Hydraulic Multi-Chamber Cylinders in Construction Machinery

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Summary
In mobile hydraulics double acting, two chamber, asymmetrical hydraulic cylinders are commonly used for linear motion control. This paper shows how a cylinder instead using four chambers can improve fuel efficiency in construction machinery. In addition to this special multi-chamber cylinder the hydraulic systems presented in this study involves the use of discretely controlled on/off valves, hydraulic accumulators and secondary controlled hydraulic motors. The proposed system solution supports potential and kinetic energy recovery and storage using hydraulic accumulators. Through proper sizing of components and sophisticated control of simple on/off valves an energy efficient, flexible and robust system is achieved. This paper outlines the basics behind this concept and provides some examples as to how the technology can be useful with an ambition to reach new levels of energy efficiency in construction machines.

Keywords: Secondary control, Digital hydraulics, Multi-chamber cylinder
1 Background

During the last couple of years electrification of vehicles and machines has been a huge trend across the world. In the automotive segment this primarily concerns the introduction of electrical components as part of the mechanical driveline. However, in construction machines there are most often also other motion control systems in addition to the driveline. Hence, when applying an electric drive system to these machines it will still have to include some degree of hydraulics to be compatible with the required hydraulic cylinders. Considering this background, an alternative to the electrification is to consider hybridization through hydraulics instead. In this paper a special type of hydraulic cylinder together with logical valves are key components in the design of a highly efficient hydraulic hybrid system.

1.1 Secondary Controlled Hydraulics

So called secondary control systems (SCS) are sometimes suggested as a promising solution for throttle-free motion control. Secondary control as a research topic has its origins in the early ’80s [1]. However, also in much more recent publications this technology has demonstrated promising results both in theory and in practice [2–4].

One way of distinguishing secondary control systems from other hydraulic systems is to look at which component in the system mainly deals with the desired input-output transformation. In a secondary control system, the control is said to be moved closer to the load side [5]. Rather than modulating the mechanic to hydraulic transformation on the supply side of the system, modulation takes place at the load side. The relative displacement of a variable motor driving a rotational load will for instance control the relation between pressure and torque.

In a SCS the hydraulic capacitance is usually greater than that of a comparable conventional system. The additional capacitance of an SCS yields means of storing energy inside the hydraulic system. It also results in the notion of a ‘pressure coupling’ between the supply and load side rather than a ‘flow coupling’. The pressure coupling takes place in a so-called common pressure rail (CPR) to which flow is provided by the supply side. At the load side, flow is either consumed or supplied back (recuperation). The capacitance connected to the CPR determines how much the rail pressure will fluctuate given a disturbance in the flow equilibrium. Depending on system layout, the CPR pressure level could be allowed to vary or be kept at some ‘quasi-static’ level. By nature, SCS are ideally suited for rotary loads, using displacement control. However, in applying this technology to construction machines, there is clearly a need for solutions to how linear-mechanic actuators should be controlled without excessive throttling losses as a result.

As is well known, the force produced by a hydraulic cylinder is the product of cylinder area and the pressure. If continuous variable force control is required, one way is to ‘throttle down’ the pressure level from the CPR to the load pressure, but this would lead to excessive power losses. A ‘throttle-free’ solution would be to use a so called hydraulic transformer where pressure and flow are transformed across the mechanical domain. This is normally achieved by using two hydraulic machines mounted on a common shaft, where one or both machines have a variable displacement to allow control of the transformation ratio. However, due to its bulkiness, its rather poor efficiencies and its high cost, this hydraulic transformer concept never found applications beyond some niche markets. In more recent research an improved hydro-mechanical transformer was developed by the Dutch innovation company Innas BV [6]. Lately, several studies have demonstrated how this technology applies to construction machinery with the purpose of reducing fuel consumption [7–9].

So, a hydraulic transformer can obviously be used to adapt the CPR pressure level to the pressure required by a certain load force, acting on a fix cylinder area. In theory another solution to the problem would be to adjust the cylinder area. Even though a practical solution to a continuously variable cylinder area is yet to be seen, solutions to achieve this in a step-wise manner already exist today. Such a solution is the main focus of this article.

2 Variable Displacement Linear Actuators

In 2009, a study [10] was presented on secondary controlled linear actuators based on ‘multi-chamber cylinders’ and discrete control of ‘digital valves’. The article presents measurements from a test rig equipped with a custom-made 4-chamber cylinder powered by two pressure levels and a large number of on-off valves. Since then, the development of this technique has evolved and Fig. [1] shows a recent design, made by the Finnish cylinder manufacturer, Norrhy-
Hydraulikdagarna, Linköping, Sweden, 16-17 March 2015

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Fig. 1: VDLA from Norrhydro Oy based on a 4-chamber cylinder, on/off valve manifold and electric I/O-control unit.

Fig. 2: The two CPR pressure levels combined with four cylinder areas yields 16 discrete output forces ($F_{cyl}$).

3 Hybrid Construction Machinery

This section outlines how secondary controlled hydraulic systems and VDLA fits into the design of efficient hybrid construction machinery.

3.1 System decoupling

For many construction machines the power required by individual actuators is very transient and the combustion engine is often forced to work in non-optimal working points. For instance, in a typical excavator truck loading application the average load power is roughly 30% of the peak power. In these systems the combustion engine and pumps are sized for a maximum specified positive load peak power plus system losses, but due to their stiff-coupling to the loads, must often operate also at part-load. Considering a secondary controlled hydraulic system with energy recuperation and hydraulic energy storage, it is rather the average load power that determines the size of combustion engine and pump. With a secondary controlled system the hydraulic pump may be either of fix or variable displacement type. If a fix unit is used a charge valve should be designed to allow pump flow to be bypassed from the CPR.
Considering the actuator as purely force controlled device one possibility would be to use open-loop force control. In some situation this could be sufficient, but in most cases the machine operator would also be interested in accurate control of velocity. Hence, a combination of force and speed control must be considered. To realize this, closed loop feedback control is necessary. Based on the appropriate sensors, position, speed and acceleration can be measured and used in any control scheme tailored for the system at hand. When accurate force control is required active control of DFCUs comes into play. How this works in detail is not covered in this paper, but in principle the pressure drop across each rail-to-chamber connection is adjusted based on a model based control algorithm. Active control of the DFCUs is also the key to handling the transitions between different steady state force modes. If this aspect is disregarded severe pressure transients and loud noise is a consequence.

4 Use Case: Wheel Loader

The wheel loader used as a reference is a Volvo in the 30 ton class (L220), which uses a drop-box type countergear transmission for the wheel drive, with 4 forward and 4 reverse gears, a lockable hydrodynamic torque converter between the engine and the power-shift gear transmissions. The hydraulic system has two load-sensing axial piston pumps and an extra pump for the fan drive and brake accumulator charging. The double-acting hydraulic work cylinders for the lift and tilt functions are controlled by means of double-acting closed-centre spool valves. A simple schematic of the system is illustrated in Figure 5.

Previous studies [12, 13] point out where in the wheel loader the predominant power losses take place. In the work hydraulics, the situation with throttle losses looks similar to the excavator case. However, in the wheel loader pressure compensation losses are somewhat less of an issue since there are fewer work functions operated in parallel. Also, in heavy duty cycles, its pumps often becomes saturated in flow (100% displacement), and since the valve lacks hydro-mechanical pressure compensation, the least pressure demanding function will inherently get flow priority. Energy potential in overrunning loads is equally large for both the lift and the tilt function. In the propulsion system, the torque converter causes significant power losses due to its shearing.
of oil when it is not in lockup-mode, something that is seldom possible due to the low speeds required in normal operation. In lock-up mode significant losses may arise due to the hard coupling between the loads and the engine that forces the engine to operate under non-optimal conditions, for instance low torque, high speed.

4.1 The Hydraulic Hybrid Wheel Loader

The introduction of VDLA’s in the wheel loader shows a great efficiency improvement potential for the work hydraulics. Conceptually this hydraulic system would greatly reduce the aforementioned problem with pressure compensation during parallel operation. Recovery of potential energy is also straight forward.

If we first consider the case where only the work hydraulics is updated with a CPR and VDLA’s, illustrated in Fig. 6. According to previous publications, e.g. [12], the input energy to hydraulic system could be reduced by approximately 60% in a short truck loading cycle, given the same work throughput and an ideal hydraulic system. Since the current hydraulic system stands for approximately half of the total energy consumption, this means that the complete machine fuel consumption can at best be reduced by approximately 30%. However, in practice, there would still be some degree of throttle losses in valves and also losses in pumps and accumulators. Taking this into account, simple static calculations indicate a 20% fuel saving potential for this particular duty cycle. This should be considered a rather big saving, but given what is offered by alternative system solutions the cost penalty for the VDLA system is expected to be high. However, if also the propulsion system is considered the situation may look different. In case a more integrated propulsion system is applied to the machine, cost efficient ‘hybrid’ solutions are anticipated. Figure 7 shows three different high-level hybrid topologies could incorporate this technology. Figure 7a shows the most simple integration where the conventional power-shift gearbox and torque converter in principle stays the same as today, but is complemented with a parallel connected hydraulic motor that can be used to add or subtract torque to the gearbox. This could be used for instance during bucket filling when using the machine for digging. Since the hydraulic accumulators will provide the ‘peak flows’ to the VDLA’s the work hydraulics will no longer dictate the speed of the combustion engine, which in turn leads to a possibility to use a lower engine rpm and instead add torque to the propulsion through the secondary controlled hydraulic motor. This will reduce the load on the torque converter hence reduce its losses. If hydraulic accumulators and motors are properly dimensioned also some kinetic energy could be recovered during deceleration and reused again during acceleration.

In Fig. 7b a so called series hydraulic architecture is applied. This is a pure secondary controlled hydrostatic transmission, a solution also found in Parker Hannifin’s hybrid drive system, Runwise®[14]. The solution offers a nearly complete freedom in engine management, and high efficiency in transient low vehicle speed machine handling.
However, the transportation mode is expected to suffer from additional losses, unless a mechanical overdrive is also added. Since both the pump and energy storage is shared between propulsion and work hydraulics one could argue that this solution should be beneficial to keep system cost down. On the other hand for larger wheel loaders the need for large hydraulic motors generally becomes an issue.

A third solution, shown in Fig. 7c, is to apply a so called ‘Power-split CVT’ hybrid solution. In this concept the power flow is divided between a ‘mechanical path’ and a ‘hydraulic path’. In comparison to the pure hydrostatic solution, this means that smaller hydraulic units can be used. A challenge in this concept is to find an appropriate gearbox design. This transmission concept has been proven successful in previous studies for ‘on-road’ applications [3, 15]. The big difference to prior art is that the hydraulic energy storage is now shared between driveline and work hydraulics. This fact changes the requirements of the gearbox and opens up for new concepts. This is studied in greater depth in [16]. For instance, in power-split concepts that would normally be discarded due to a high degree of recirculation of energy, could now actually become most interesting, since this recirculating energy can instead be directly utilized by the work hydraulics or stored in the accumulator.

5 Laboratory Test Rig

Equipment for experimental evaluation of a VDLA system was constructed at the laboratory facilities of the Fluid and Mechatronic Systems division at Linköping University, and has been in operation since 2013. A simplified system schematic is depicted in Fig. 8. The test equipment is built around a re-purposed excavator arm and boom structure from a Volvo mini-excavator. Since the main purpose of the test rig was to investigate the control of a VDLA, the system was designed with a simplified charging circuit and small accumulators. Actuators and control valve manifolds enable use of up to 3 constant pressure rails. This configuration leads to 81 possible steady state force combinations as visualized in Fig. 9. The manifold contains, for each supply line and actuator port, a set of solenoid valves with replaceable orifices (DFCU’s) which can be used to investigate different approaches for digital flow control and pressure switching dynamics. One of the key insights from experimental testing is the importance of proper mode switching logic [17]. This is due in some part to the nature of the system, which relies upon rapidly switching pressure levels in the actuator chambers. As the time required for changing pressure in a given actuator chamber will depend on many different factors (valve dynamics, cylinder stroke, hose characteristics and more) the different rates of change for each chamber pressure may result in rather large over- or undershoots in the net force output of the actuator. Fig. 10 illustrates the issue in one of the more difficult mode switches (all chambers change pressure at the same time), and how this is mitigated through selection of a suitable orifice area in the flow paths to each individual actuator chamber (DFCU control). Successful implementation of
a VDLA system requires careful design of both hydraulic components and control software, taking these issues into account.

Fig. 8: Schematic over the 2-DOF excavator work implement installed in Flumes laboratory.

6 Conclusions

Multi-chamber cylinders combined by simple digital hydraulic valves and intelligent controls has a potential to significantly improve the fuel efficiency of construction machines. The proposed solutions effectively eliminate the most critical energy losses in the current hydraulic system of both wheel loaders and excavators. The variable displacement actuator has a potential to provide a control performance exceeding current mobile valve technologies. Each actuator contains a large number of valves, which could be an argument for high cost and poor reliability. The counter argument is that the valves are simple and configured in a redundant way allowing for operation even if some valve would fail. The greatest technical challenge observed is related to the actuator low level controls. The problem lies mainly in the transitions between steady-state force modes. Solutions are expected to be found through sophisticated model-based control which will be the subject for future work.

Fig. 9: Force spectrum of the VDLA laboratory test equipment, the CPR connecting to the actuator uses three pressure lines, hence its high resolution.

Fig. 10: Improved pressure transient control using the DFCU’s to restrict flow.
References


