much more cost effective than the existing combinations of a secondary controlled unit and a constant displacement machine.

This paper will address the effects the IHT will have on the design of hydraulic systems and the technical and economical value of these systems. It will start with a brief description of the design principle. A special emphasis will be put on the combination of the IHT with constant displacement motors in 4-quadrant operation as well as on the control of double acting cylinders.

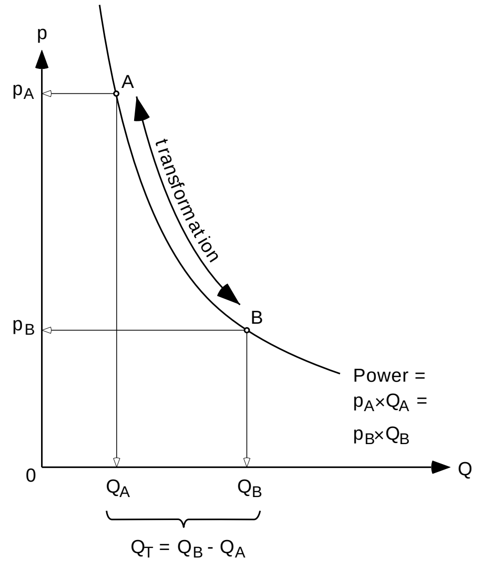
2. NEW KID ON THE BLOCK

In common pressure rail systems the control of the output has to occur predominantly at the motor side of the system. Contrary to flow controlled systems the flow is not commanded by the pump but is the result of the interaction between the load curve and the torque or force generated by the motor. Whenever there is an unbalance of the static forces the motor will accelerate or decelerate. As a result the flow will change until a new force equilibrium is reached. By controlling this unbalance the speed at the load points can be governed.

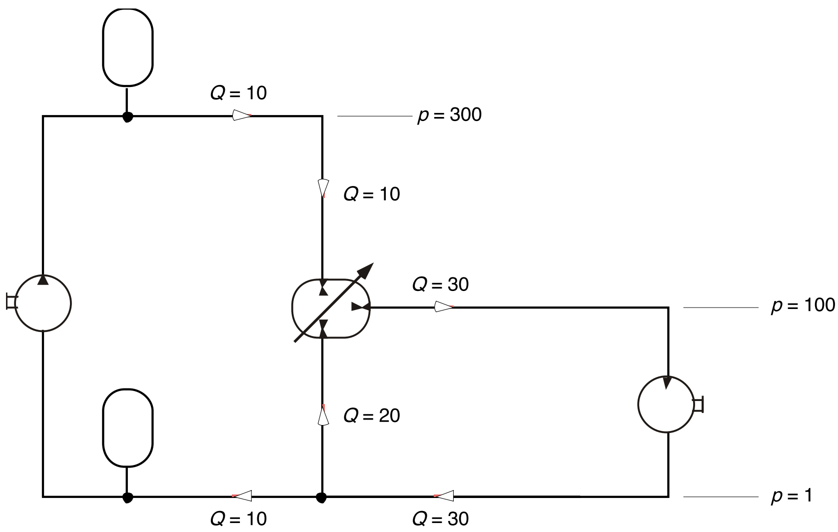
In a hydraulic motor the hydraulic pressure is converted into a mechanical force or torque by means of a mechanism. If the hydraulic motor is a constant displacement unit (like a hydraulic cylinder or a constant displacement radial piston unit) the conversion ratio between the hydraulic pressure and the force or torque generated by the motor is constant. In that case the control of the unit can only be accomplished by changing the input pressure of the unit. Consequently, in secondary controlled systems there is need for a hydraulic component that will transform the pressure of the common pressure rail to the required input pressure of the constant displacement unit.

The Innas Hydraulic Transformer (IHT) has been developed for this purpose (figure 1a). The IHT converts or transforms hydraulic power at the input side, being the product of a flow Q_A and pressure p_A into hydraulic power at the output, being the product of a flow Q_B and a pressure p_B (see Figure 1b). Aside from some friction and leakage this transformation should in principle be without any losses i.e. the hydraulic input power should be equal to the hydraulic output power. This is essentially different from valve control, in which the difference between input and output pressure is representative for the energy loss created by the valve. The essential characteristic of a throttle valve is that the output flow equals the input flow, whereas in a transformer a third flow has to be admitted in order to fulfil the mass and energy equations.

1a. Photo of the first prototype of the IHT



1b. Operation of the IHT in the pQ-diagram



1c. Example of a flow (and energy) balance of the IHT in a hydrostatic application

Fig. 1: The Innas Hydraulic Transformer and its operation

That the flow balance is fulfilled can be seen in the example shown in figure 1c. Whereas the pump only needs to deliver 10 units of flow rate, the transformer increases this flow to 30 units per minute, simultaneously lowering the pressure with a factor of three. There are two T-junctions in this diagram: at the low pressure side between the motor and the suction side of the pump, and at the IHT. As can be seen in the example of figure 1c, in both cases there is a flow balance.

An important difference between valve control and transformation is that with a valve, oil can only flow from a high to a low pressure. In a transformer however the opposite direction is also possible as long as the mass and energy equations remain valid. This means that with a transformer a large flow at a low pressure can be transformed into a smaller output flow at a higher pressure level.

3. WORKING PRINCIPLE OF THE IHT

The design principle of the IHT is based on a constant displacement unit (like for example a bent axis axial piston unit) with a valve plate to switch internally from one pressure to the other. However, there are two important differences between the IHT and a conventional pump or motor:

- In pumps and motors, the valve plate has only two kidneys: one connected to the high pressure side and one to the low pressure side. In the IHT the valve plate has three kidneys: one connected to the high pressure side of the common pressure rail, one connected to the low pressure side of the common pressure rail, and one connected to the load.
- In pumps and motors the valve plate has a fixed position relative to the pump of motor house. In the IHT the valve plate can be rotated.

By having three kidneys or ports in the valve plate, the IHT combines the functions of a pump and a motor in one unit. As in hydraulic motors and pumps there is a mechanism to convert the forces generated by the hydraulic pressure into torque. In the IHT this conversion can be influenced by rotating the valve plate over a certain angle.

The IHT has to transform hydraulic power into hydraulic power: there is no external mechanical power or a driving shaft involved. The rotation of the barrel is generated by the forces that act upon it, of which the hydraulic forces and the inertia force are the most important. In this respect the IHT can be compared to a differential piston which can also act as a transformer (see figure 2)

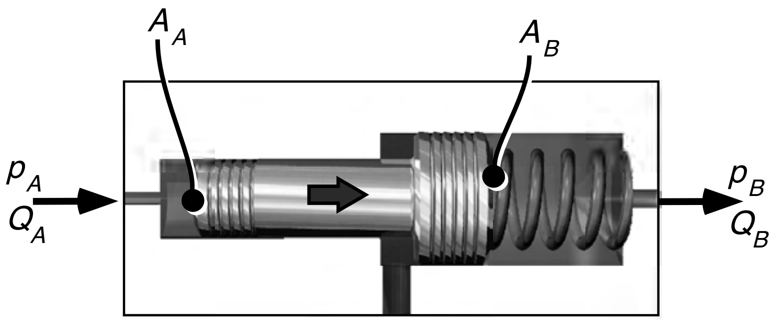


Fig. 2: Differential piston transformer.

If the sum of all static forces acting on the piston is not equal to zero, the piston will accelerate. If for instance the forces acting to the right are larger than the forces acting to the left, the piston will start to move to the right. Since the piston area A_A at the left side of the piston is smaller than A_B at the right side of the piston, this implies that the pressure p_A at the left side will be higher than the pressure p_B at the right side. To allow this differential transformer to make more than one stroke, valves are needed to switch the pressure levels at the A- and B-side.

Based on the same dynamic principle, a 'seesaw' transformer could be build with two equal pistons (see figure 3). Now the transformation ratio is determined by the ratio of the two arm lengths relative to the pivot point of the seesaw:

$$\frac{p_B}{p_A} = \frac{x_A}{x_B}$$

Since the length of each of the arms can be varied, the transformation ratio can be varied to. This is an important difference compared to the differential piston transformer shown in figure 2 of which the transformation ratio can only be varied by changing the surfaces of the differential piston.

Also with the seesaw transformer, valves are necessary to give the transformer a more or less continuous operation. But even then, the flow delivered by the transformer will have a block shape. By combining several of these transformers and operating them sequentially out of phase, the flow delivered by the transformer can become more or less constant.

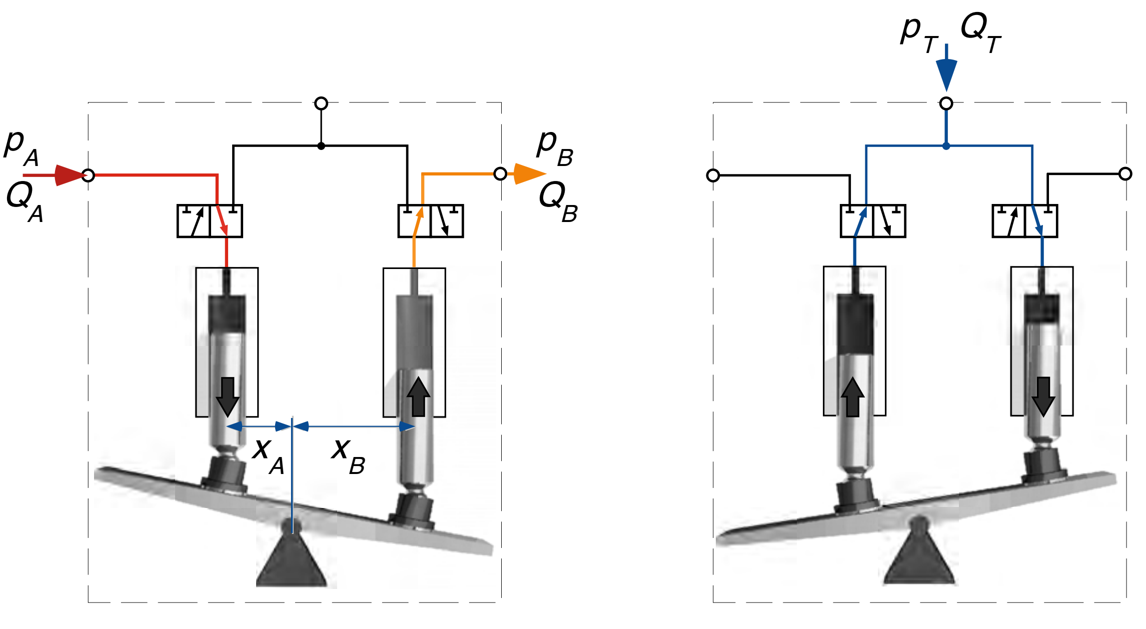


Fig. 3: 'Seesaw' transformer

Aside from pressures, also the flows are 'transformed'. As can be seen from figure 3 the seesaw transformer has three ports. The flow equations are dependent on the length of arms x_A and x_B :

$$Q_A \propto x_A$$
$$Q_B \propto x_B$$
$$Q_T \propto (x_B - x_A)$$

A much simpler construction would be obtained if the pistons would be mounted on a drive plate, sliding up and down in a rotating barrel, and the valve action would be realised by a valve plate. Since this concept would need three connecting ports, like the seesaw-transformer shown above, the valve plate necessarily would also have three ports. In stead of an arm length, now the position of the piston on the drive plate becomes important. The principle is shown in figure 4 in which the movement of the pistons is shown in the vertical direction whereas the horizontal axis represents the angular position of the barrel. The figure represents a layout of the cylindrical barrel and valve plate.

The most important advantage of the rotating version of the seesaw-transformer however is that the transformation ratio can now be varied simply by rotating the valve plate around its axis. If a piston is at its top or bottom dead centre position, the torque created by the piston is zero. The more the piston moves from these dead centres, the higher the torque will become. The position of the valve plate will determine the position of each of the three ports relative to the dead centres and therewith the effect of the pressure forces on the barrel torque for each of three pressure levels.

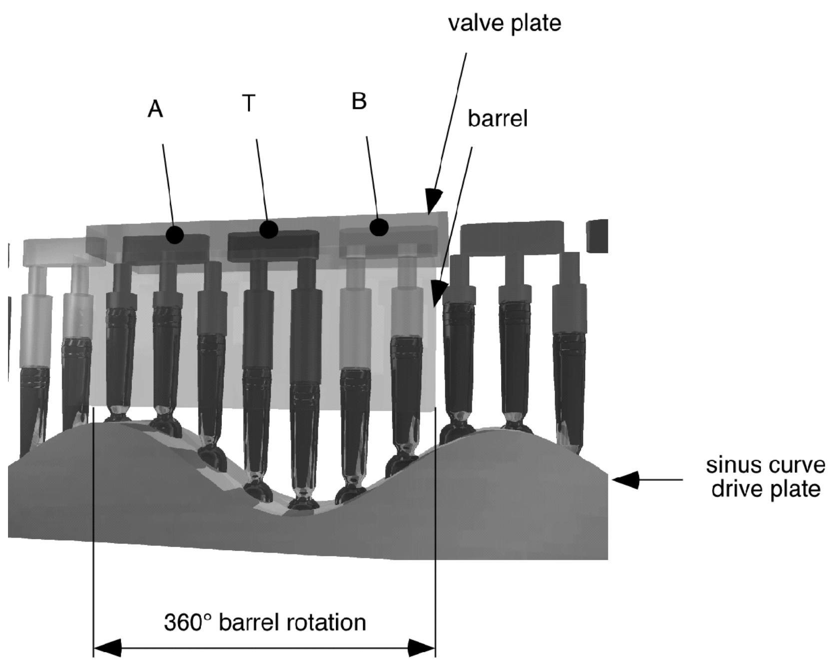


Fig. 4: Principle of the Innas Hydraulic Transformer. By shifting the position of the valve plate (i.e. rotating the valve plate) the contribution of each of the pressure connections to the barrel torque can be changed. This drawing is a layout of the cylindrical barrel and valve plate.
A = high pressure side of the common pressure rail
T = low pressure side of the common pressure rail
B = load or motor side

This is the basic concept of the IHT. The construction is not limited to that of bent axis axial piston units but can be applied to any other principle which works with some kind of valve system. This implies that also radial piston units, in-line axial piston units, vane motors and gerotor or orbital-type pumps and motors can be converted to the transformer concept. Also the principle is not limited to only three kidneys per valve plate.

4 CHARACTERISTICS

The IHT enables transformation of hydraulic power without throttling. It can transform pressure from a common rail pressure to any desired level between zero and a required maximum value. The IHT can also operate as an amplifier, creating a larger output pressure than the input pressure. In its simplest form the port plate has a fixed position, thereby creating a transformer with a fixed pressure ratio. By allowing the valve plate to rotate the transformation ratio can be varied. Both the flow and the pressure can be controlled. Furthermore the IHT can be operated in both ways, using the common pressure rail as the supply or using the load side as the supply side of the IHT. In the latter case the IHT will recuperate energy from the load to the common pressure rail.

Since the IHT is not mechanically connected to a motor or a load the barrel speed is also not limited to the motor or load characteristics, which results in small dimensions and a low weight of the transformer. The valve plate is small, light and completely balanced and can be operated manually or electromechanically, without the need for a hydraulic interface. The transformer is very responsive to changes of the rotational position of the valve plate. Due to the high force density of hydraulics, a rotation of a few degrees of the valve plate can result in a considerable change of the torque balance. Since the rotating parts of the transformer are small and have a low inertia, the change of the torque balance will immediately be followed by a change of the rotational speed of the barrel, and thus of the flows going in and out of the transformer. In this respect the IHT combines the dynamic response characteristics of a valve and the high efficiency of a variable displacement unit [3].

Figure 5 shows two different versions of the IHT. The symbol for the IHT has already been introduced during the last Scandinavian International Conference on Fluid Power [1]. If the IHT only has three ports, the transformer-motor-combination can only be operated in two quadrants (see figure 5a). However, if the motor needs to be operated in all four quadrants, and the motor is of a fixed displacement type, the IHT needs to fulfil the requirement of the 4-quadrant operation. Therefore a special IHT has been designed, which could be regarded as a combination of a 2-quadrant IHT and a directional valve (see figure 5b). The operation of the directional valve is directly connected to the position of the valve plate. The valve is switched as soon as the middle of the A-kidney passes the top-dead-centre-position of the pistons in the barrel. Because of this strict mechanical relationship it is possible to integrate the directional valve in the design of the IHT.

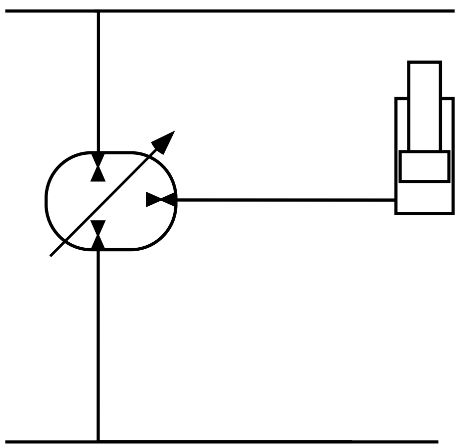


Fig. 5a Two-quadrant IHT

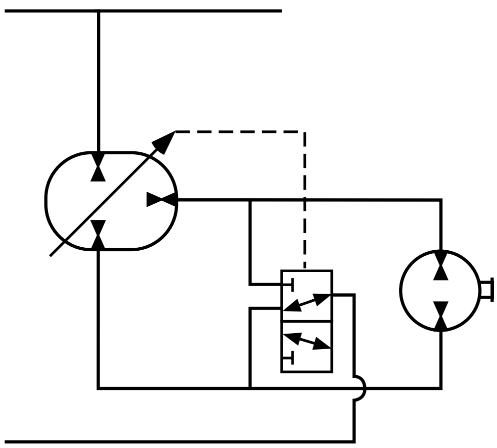


Fig. 5b Four-quadrant IHT

Fig. 5 IHT-versions

The four-quadrant IHT allows the IHT to be applied in hydrostatic drives. In principle, the combination of a transformer and a constant displacement motor can do the same as a secondary controlled variable displacement unit. The IHT-motor-combination however has a number of advantages:

- Secondary controlled machines are of the variable displacement type, whereas the construction of the IHT is based on the design of constant displacement pumps and motors. The production costs of a constant displacement unit are about 60% less than the costs of a comparable variable displacement unit.
- Aside form the variable displacement principle, secondary controlled units are quite expensive due to the difficulties of controlling the unit. In the IHT, the port plate can be actuated directly by means of an electromechanical actuator, thereby avoiding the costs of the hydraulic servo-system;
- With secondary controlled units the differential function has to be achieved by means of two units; one for each wheel. With the IHT the wheel motors can be simple constant displacement motors and the differential function can be realised hydraulically. In that case one transformer can control both motors.

The 4-quadrant IHT also offers an opportunity for controlling double acting hydraulic cylinders, although such a cylinder can also be controlled by means of a 2-quadrant transformer (see figure 6). In that case the ring side of the double acting piston will be connected to the high pressure side of the common pressure rail.

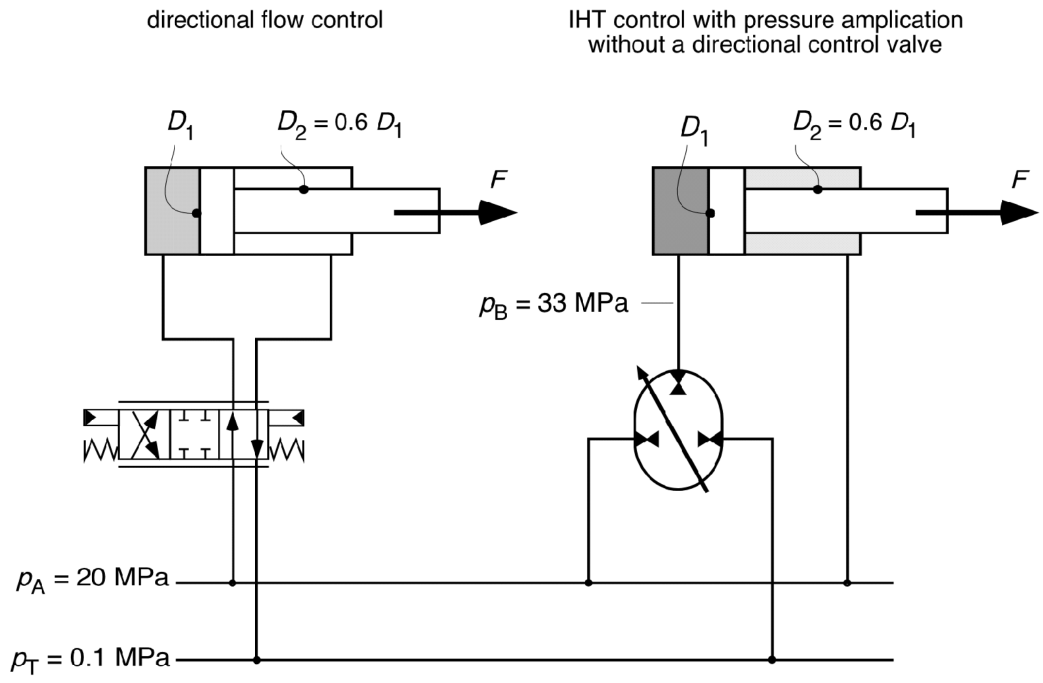


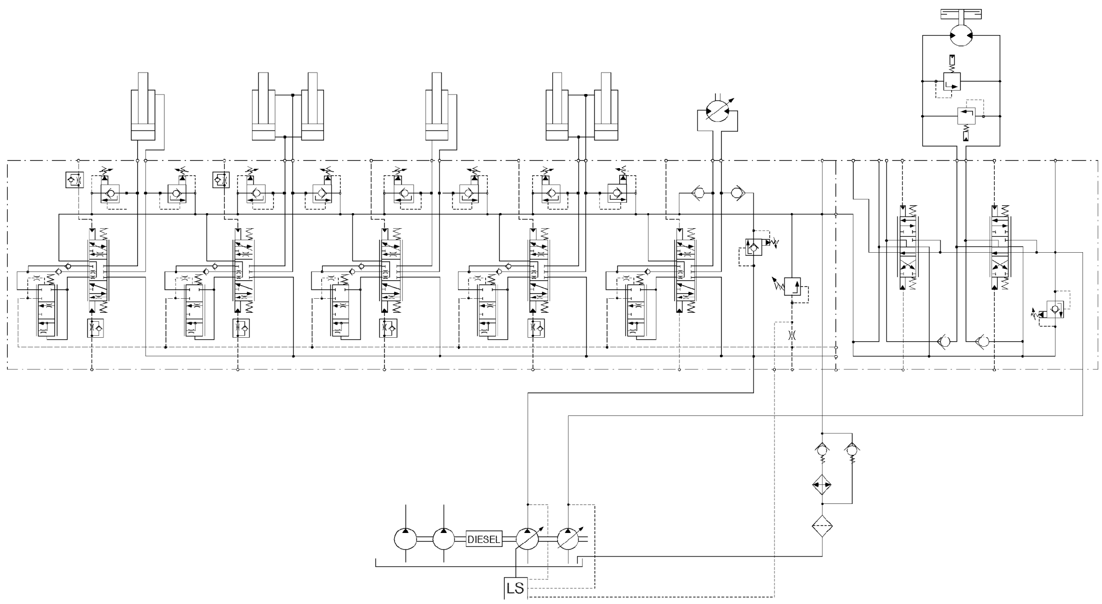
Fig. 6: Example of IHT-control versus directional flow control of double acting cylinders

To compensate for the continuous force generated by the pressurised ring side of the piston, the other (larger) area of the piston must be controlled over a wider pressure range, with maximum pressures exceeding the pressure level of the common pressure rail. If, for example, the piston rod has a diameter D_2 of 60% of the piston itself (D_1), the pressure p_B generated by the transformer must be about 67% higher than p_A. Since the IHT can also operate as a pressure amplifier this situation can be realised. The complete range of operation modes of the cylinder can now fully be controlled by means of the 2-quadrant transformer, without any directional valves.

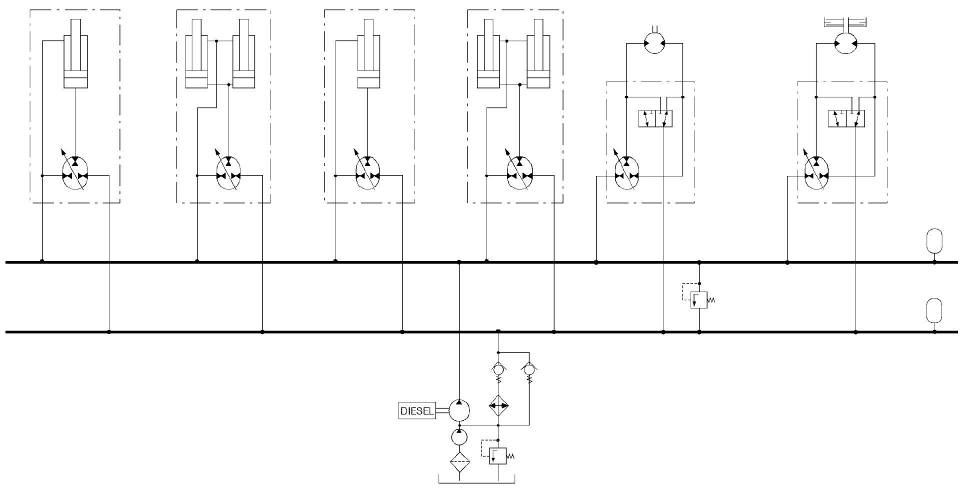
5. NEW THINGS TO COME

As is mentioned before the IHT transforms both pressure and flow. The principle is not limited to be applied in CPR-systems and can –in theory– also be used as a 'flow-converter' in flow controlled systems. In that case it could be seen as a new flow control component and as an alternative for some of today's valves.

From a component point of view the difficulty with this approach is that the transformer will be applied in a system which is rather stiff: not only at the load side (where it should be stiff to get a good controllability), but also at the supply and tank side. This is different from the application of the IHT in CPR-systems. In these systems only the load side is stiff, whereas the other two connections have a low stiffness due to the presence of accumulators in the system. This reduced stiffness allows the transformer to vary the speed which reduces the pressure pulsation's in the supply line and decreases the noise level.



7a State-of-the-art load-sensing system



7b Alternative CPR-system with IHT-control

Fig. 7: Comparison between a load sensing system and a CPR-system for an excavator

Of much greater importance are the benefits of the CPR-approach itself. Figure 7 shows a hydraulic load sensing system compared to the lay-out of a CPR-system. In figure 7b the common pressure rail can clearly be recognised. To this hydraulic 'grid' the various constant displacement units are connected. The transformers are the interface between the common pressure rail and these motors.

On the pump side, the CPR-system reduces the number of pumps. The accumulators in the system can be dimensioned not only to recuperate energy from the various loads but also for power management i.e. peak shaving. In that case the pump only needs to deliver a kind of base flow.

The next step in the development of the IHT will be to integrate the transformer into the design of hydraulic cylinders. The position of the piston in the hydraulic cylinder can then be used as a sensor signal for the speed control of the hydraulic cylinder. This will result in ‘intelligent’ cylinders which can be fully controlled in both the speed and the load domain. At the outside these cylinders will only have two hydraulic connections (the third one will be internal): one for the high pressure side and one to the low pressure side of the common pressure rail. These cylinder-transformer-combinations can be designed as separate modules.

For evaluating the commercial value of the IHT it is clear that this can only be done on a system level, similar to the comparison shown in figure 7. Even then a comparison is difficult to make since the characteristics are not the same for both systems. Some of these characteristics can be taken into consideration in an evaluation that is based on operational costs. In that case the increased energy efficiency of the CPR-system will also be evaluated. Even then the differences in dynamic behaviour between load-sensing and CPR systems are difficult to assess in terms of economic or commercial advantages.

Together with the industry NOAX evaluated the cost benefits of the IHT. The prospects are looking good. The IHT based CPR-systems are in most cases cost-efficient, often reducing hydraulic system costs with more than 30%. The fuel consumption can be dramatically improved. Closely related to the reduced fuel consumption are the benefits in terms of exhaust emissions which will be reduced as well. Already proven is the high dynamic response of the transformer. Finally the IHT opens the way to increased functionality and will make it possible to design machines more user-friendly.

The IHT will increase the need for hydropneumatic accumulators and constant displacement pumps and motors. It will be a competitor for load sensing valves and will reduce the need for variable displacement motors and pumps. In the market of hydraulic cylinders it will bring intelligence to the cylinders. Last but not least it will open up the market for new motor-pump-combinations like the free piston engine [4]

6. GAUNTLETS

There is no doubt that for the success of CPR-systems there needs to be a solution for connecting fixed displacement motors to the common pressure rail. To solve this issue the Innas Hydraulic Transformer is of course not the only solution. There are however obvious arguments in favour of the IHT-concept. One important benefit is the energy efficiency with the inherent ability to regain braking energy. Also important are the energy density and the speed of response.

In collaboration between the authors of this paper a simulation model of the transformer has been developed which describes the dynamic properties of the transformer very accurately. The model is based on a general simulation model for piston machines [5], that is experimentally verified in a great number of applications [6]. The model has been used to optimise internal parameters in order to improve efficiency and performance. The timing of the port plate is here of utmost importance. Many rules of thumb of port plate design for ordinary piston machines had to be reviewed. Simulation investigations showed that the apprehended risk of cavitation can be controlled. Experiments have confirmed this.

In order to make the transformer into a regular fluid power component, there are still some gauntlets to be taken. Noise and flow pulsation's are the most important. The flow from and to the transformer will be more pulsatory than that from a piston pump or motor. The reason is the kinematic properties of the machine. It is, however, well known that kinematic flow pulsation's are less severe than those due to flow compressibility in most operating points of a fluid power machine. In particular this is true at high power operation. This is also the area were noise is most severe. Still, the flow pulsation properties are a key issue to be handled. One important observation regarding the noise generation of the machine is the absence of mechanical connections: there is simply no mechanical shaft. This makes it much more convenient to make use of noise isolation techniques. Furthermore, because of the absence of a mechanical shaft, the speed of the barrel of the transformer is not constant but will follow the torque variations. This will damp the flow and pressure pulsation's, especially at the load side. Last but not least, in the IHT the pressure change due to compressibility effects between the subsequent kidneys can be matched with the pressure difference between the kidneys by choosing a good valve overlap and optimising the dead volume in the cylinders of the barrel [7].

Another challenge is the low speed performance of the transformer. However, control methods are available which can handle the low speed performance. This has been the subject of the work reported in [8].

Today there are working prototypes of the Innas Hydraulic Transformer showing that the efficiency data predicted by simulation models are met [9]. So far the prototypes are modified standard bent-axis pumps. Simulations indicate that transformers with a design optimised for its purpose will have a top efficiency exceeding 90% and an efficiency above 80% over a substantial part of the operating area. Efficiency is, however, not the best way of describing the system. It is more informative to study the work needed for complete working cycles. In this respect the energy recovering properties can be judged in a proper way. The control properties of the machine, well described by the simulation model, are also confirmed by experiments.

In some applications the Innas transformer requires active control using sensor signals for position, speed or whatever is the required control signal. In this respect it is to be compared with, for instance secondary controlled machines. Is this to be judged a weakness or strength? A few years ago the answer would most certain been a weakness. But this is not necessarily true anymore. Several reasons are behind this. Firstly the sensors are becoming robust and less expensive and microprocessors are integrated in machine systems to fulfil various tasks, control being just one. Secondly, the market accepts actively controlled systems. Actually in competing technologies like electrical drives, active control is a necessity when servos are designed. The transformer is a component intended for the fluid power market. It must then be judged by the market requirements of the future. A future in which actively controlled systems will soon be the main stream, not the exception.

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