Toward Maximum Flexibility in Working Machinery, IHT Control in a Mecalac Excavator

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1 Introduction

The Advanced Multi-functional Machinery for Outdoor Applications project (the 'IBIS' project) is a project sponsored by the European community in the GROWTH program under the fifth framework. It is a shared-cost Research, Technological Development and Demonstration (RTD) project. One of the goals of the IBIS project is to research and develop alternative hydraulic actuator technologies for mobile machinery. These technologies offer better controllability and energy efficiency than the so called Load Sensing (LS) technology, which is currently one of the most widely spread hydraulic actuator technologies.

In the IBIS project, three different innovative actuator technologies will be researched:

- Displacement Control (DC) technology ,
- Cartridge Valve (CV) technology and
- Hydraulic Transformer (HT) technology.

Each technology will be incorporated in a different machine platform.

This paper treats the HT technology and the way it will be incorporated into a Mecalac multi functional excavator.

2 Basics of the Hydraulic Transformer technology

The basis of HT technology is a system set-up, in which all loads attach to a common pressure rail (CPR), which consists of a high pressure line and a low pressure line. The pressure difference between the two lines is maintained by a source, which is controlled in such a way that it keeps the pressure level in the high pressure rail semi-constant. Accumulators are connected to the rail, effectively isolating the loads from the source and the loads from each other. **Figure 1** shows a somewhat simplified scheme of this system type applied in a typical excavator.

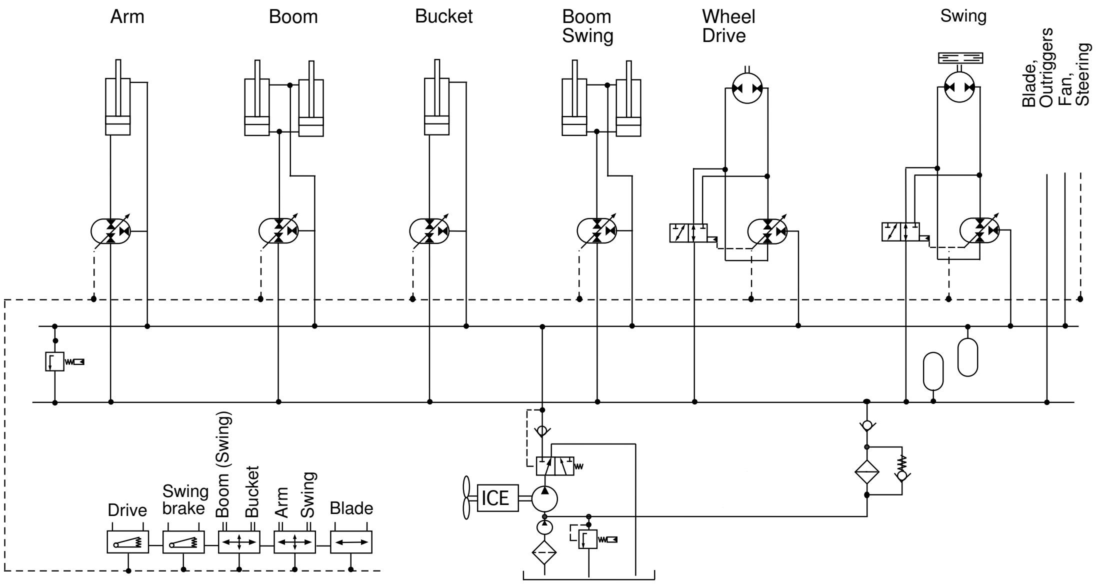

Figure 1: The hydrostatic Common Pressure Rail system applied in an excavator

In this system lay-out all loads are controlled directly at the load and in this way a truly modular system lay-out is reached. As long as the source can provide the average power demand, load axes can be added or omitted without an elaborate redesign or re-tuning of the system. For machines with short term peaks in their power consumption, the accumulators can be used to to realize peak-shaving, which leads to a lower installed engine power and to a higher average efficiency of the engine. If a machine has functions that require braking, larger accumulators can be installed, in which the braking energy can be stored for use at a later point in time.

The CPR system is not new. It was researched extensively in the 1970's and was then mostly referred to as a 'secondary controlled' system. At that time, it did not really brake through by lack of a good solution to drive linear loads from the pressure rail without throttling (for an overview of the history and applications of secondary control, see for instance /1/). In 1996 the Innas Hydraulic Transformer (IHT) was developed in order to provide a solution for linear loads. The scheme in figure 1 already contains IHTs, which are indicated by the three ported symbol that was coined specifically for the IHT.

The detailed functioning of the IHT and the basics of the CPR system set-up have been described in several earlier articles (for instance in /2/ and /3/). Here, only the geometry of the IHT and its functional behaviour are recapitulated.

In principle, any hydrostatic positive displacement unit can be built as an IHT but until now, only axial piston units have been used. In the first few years of IHT development, prototypes were built by simply replacing the port plate of an axial piston hydrostatic pump or motor, a fixed port plate with two kidneys, by a port plate with three kidneys that can be swivelled over a limited angle range. Of course, also the end caps had to be changed in order to provide the corresponding three connections to the outside world. Functionally, the IHT transforms a given and semi-constant pressure at its supply connection (p_A) to a variable pressure (p_B) at its load connection. It does so at the high efficiency that is typical for axial piston displacement units.

In **figure 2** the construction of this type of IHT can be seen. The figure also shows the difference between transformation and throttling. Where throttling introduces, by principle, a loss $P_{loss} = Q_B \cdot (p_A - p_B)$, transformation along a constant power curve is loss-free, apart from small hydromechanic and volumetric losses in the base unit.

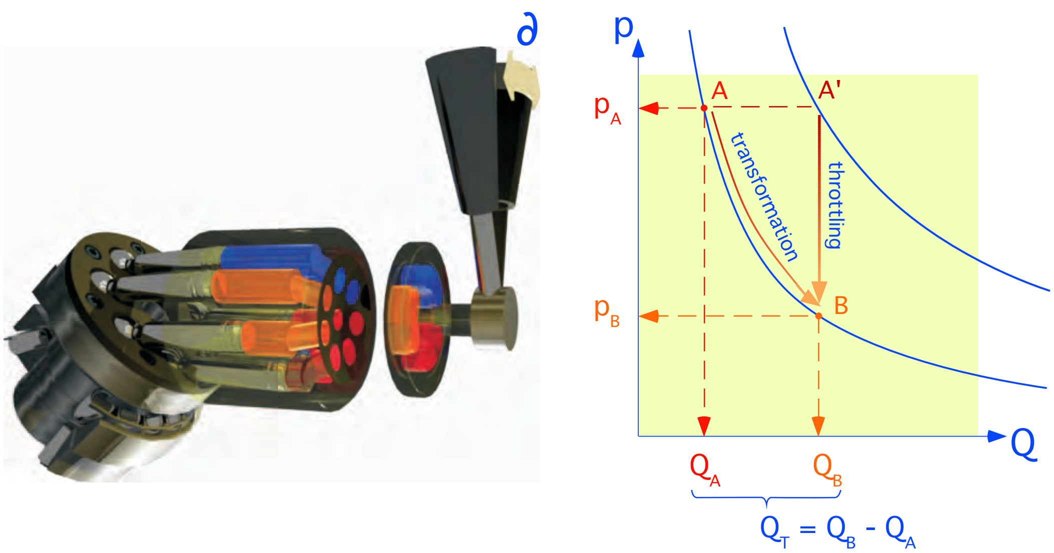

Figure 2: A 10cc A2FM based IHT and the principle of pressure transfomation

The diagram also shows why every transformer needs a third pressure connection: for the pressure transformation along a constant power curve, it is obvious that $|Q_A| < |Q_B|$ if $p_A > p_B$. As the IHT is also a node in the flow network, the sum of all flows into the IHT must be zero. Hence a third connection is necessary, which provides the make-up flow $|Q_T| = |Q_B - Q_A|$.

The left part of **Figure 3** shows the theoretical pressure transformation factor $\Pi = \frac{P_{load}}{P_{supply}}$, of an IHT design with three kidneys, each spanning an an arc length of $120°$. With the kidneys thus defined, Π is only a function of the port plate control angle, δ.
The diagram shows that the supply pressure can also be amplified. Here the curve is

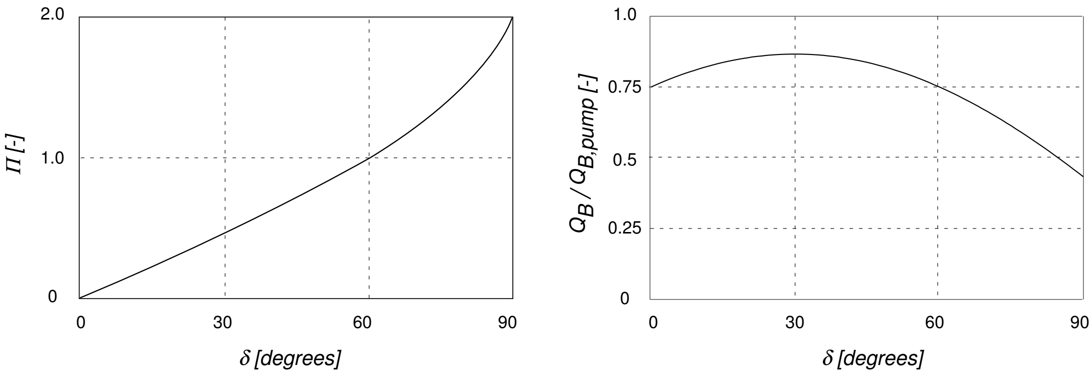

Figure 3: Pressure Transformation curve and scaled flow

given up to $\delta = 90°$, which gives a theoretical maximum value of $\Pi = 2$. The port plate can be turned further to reach even higher amplification factors but at higher values of δ, the transformation efficiency will gradually worsen.
Π is not a function of the unit's size but the output flow is. Assuming that the maximum IHT speed is equal to the maximum speed of a primed hydrostatic pump of the same swept volume, the IHT output flow as a function of δ can be scaled with the flow from that pump at the same speed. The right part of figure 3 contains this curve for the same $120°$ kidney lay-out.

3 The 'Floating Cup' IHT design

Just before the start of the IBIS project, toward the end of 2001, Innas had started to develop a dedicated IHT. The design process quickly resulted in the new 'Floating Cup' (FC) displacement principle /4/. As the FC displacement principle held a lot of promise for pumps and motors too, design and testing activities were first concentrated on those. As soon as the potential of the FC principle had been confirmed, the design of the first FC IHT prototype was continued, aimed at unit sizes that would be suitable for application in the IBIS project.

Figure 4 shows the rotary group of an FC IHT, currently under development for the IBIS project. In this design, 12 pistons are arranged on each side of the central rotor. That rotor is fixed rigidly on to the axle and the pistons are fixed rigidly in the rotor. Each piston has its own cup-like cylinder and all the ‘cups’ of one rotor half rest on a common ‘barrel plate’. The opposite side of each barrel plate runs on the inclined face of a port plate. The inclination ensures that the pistons move relative to the cups and thus that they pump oil. With a rack and pinion drive, fed from the high pressure rail, the port plates can be turned over an angle range of 90^0

A hole in the bottom of each cup connects to a corresponding hole in the barrel plate.

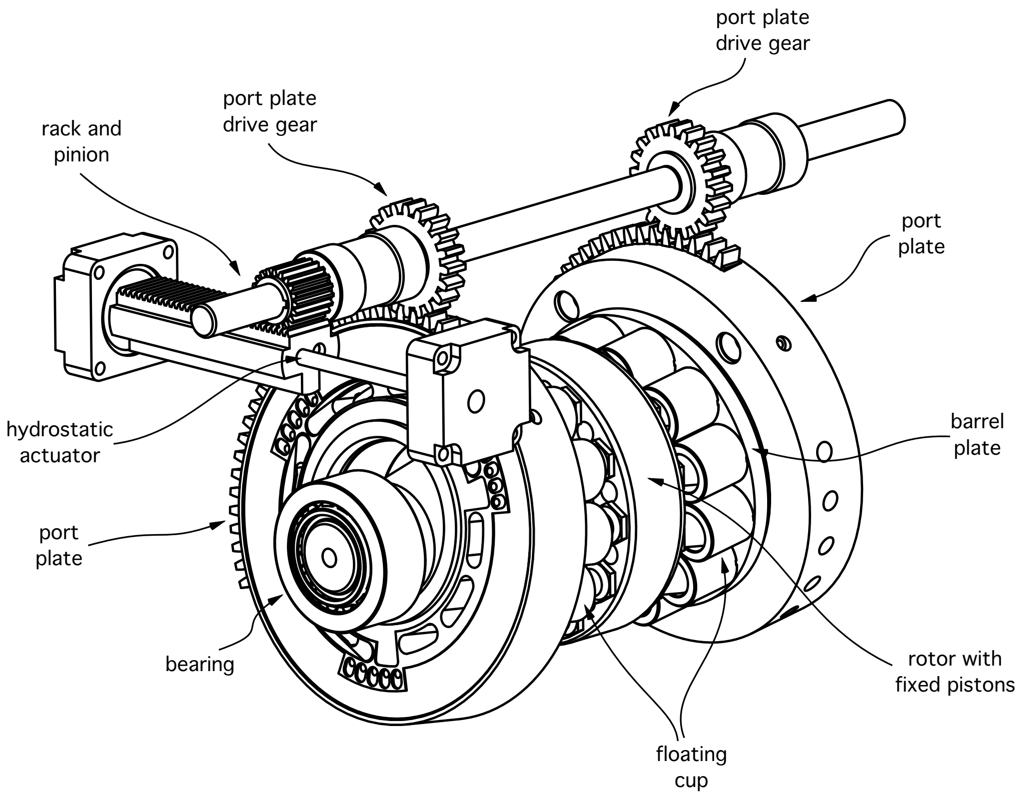

Figure 4: The Floating Cup displacement principle

The hole in the cup and the seal land around that hole are carefully tuned to give a resulting hydrostatic force that is large enough to press the cup down on the barrel plate. The cups are free to move over the barrel plate and this ‘floating’ motion provides the degree of freedom which allows the cups to follow the ellipsoidal track which is the projection of the piston circle on the barrel. In each cup a hollow clamping plug ensures that the cups do not break out or lift off at high rotational speeds and low internal pressures. The barrel plates are connected to the axle by means of a spherical joint. In each joint, two simple synchronizing pins force the barrel plate to rotate synchronously with the axle.

The number of 24 pistons was chosen after a thorough analysis of output flow pulsations, pressure pulsation in the displacement volumes and the start up and low speed behaviour of the IHT. These important characteristics of the IHT are greatly improved relative to an IHT based on a 7 piston bent axis or a 9 piston slipper type unit. This illustrates that building IHTs as slightly adapted axial piston units was useful to research and prove the base IHT concept but to open up the full potential of the IHT, a dedicated design was necessary. It is beyond the scope of this paper to go deeper into that subject. More can be found in for instance /4/ and /5/.

4 The Mecalac Platform.

Within the IBIS project, the HT technology will be implemented in a multi functional mobile excavator of the Mecalac brand. Mecalac machines are designed and built to be versatile rather than specialised and they are aimed at markets where this versatility is an important asset. A typical Mecalac could be used for digging and pipe laying operations on one day, for road construction and levelling on the next and to provide logistic support at a building site on the day after that. This requires the machine to dig, to load and to handle, without sacrificing too much of the efficiency in each of these modes of operation, to the ability to perform in all of them.

In order to realise these conflicting demands, all Mecalac vehicles use the same typical working arm kinematics. The working arm consists of four main segments: boom, second boom, arm and bucket. Each part is actuated by one cylinder. An extra degree of freedom is available through an out-of-plane joint in the second boom. With this, the plane through this part of the second boom, the arm and the bucket can be off-set with respect to the plane through boom and the remaining part of the second boom.

The working arm kinematics can be seen in **figure 5**. It shows the patented parallelogram construction that Mecalac has used for the boom cylinder up till now, next to the recently introduced, new construction with two smaller cylinder acting directly on the boom segment.

For continuous control of the four main working arm cylinders and the auxiliary function, three joystick axes and one pedal are available. Like in a conventional excavator,

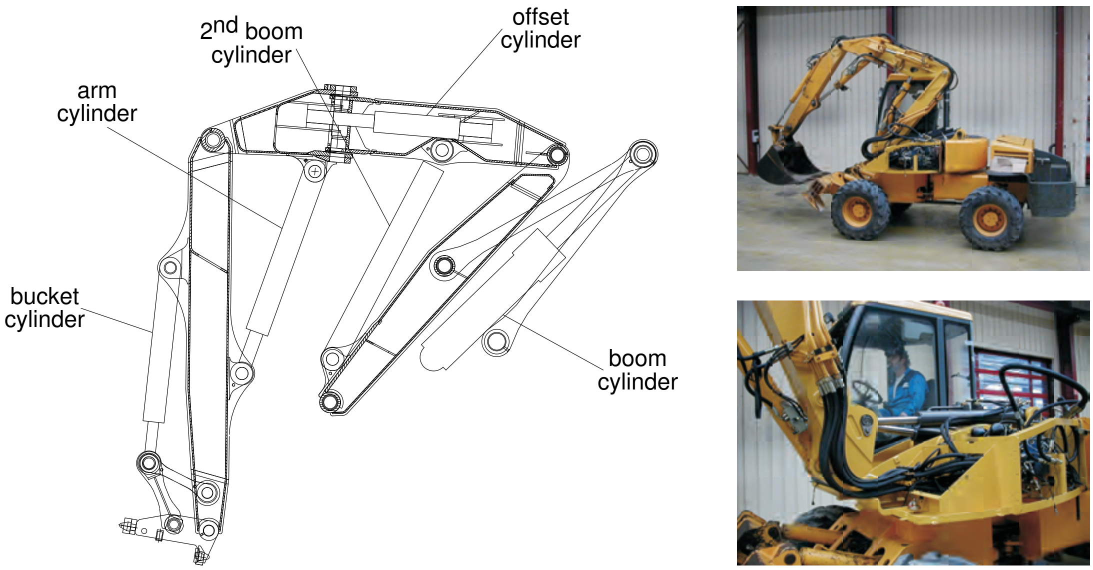

Figure 5: The Mecalac working arm, and the new boom cylinders

the fourth joystick axis is reserved for the rotational movement of the vehicle's superstructure. Mecalac solves the discrepancy between the available number of controlling elements (4) and the number of functions that need control (5), by offering four different 'modes of operation' that can be pre-selected by the operator. In each 'mode' different controls are assigned to different axes, in order to give the easiest set-up for the task at hand.

In 'excavator' mode, for instance, the left joy-stick's forward/backward signal results in synchronised movement of both the second boom and the arm. Apart from this 'excavator' mode, a 'loader' mode and – for the more experienced operator – two different 'Mecalac' modes are available.

In all modes but the 'excavator' mode, the operator can use a 'boom – second boom' switch while working, in order to change part of the functionality of the controls to a different cylinder.

In the current hydraulic system lay-out, the four modes and the choice between 'boom – second boom' functionality are realised by switching the pilot pressures from the three joy-stick axes and the pedal to the appropriate LS section. This is done in the so-called 'matrix' valve-block. For instance, when the 'excavator' mode is pre-selected, the valves in the matrix are switched in such a way that the pilot pressures from forward/backward axis of the left joy-stick are sent to the LS sections of both the second boom cylinder and the arm cylinder.

Apart from its typical working arm kinematics, the archetypal Mecalac vehicle is built in

such a way that it can operate in very close quarters. Hence the typical superstructure: the cabin and the working arm are combined into one compact unit which can turn on the turntable within a very small radius. The engine compartment is separate and fixed onto the rear side of the articulated chassis.
Currently Mecalac produces this vehicle type in four variants: the 10MSX (7 tonne), the 12MSX and the 12 MXT (both 9 tonne) and the 14 MBX (13 tonne).
Recently two new 13 tonne vehicle types were introduced. They also use the Mecalac working arm concept but combined with a more conventional excavator superstructure and a rigid undercarriage: the 714MW is a wheeled vehicle, the 714MC is a crawler vehicle.

5 The scope of the IHT technology in the IBIS project

In principle, the full energy saving potential of the CPR system type, can only be exploited if the total vehicle hydraulic system is changed to a CPR system. In the context of the IBIS project however, only the four main axes on the boom of a Mecalac excavator will be driven from a CPR. The swing function, the hydrostatic drive and a number of secondary functions will not be changed. The main reasons for this limitation in scope are the project's budget and time-frame, which do not allow for more then the working arm hydraulics to be tackled.

As the goal of this part of the IBIS project is to research and develop alternative actuator technologies, the fact that the CPR's energy saving potential is not fully exploited is not too important. The main issue for the Mecalac vehicle is the controllability of the main cylinders in the working arm and especially the effect the change to IHTs may have on the ease with which the arm control can be adapted to different circumstances, jobs or operators. To answer these questions, it is not necessary to change the total hydraulic system into a CPR system.

In order to be able to compare the performance of the current LS working arm hydraulics to the performance of the IHT based working arm hydraulics, a prototype will be built, in which both systems will be mounted in parallel. With a number of manual valves, the switch between the two system types can be made within a couple of minutes. In this way, the influence of the base vehicle, the driver, the job at hand and the environment will be neutralised and the operational qualities of both systems can be directly compared.

6 The local hydraulic circuit

There are several ways in which a cylinder can be connected to a CPR. The most interesting options have been treated in detail in /6/. The simplest solution presented there, is the one that is also shown in figure 1. In this lay-out, the annular side of each cylinder is always connected to the high pressure rail pressure. For the Mecalac prototype, this pressure is equal to the maximum pressure from the existing LS pump. The area difference between bottom and annular area of the cylinder, in combination with the amplification capability of the IHT, ensures that a net force in extending direction can be exerted. At the maximum practical pressure amplification ratio, however, this force would still be lower than the force that the conventional LS system can generate. In order to achieve the same extending force level the bottom side area should be increased. In a 13 tonne Mecalac, a 7 to 10% bigger bore would be required. This also adds weight to the boom structure and thus it reduces the maximum payload weight.
Another drawback of this solution can be explained with figure 3. As can be seen there, at port plate angles that give amplification, the relative output flow diminishes rather sharply. This implies that if the IHT's amplification capabilities are used, a larger IHT size has to be chosen in order to realise the required output flow.

For the Mecalac vehicle, the hydraulic lay out of **figure 6** was chosen. In this lay-out,

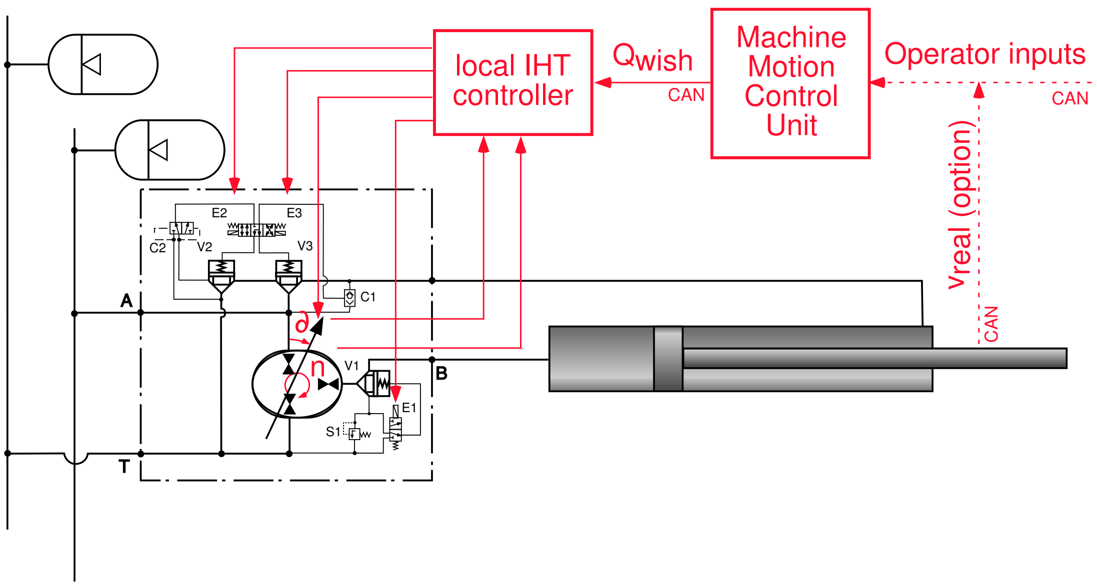

Figure 6: The local IHT circuit and the control concept

the cartridge valves V2 and V3 are used to switch the annular side of the cylinder to the high pressure rail when an inward force is necessary and to the low pressure rail

when a large extending force is required. In this way, the same cylinder forces can be generated as in the current LS system type without having to change the cylinders.
V2 and V3 also serve to prevent the cylinder from moving in extending direction when it is not actuated but subject to reaction forces that may result from the interaction of the vehicle with its surroundings. If solenoids E2 and E3 are not activated, valve C1 ensures that V2 and V3 are kept close by either the high rail pressure or the load pressure at the annular cylinder side, whichever is highest. In this way the system can meet the Mecalac requirement, that the lock-up pressure at the annular side must be able to rise to values up to 430 bar. At the bottom side, lock-up valve V1 prevents retracting movement of this cylinder under reaction forces in that direction.
With these lock-up valves on both sides of the cylinder, the cylinder can also be secured from lowering under a gravity load, even when left unattended and unpowered. This safety functionality is required by the largest part of the Mecalac customers.

7 The local IHT controller

As can be seen in figure 3, setting the port plate angle δ will result in a corresponding load pressure level p_B. In the Mecalac, as in any excavator, the operator's task is to synchronise the movements of the different sections of the arm. Therefore he needs stick positions to correspond with cylinder speeds rather then cylinder forces. In order to achieve this, every IHT will get a local speed controller. This controller continuously senses the port plate angle and the speed of the rotary group. With this information it calculates the actual output flow from the IHT, and compares this to the desired flow signal which originates from the Machine Motion Control Unit. Through the port plate actuator, it takes the necessary corrective actions. Apart from this fast, continuous control task, the local controller also switches the cartridge valves V1, V2 and V3, as and when necessary. Essentially, this is an event driven control process.

8 The Machine Motion Control Unit.

The Machine Motion Control Unit (MMCU) determines the desired flows for each local IHT controller and sends these over the CAN bus to them. Input for the MMCU are the positions of the operator's controls (three joy-stick axes, a foot pedal and the 'boom – second boom ' switch) and the desired vehicle mode he has pre-selected. All these signals reach the vehicle motion controller over a CAN bus.

If the MMCU would only convey the operator's input signals to the appropriate local

IHT controller, it would be a digital replacement of the matrix block rather than a‘control unit’. However, with all in- and output signal in digital form, extra functionality can be introduced in a very flexible way. So far, the following requirements and possible additions for the MMCU have been set:

- First of all, of course, the MMCU must be that digital replacement of the matrix block. In addition to that, it can also provide more or personalised ‘modes’.
- The MMCU must provide an adjustable ‘fine’ mode. In this mode, the desired flow signals to the local IHT controllers will be reduced, in order to give the operator the full stick range for a reduced cylinder response, enabling him to do precise work more easily. With the MMCU, the reduction can be made adjustable, by the driver or by a service department.
- With the addition of some angle sensors, the MMCU must provide the ‘easy-drive’ function that is available as an option on the current Mecalac vehicles. This function ensures that the bucket or fork is kept at a constant orientation to the vehicle, independent of the movement of other working arm sections. This is a real closed loop control, which is currently realised through the pilot circuit of the LS system. With the IHT based system, the control loop is much more direct and can be adjusted and fine-tuned more easily.
- When angle sensors have been introduced because of the ‘easy-drive’ option, they will be used to increase the vehicles functionality further. Electronic cylinder cushioning will be introduced, giving a soft stop at the end of the cylinder stroke.
- With the angle sensors, also the actual cylinder speeds are known and thus the MMCU can compare them with the desired speeds, communicated to the local IHT controllers as desired flows. If there is a difference, the MMCU can correct the desired flow in order to reach a very precise control.
- With angle sensors, in addition to the ‘easy-drive’ function, still more automated or teach-in motion control tasks can be introduced.

The split-up over a fast local control and a slower Machine Motion Control motion control has the advantage that it is not necessary to close the fast IHT control loop over the CAN bus. The fast loop is closed locally in the dedicated IHT controller. With this set-up, it is also relatively easy to respond safely to a possible failure of the vehicle motion controller: if detected, the system can be switched in such a way that the local controllers react directly to the CAN signals from the driver controls and interpret those as a required flow input. This would give a system response that resembles the response of the current LS system and with that, the vehicle can be safely brought down or it can even be used further until service of the vehicle motion controller is possible.

9 Conclusion

With the change of the main boom functions of the Mecalac vehicle to IHT technology, and with the associated motion control concept, the flexibility of the Machine will already be increased when no boom angle sensors are present. When also angle sensors are added to the system, a host of extra functionality will become available. Not all possible control functionality may be offered in the market right away but IHT technology will open up a host of new possibilities for the OEM to design machines that can be tuned to the customer's wishes, without changes in the hydraulic hardware.
The FC IHT technology is still very young. If it performs as expected and predicted, the IBIS project will show that the IHT technology is a hughe improvement compared to the current LS technology.

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