Experimental Evaluation of the New Meter Out Sensing Architecture

Marani Pietro*, Massimo Milani**, Davide Mesturini*** and Ulderico Busani***

C.N.R.-IMAMOTER, Via Canalbianco 28, 44124 Cassana, (FE), Italy*
Department of Sciences and Methods for Engineering, University of Modena and Reggio Emilia,
Via Amendola 2 - Pad. Morselli42122 Reggio Emilia, Italy**
Walvoil S.p.A, Interpump Group, Via Adige 13/D - 42124 Reggio Emilia – Italy
E-Mail: p.marani@imamoter.cnr.it

This paper presents the experimental assessment of the very first prototype of Meter Out Sensing System architecture. The system, based on the proportional control of meter out valves, is a novel hydraulic architecture in the field of Mobile Machines. The objective of the hydraulic control is obtained firstly by a negative control of the supply system, adjusting the pressure drop on the meter out to a given value, secondly by a three way compensator able to regenerate the flow. The energy saving is then obtained because of lower throttle losses on meter in connection and the regeneration feature that is enabled hydraulically under specific operating condition.

Keywords: Regeneration, Meter Out Control, Energy Saving, Proportional Hydraulic Controls,
Target audience: Mobile Hydraulics, Proportional Valves, Hydraulic Architecture Design

1 Introduction

Looking at the Mobile Machines Currently in production, two hydraulic control architectures dominate the market: Open Centre and Load Sensing. In the field of open circuits the Independent Metering architecture is as well available but with low market share, until now.

The Open Centre architectures are less user friendly than LS because they are not locally compensated, thus the flow rate depends on the load, especially in case of multiple actuations, even if nowadays their energy management is enhanced through variable displacement pumps use (Negative, Positive Control /1/),.

In spite of a big share of the Off Road Machines Market, Load Sensing (LS) systems /2/ are often criticized for their energy efficiency, in particular pointing out at the compensation mechanism that equalizes the difference in pressure loads (interference) through throttling losses, then it clearly follows that high energy waste and heat generation occur in case of high pressure unbalance between simultaneous actuators /3, 4/. Moreover, LS systems don't allow energy recuperation nor regeneration, since they are based on a meter-in control. High overrunning loads, in fact, can only be controlled by means of additional throttling elements such as overcenter valves.

On the other hand the Independent Metering (IM) Systems /5/ represent a step forward in the state of the art: first of all IM are able to manage regeneration functions basing on electronic sensors feedback and secondly they optimize the throttle losses to minimize parasitic losses. Going more into detail, in case of multiple actuation, the flow area of proportional valves is adjusted to compensate the interference with a real time control of the position of the spool according to measured pressure drops and spool area map. Then, one can conclude that if the parasitic losses are neglected, IM systems introduce the same theoretic throttle loss of the conventional closed centre systems, including LS systems.

However the Independent Metering System are limited to quite few applications on the market with respect to competitor architectures /5/. One reason for this fact is the complex control requirements, in fact accurate spool position control is required and, moreover, complex electronic strategies command the shifting between different operating modes. Furthermore, additional expenses regarding components such as high performance valves and transducers have to be taken into account.

MOS system aims at overcoming the drawbacks of open circuit systems at state of the art. The system in fact offers a control in which the flow rate is proportional to Meter Out Area, without additional motion control valves to manage overrunning load. The MOS system can manage positive and negative loads and implement regeneration with fully hydraulic controls, this means that sensors and complex electronic controls are not required, moreover costly high precision / high dynamic valves are not mandatory.

In /6/ the system was simulated showing the capability to provide proportional flow control to actuators according to the metering area of the inherent spool valve, for single or multiple actuation such as in Load Sensing systems. The Flow Rate obtained for given control area is approximately the same in both overrunning and resisting loads (even in regeneration), with a big energy saving potential demonstrated with proper energy figures of merit.

In /7/ the system was described more into detail from the mathematical point of view and additional results of the multiple actuation were displayed, showing the feature of compensation and of flow regeneration that can be achieved even from one section to another.

2 The Meter Out Sensing Architecture and Operating Principles

The Architecture and Operating Principles are explained into detail in /6,7/ but for the sake of comprehension the architecture and the operating principle will be briefly summarized

2.1 Architecture

The architecture can be explained referring to figure 1. In first place it is important to understand the supply system consisting of a variable displacement pump controlled by a pump compensator according to the pressure on the pilot system connected to the actuators.

The Meter Out Sensing signal line 3, is supplied by a two way flow control valve 7 and it is sensing the lower among all working ports signal through the check valves connected to actuators ports

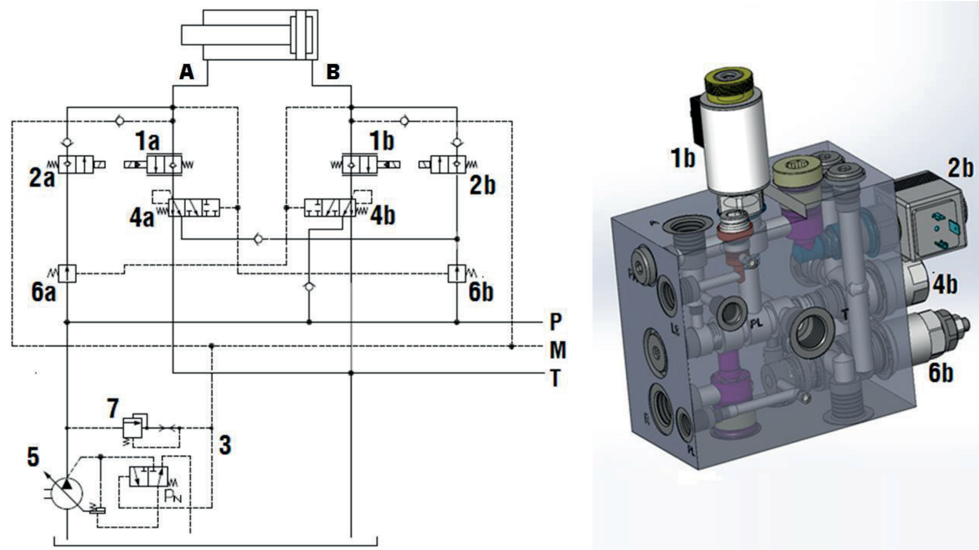

Figure 1: Meter Out Sensing System.

In case of resisting loads, by convention positive, the Metering Out Sensing line pressure is related to the flow rate through meter out edge of the higher load section through turbulent flow equation, if it the signal higher than a given Pressure Margin the pump will decrease the displacement, if it is lower it will swash out according to the compensator setting “p_N”. In case of overrunning loads the Meter Out Sensing line will adjust to pressure of inlet of actuator at least at the compensator setting “p_N”, avoiding cavitation.

Each section includes two proportional valves (1a, 1b), commanded one at a time, simultaneously activating the opposite side ON–OFF inlet valve (2b, 2a). The speed of actuator is proportional to metering area of metering out valve according to turbulent efflux equation in both positive negative/ regenerative load condition thanks to 3 way compensator.

The 3 way compensator (4a, 4b), in case of multiple actuation, is able to set the correct pressure margin to all active sections, but it also provides important additional features. In fact the system controls overrunning loads without additional motion control valve, moreover the architecture automatically enables the regeneration if the load is overrunning, reducing the flow supplied by the pump thus reducing energy consumption.

The Indirect Pressure Reducer (6a, 6b) is a normally open valve placed on inlet line of actuators and indirectly controlling the pressure at opposite side. The valve is useful to avoid the pressure multiplication effect in regeneration or in presence of simultaneous opposite loads.

The distributor architecture was implemented into two prototype hydraulic blocks including the control valves listed before. Looking at the supply system, the prototype of the pump is still not available then an alternative supply system was implemented with the same control logic for the test bench.

2.2 Operating Principles

In the following paragraphs the Operating Principles of a Single Section in Power Extension, of a Section in Power Extension Compensating and of a Single Section in Overrunning Extension are considered.

The first case is those of the Power Extension Mode, in case we have a single section actuation (or the section is controlling the maximum among the loads). The pump regulates the flow rate according to the pressure on rod side p_B to the pump compensator setting. The 3 way compensator 4a is near to saturated open position and the proportional valve 1a is subjected to the pressure drop p_N, then the flow rate across valve 1a depends only from the flow area obtained for a particular spool position.

The second case is those of Power Extension Mode, in case we have another section controlling an higher load, then considering the compensation. In this case the supply pressure sets according to the maximum load in the system and supplies directly the actuators. The interference on the compensated section is controlled by the 3 way compensator 4a to keep a constant pressure drop across valve 1a (achieving a compensated proportional control), then the pressure on port B will increase accordingly.

In Overrunning Retraction Mode the Load is controlled by the three way compensator 4b, controlling the pressure drop across 1b by regenerating from base side to rod side and discharging the excess to tank. The pressure on both sides of actuator will be more than the setting p_N, thus the pump will decrease the displacement towards zero. Also in the third case a compensated flow control is achieved.

The energy saving is then obtained because of lower throttle losses on meter in connection and the regeneration feature that is enabled hydraulically if the load is overrunning or under specific operating condition including high load pressure difference between different actuators (interference).

It is important to recall that in each work condition (resisting load, overrunning load,) or operating mode (compensation, regeneration) the flow rate is kept proportional to the area proportionally controlled by meter out valve.

3 Testing of the MOS System

In this paragraph the Test Rig will be discussed. The Test Rig is powered by a 37 kW Electric Motor moving a variable displacement pump coupled to a Load Sensing proportional valve, then the system is capable to work at constant flow rate. The Coupling of LS pump and distributor basically works like an ideal fixed displacement pump at constant speed. For the sake of simplicity the Supply Group (Pump + Distributor) is represented as a fixed displacement pump in the following scheme. The test bench has a Lift Arm to simulate a cycle in a real mobile machine and to create a proper load on the hydraulic blocks mounted on the bench. The Lift Arm can be loaded with variable ballast until 2 ton. The MOS hydraulic system is supplied at constant flow rate by the test rig supply group and feeds the lifting boom of the bench.

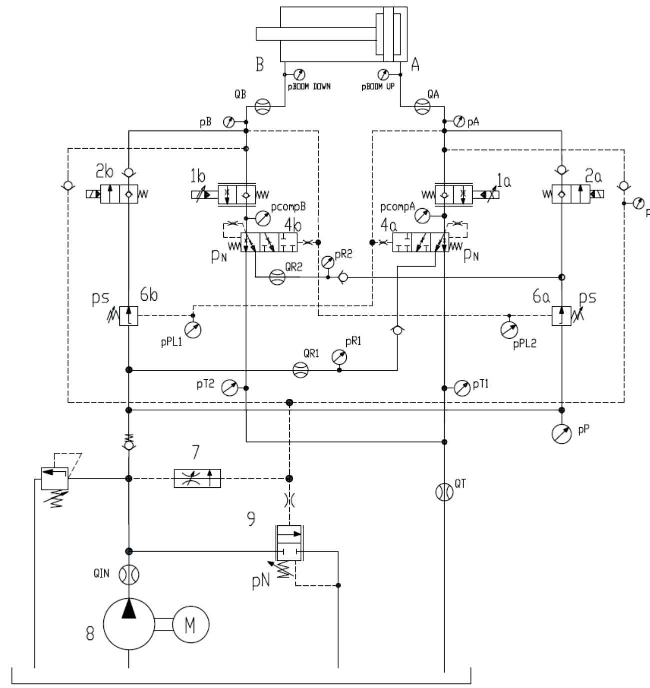

Figure 2: Test Bench Layout

Since the prototype of variable displacement pump with proper control (see figure 1, part 5) is still not available, the tests were carried out with a Constant Flow Supply (Fixed Pump 8 and Flow Compensator 9). In next lines it will be made more clear that this alternative system is equivalent to a variable displacement pump from the point of view of functionality of hydraulic block, even if it is clearly worse from the energy point of view. The hydraulic block can then be tested in all its functionalities while the complete system will be tested when the MOS pump prototype will be available.

Comparing the operating principles of the Test Rig Supply System (element 8 and 9 fig 2) to the variable displacement pump (7 in figure 1) it can be seen that the pump adjusts its displacement according to the pilot pressure signal, thanks to a pump compensator. The metering out sensing pressure is compared to a fixed setting “p_N” (Pressure Margin) just as flow compensator 9 adjusts its position according to the balance between the metering out sensing line and the valve spring set to p_N value.

If the pilot pressure is greater than the setting, the displacement of the variable pump 7 is decreased, conversely valve 9 discharges excess flow. On the other hand , if the signal is lower than “p_N”, the pump swashes out, increasing the displacement and the valve 9 closes increasing the flow to MOS hydraulic blocks. The result of the working principles is the adjustment of a constant pressure margin on the meter-out edge, like an LS systems controls the pressure drop on the a meter-in edges.

Physical variable	Designation	Sensor type	Measurement Range	Overall precision
Volumetric flow rate	QT	Gear flow meter	0,1 ÷ 120 lpm	±0,3% reading
Volumetric flow rate	QA	Gear flow meter	1 ÷ 250 lpm	±0,3% reading
Volumetric flow rate	QB	Gear flow meter	1 ÷ 250 lpm	±0,3% reading
Volumetric flow rate	QR1	Gear flow meter	0,1 ÷ 120 lpm	±0,3% reading
Volumetric flow rate	QR2	Gear flow meter	0,1 ÷ 120 lpm	±0,3% reading
Volumetric flow rate	Qin	Gear flow meter	0,1 ÷ 120 lpm	±0,3% reading
Gauge pressure	pP	Thin film press. transd.	0 ÷ 600 bar	±0,3% Full Scale
Gauge pressure	PNS	Thin film press. transd.	0 ÷ 600 bar	±0,3% Full Scale
Gauge pressure	pA	Thin film press. transd.	0 ÷ 600 bar	±0,3% Full Scale
Gauge pressure	pBoomdown	Thin film press. transd.	0 ÷ 600 bar	±0,3% Full Scale
Gauge pressure	pR1	Thin film press. transd.	0 ÷ 600 bar	±0,3% Full Scale
Gauge pressure	pC1	Thin film press. transd.	0 ÷ 600 bar	±0,3% Full Scale
Gauge pressure	pCompA	Thin film press. transd.	0 ÷ 600 bar	±0,3% Full Scale
Gauge pressure	pT1	Thin film press. transd.	0 ÷ 600 bar	±0,3% Full Scale
Gauge pressure	pB	Thin film press. transd.	0 ÷ 600 bar	±0,3% Full Scale
Gauge pressure	pPL1	Thin film press. transd.	0 ÷ 600 bar	±0,3% Full Scale
Gauge pressure	pCompB	Thin film press. transd.	0 ÷ 600 bar	±0,3% Full Scale
Gauge pressure	pBoomup	Thin film press. transd.	0 ÷ 600 bar	±0,3% Full Scale
Gauge pressure	pT2	Thin film press. transd.	0 ÷ 60 bar	±0,3% Full Scale
Cylinder stroke	Boom_str	Magnetostrictive	0 ÷ 605 mm	±0,4% Full Scale
Cylinder stroke	Bucket_str	Magnetostrictive	0 ÷ 595 mm	±0,4% Full Scale
Current	Iprop	High curr. analog input	0 ÷ 3 A	±0,1% Full Scale
Current	IEC	High curr. analog input	0 ÷ 3 A	±0,1% Full Scale

Table 1: List of Sensors Acquired

The operation of lifting and lowering in this first test is done manually by an human operator, controlling an electronic joystick piloting the electronic valves. The currents controlling the valves are measured to acquire the operator's command. After this early stage an automatic electronic command will be implemented to ensure better repeatability of the tests.

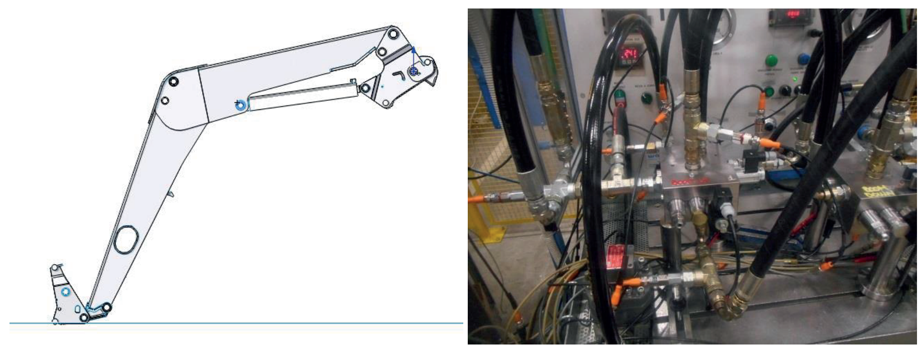

Figure 3: Left Lifting Arm CAD model, Right MOS hydraulic block on Bench,

From figure 2, representing the hydraulic test rig with sensors, it can be noted that a great number of measurement points are available in order to obtain a complete characterization of the system. Table 1 reports a complete list of the sensors mounted on the test rig and simultaneously acquired at 1kHz frequency.

4 Experimental Testing Results

Some samples of the testing results are displayed and commented in this section. Even though the activity of testing and optimization is still ongoing, some interesting evaluations can be done from this first results.

4.1 Power Extension Compensation Test

The Power Extension Compensation Test was carried out at constant supply pressure, this condition simulates the operation of an additional section at constant pressure. This condition assesses the flow control through the proportional meter out valve through the proper operation of the 3 way compensator in compensation mode.

The test is carried out with the load at the minimum height, then the proportional valve 1a is gradually opened causing the lifting of the ballast. The supply pressure is connected directly to A port of Actuator (via ON-OFF valve 2b) and since the supply pressure is higher than the load pressure, the pressure must be increased on B port of the actuator to compensate any load difference (interference of loads). The purpose of the compensation is to have a constant pressure drop between B port and the measurement point PCompB (fig. 2) in order to have a proper control of the flow through proportional valve 1a.

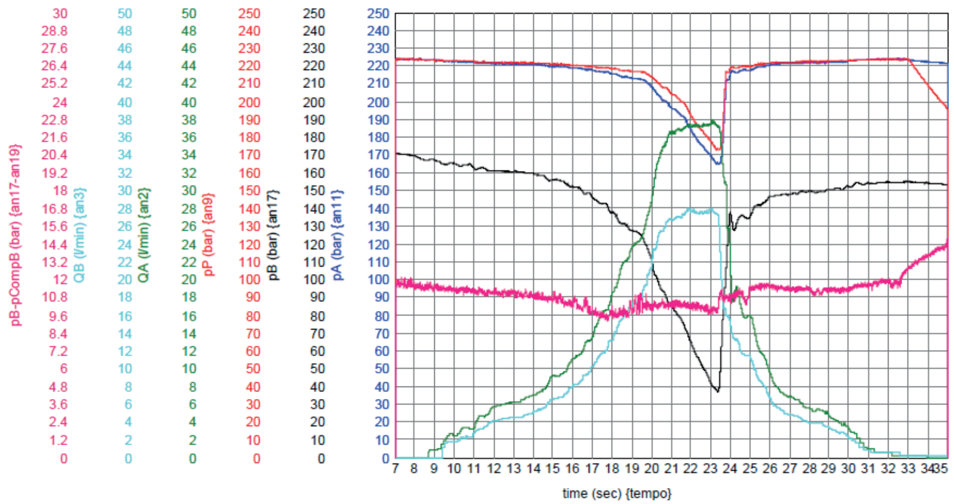

Figure 4: Power Extension- High Load (1000 kg Ballast).

Figure 4 Shows the results of a Power Extension Test with Compensation and high load, more specifically, the boom lifts a ballast of 1000 kg. The pressure is kept at about 225 bar at the beginning of the test via pressure relief valve. This test represents the condition of a load on another section of an hydraulic sectional distributor.

In the starting phase (11-21s) the proportional valve on B side (1a on figure 2) is gradually opened, the flow increases on A side (Green Line) and conversely on B side (Light Blue Line), the compensator on B line keeps the pressure drop on B side at almost constant value (Purple Line) at 10-12 bar of pressure margin.

Then, increasing the opening of the valve the flow saturation is reached and the supply pressure decreases sharply (21-23.5s). In the phase from 23.5s to 34s the opening of the valve is decreased and at second 24 the system exits from flow saturation condition and the supply system is able to keep the nominal pressure, in this phase QA and QB decreases until complete closing position of the valve.

With this test the feature of compensation is confirmed, it is possible to note a slight variation of the pressure drop across the proportional valve that can be in general found in the most common load sensing locally compensated systems as well.

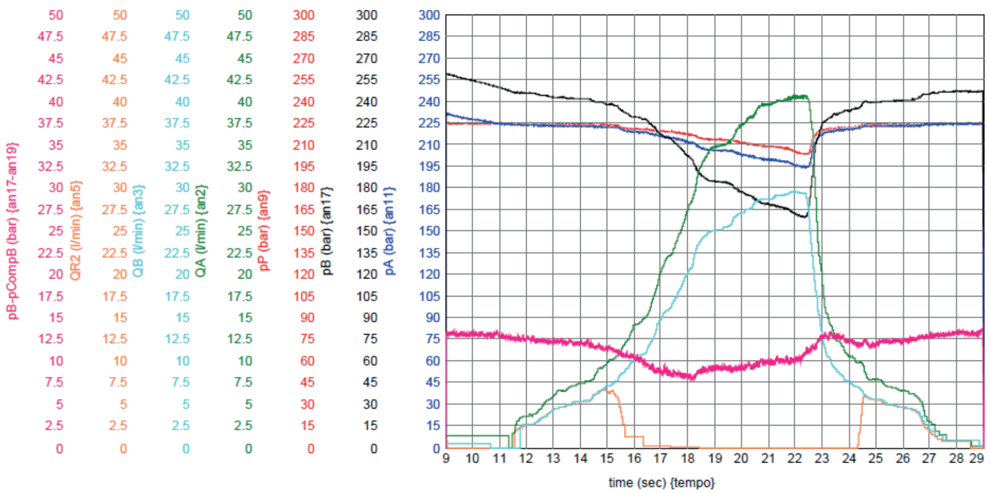

Figure 5: Power Extension- Low Load (0 kg Ballast).

Figure 5 Shows the results of a Power Extension Test with Compensation and low load. The Boom Lifts an empty ballast container, then the load is represented by the mass of the lifting machine itself. The pressure is kept at about 225 bar, as in previous case, representing the condition of a high load on another section.

It can be noted that, similarly to the previous case, the compensator on B side increase the pressure on port B to compensate the load difference between sections (the section under test and a second virtual section at 225 bar load). Because of area differential of cylinder the pressure on B side could be higher than those on A side, this condition is favourable to regeneration, even if the load is of the resisting type.

From 11s to 21s the proportional valve on rod side is gradually opened, the compensator 4a keeps the pressure drop across the valve almost constant increasing the pressure on B.

It can be noted that from 11s to 16.5s the pressure on B (pB, black line) is higher than in A (pA, blue line) then regeneration is obtained, to confirm that one can note that QB, light blue line equal to QR2, orange line. Then the flow rate from B port is discharged through regeneration line to A side (connected to supply), the difference flow rate (QA-QB) is integrated by the pump.

In subsequent phase (16.5-21s) all the flow rate to base side (QA, green line) is supplied by the pump with no regeneration because the rod side pressure (black line) drops under the base side pressure (blue line).

In the phase from 21 to 22.5 we can hypothesize flow saturation recognisably by the drop of supply pressure (pP, red line). Then we have a decrease of the flow rate according to proportional valve position (22.5-29s), at second 24.5 until the closure of the proportional valve regeneration is activated again in reason of the pressure difference between B and A, as in the beginning phase QB flows through regeneration line to A port, adding to the supply flow .

One can note that the flow rate supplied to the Base side in lifting operation is less than a conventional system, in particular the supply flow is decreased in the regeneration phase. The amount of energy saving obtained thanks to regeneration depends on the duration of regeneration phase.

4.2 Overrunning Retraction Test

The Overrunning retraction test is carried out with the load at the maximum height, then the proportional valve 1b is gradually opened causing the lowering of the ballast. In this test the system automatically sets to zero the flow rate from supply group and the fluid from A port divides in two flow rates: one to tank and the other supplying B port.

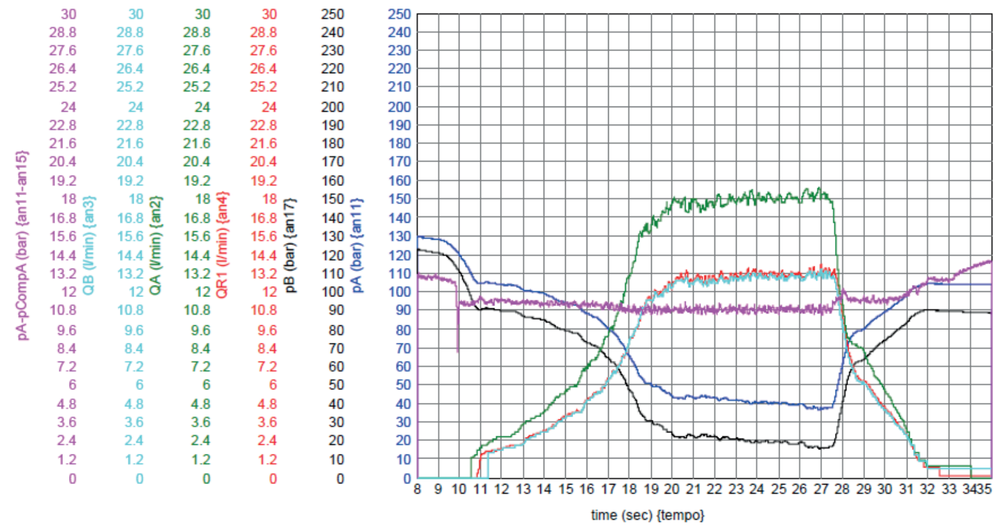

Figure 6: Overrunning Retraction Test - Low Load (0 kg Ballast).

Figure 6 Shows the results of an Overrunning Extension Test with low load. The Boom lowers an empty ballast container, then we have only the load of the lifting equipment.

The pressure generated in base side (pA) is able to feed rod side of the Boom (pB). Proportional valve 1b is gradually opened (and conversely the ON-OFF valve 2a on rod side) the flow rate is regenerated via compensator 4b, then the system reaches maximum opening and finally it gradually closes.

It can be noted that all of the flow to port B is regenerated then the flow rate at port B QB (green line) is equal to flow rate regenerated (QR1, red line), the rest of the flow outgoing from A port is discharged to tank. Another interesting point is that the pressure drop across the proportional valve 1b (purple line) is kept constant by the compensator.

From the flow rate balance it can be deduced that the flow rate introduced to the system by the supply group is zero, then in case of a system variable displacement pump the operation would be at zero energy expense. Finally it is important to recall that the movement of the cylinder is proportionally controlled by a compensated system, independently from the load.

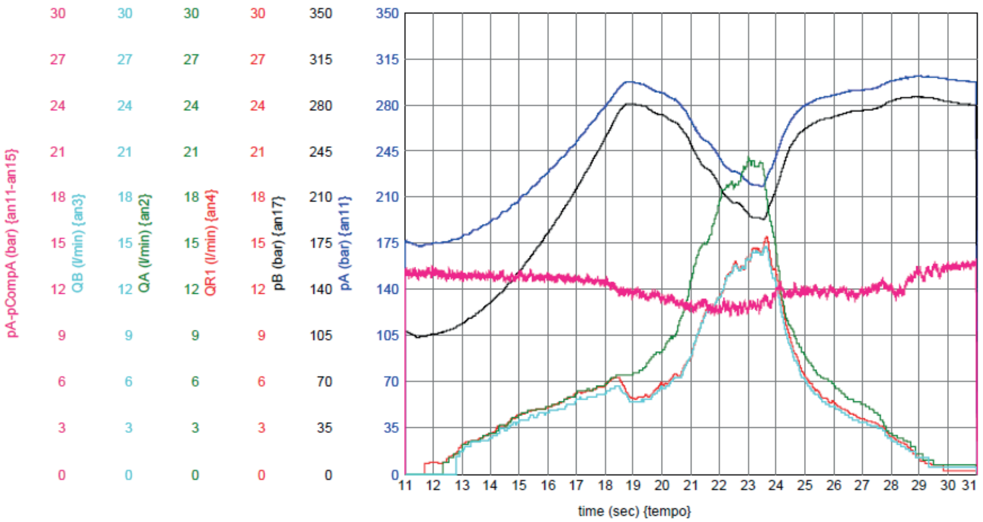

Figure 7: Overrunning Retraction Test - High Load (1000 kg Ballast).

Figure 7 Shows the results of an Overrunning Extension Test with high load. The Boom lowers a 1000 kg ballast container.

As in previous case the Proportional valve 1b is gradually opened and the valve 4b modulates both to Regeneration Line and Tank discharging the excess. Looking at pB black line and pA blue line from12-18s, it is possible to note that the connection of A side of Boom to B side cause an increase of pressure of the system.

Then the increasing opening causes a decrease of pressure on B side caused by the increase of pressure drops in the system for increasing flow rate (18-23.5s). Finally, the pressure increase (23.5-31) with the decreasing of flow rate from A to B for the above mentioned reason.

The first thing to note is that the pressure drop across the proportional valve 1b (purple line) is almost constant because of the compensator, moreover as mentioned before the flow rate introduced by the supply line is zero because the flow rate to B port is equal to Regenerated Flow (QR1). In this case we would have zero energy expense in case of system with variable displacement pump, but it can be further hypothesized that if we have an additional section activated the excess flow discharged at high pressure from base side side of actuator will be able to feed the second actuator with consequent energy saving.

Another aspect to note is that the pressure could rise above safe levels in regeneration , for this reason the valve 6a is implemented, reducing the pressure in B side to keep A side below the maximum permissible pressure. In the test shown above (fig. 7) the valve 6a is kept mechanically opened so the pressure could theoretically rise indefinitely.

In next test shown (fig. 8) it can be seen that properly setting the valve 6b, the system is able to reduce the pressure on rod side indirectly regulating the pressure on base side. In this test, similar to the previous one with regard to load and operator's command, it can be seen the effect of indirect reducer 6a. Without going into detail of all the plots, since the results are similar to previous, it is possible to note the limitation of pressure on A side (blue line) caused by the effect of the reducer 6a on line B (black line).

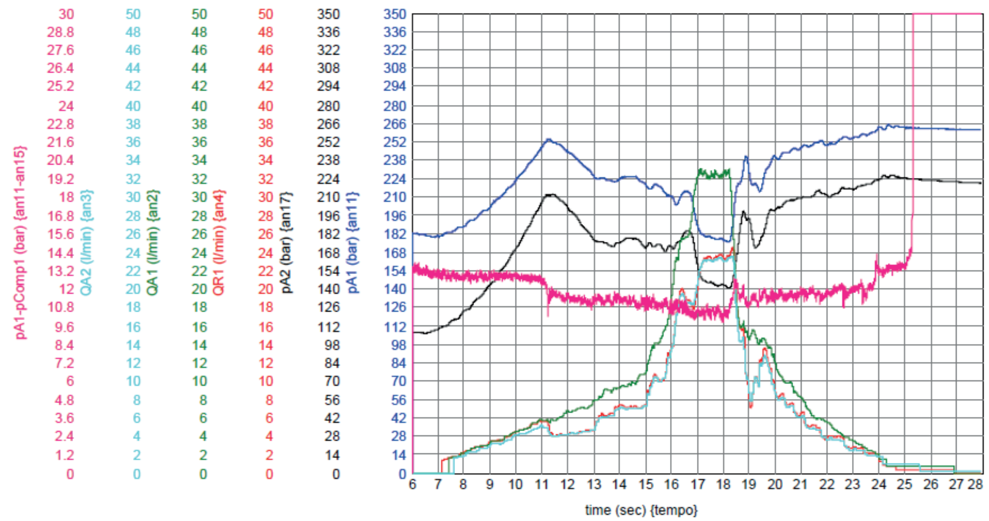

Figure 8: Overrunning Retraction Test - High Load (1000 kg Ballast), with indirect pressure reducer activated

The Flow Rate Plots indicate the equivalence of Flow rate to Rod Side (QB, light blue line) to Regeneration Flow (QR1, red line) and a proper control of the pressure drop on the meter out proportional valve (purple line). So it is verified that even in this case the proper control (correct pressure drop) is achieved and the energy saving can be obtained (regeneration is activated).

5 Summary and Conclusion

The paper has presented the results of the first tests on Meter Out Sensing System. In the introductory part the characteristics of the architecture were briefly summarized.

The operating principle of Meter Out System is based on the meter-out edge control instead of the meter-in edge control of conventional systems; the supply group is able to set the flow rate in the system according to the minimum pressure among all the operating actuators, a 3 way compensator valve is able to control the interference between loads and to activate the regeneration according to the operating conditions.

The MOS System aims at improving the energy management with respect to Load Sensing Systems for the low throttle losses on the supply line of actuators and for the absence of motion control valves. Moreover the regeneration feature reduces the power demand from the pump.

Comparing to Independent Metering Systems, the MOS system can manage positive and negative loads and implement regeneration as well, but in more cost effective implementation, because sensors, electronic controls and high precision / high dynamic valves are not mandatory.

The results of the test carried out at Walvoil Testing Department has assessed some important features of the system.

Power Extension Compensation Tests have shown that the prototype hydraulic block is able to control resisting loads and to perform compensation, the pressure drop across the proportional valve is therefore constant, thus the system can work properly in Multiple Actuator Operation. For high load interference it is possible to obtaining regeneration through the compensation.

Overrunning Retraction Test highlight the feature of regeneration, a gravity load is controlled through the compensator, regenerating the flow from the rod side of the cylinder to the Base Side, in this case the necessary flow is regenerated without any contribution from the supply group. The overrunning operations shows potential for energy savings because in the conventional systems these operations are often performed with the aid of overcenter valves working at the expense of the supply group.

The paper has shown are the first available results, however the development of the system is still ongoing, additional test are necessary to further assess and optimize the MOS system.

The Lumped Parameters Models /6,7/, not shown in this paper but still in progress, will be compared to the test results and improved as well. These Models will be further used in the subsequent phase of optimization of the system. Finally an important task towards implementation on a Mobile Machine will be that of designing, testing and optimizing a variable displacement pump with proper hydraulic control to be coupled with the MOS hydraulic blocks.

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