On Energy Efficient Mobile Hydraulic Systems

with Focus on Linear Actuation

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To Lina

I almost wish I hadn't gone down that rabbit-hole—and yet—and yet—it's rather curious, you know, this sort of life!

Lewis Carroll, *Alice's Adventures in Wonderland*

Abstract

IN THIS DISSERTATION, energy efficient hydraulic systems are studied. The research focuses on solutions for linear actuators in mobile applications, with emphasis on construction machines. Alongside the aspect of energy efficiency, the thesis deals with competing aspects in hydraulic system design found in the development of construction machines. Simulation models and controls for different concepts are developed, taking the whole machine into account. In line with this work, several proof of concept demonstrators are developed. In the thesis three main system topologies are covered:

First, pump controlled systems are studied and a novel concept based on an open-circuit pump configuration is conceived. Special consideration is paid to multi-mode capabilities that allow for a broadened operating range and potential downsizing of components. Simulation models and controls are developed and the system is experimentally validated in a wheel loader application.

Second, the possibility for energy recuperation in valve-controlled systems is investigated. In such solutions, a hydraulic motor, added to the meter-out port, is used for energy recovery during load lowering and in multi-function operation. Recuperated energy is either used momentarily or stored in a hydraulic accumulator. The proposed solution means an incremental improvement to conventional systems, which is sometimes attractive to machine manufacturers due to fewer uncertainties in reliability, safety and development cost. The energy recovery system is studied on a conceptual level where several alternative systems are proposed and a concept based on a two-machine hydraulic transformer is selected for a deeper control study followed by experimental validation.

Third, so-called common pressure rail systems are considered. This technique is well established for rotary drives, at least for the industrial sector. However, in applying this technique to mobile hydraulics, feasible solutions for linear actuators are needed. In this dissertation, two approaches to this problem are presented. The first one focuses on hydraulic pressure transformers and the second one on secondary controlled multi-chamber cylinders.

Populärvetenskaplig sammanfattning

Huvudtemat för denna avhandling är energieffektivisering av hydraulsystem. Forskningen rör främst linjära rörelsesystem inom mobila tillämpningar, med fokus på anläggningsmaskiner. Avhandlingen berör åtskilliga aspekter av systemdesign, där simulering och styrning av dynamiska system samt helfordonsmodellering är återkommande inslag. Ett led i forskningsstudien har varit att bygga in och utvärdera framtagna koncept genom fullskaliga demonstratorer. Ett flertal nya hydraulsystem har studerats inom tre huvudsakliga inriktningar:

En första inriktning är mot så kallade pumpstyrda system, där ett nytt koncept baserat på pumpar anslutna i en öppen krets har utvecklats. Inom detta har smart reglering av ventiler visat sig vara central för att uppnå en hög energieffektivitet över ett brett arbetsområde. Konceptet valideras i simulering och genom praktiska prover i en hjullastare. En reducerad bränsleförbrukning (liter/h) på ca. 10% har påvisats i mätningar.

I en andra inriktning, behandlas system för energiåtervinning som avser öka energieffektiviteten på redan befintliga hydraulsystem. I studerade fall består ett sådant system av en hydraulmotor och en hydraulackumulator anslutna till utloppsstryppningen på ett i grunden ventilstyrt system. Ett flertal systemlösningar presenteras och ett av koncepten väljs ut för en djupare reglerteknisk studie där en så kallad hydraulisk transformator simuleras, konstrueras och provas.

I en tredje inriktning studeras så kallade sekundärreglerade system, en teknik som idag saknar praktiskt gångbara lösningar för linjära rörelser. För detta ändamål identifieras den hydrauliska transformatorn som en potentiell lösning vilket utreds i en simuleringsstudie med en hjullastare som exempel. I en efterföljande studie undersöks en hydraulcylinder med fyra cylinderkammare, där reglerprinciper för systemet utreds i en teoretisk studie. Slutligen designas, implementeras och testas multikammarcylindern i en grävmaskin där mätresultat påvisar en halvering av de hydrauliska energiförlusterna samt en ökning av bränsleeffektiviteten (ton/liter) i storleksordningen 30-50%.

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Acronyms

CPR	Common Pressure Rail
CRS	Complementary Recuperation System
CVT	Continuously Variable Transmission
DFCU	Digital Flow Control Unit
DP	Dynamic Programming
DRM	Design Research Methodology
EMS	Energy Management Strategy
EPA	The United States Environmental Protection Agency
IHT	Innas Hydraulic Transformer
IMV	Independent Metering Valve
LS	Load-Sensing
MISO	Multiple Input Single Output
PCS	Pump-controlled system
SCS	Secondary Controlled System
SOC	State-Of-Charge
VDLA	Variable Displacement Linear Actuator

Notations

A_A	Cylinder area in chamber A	[m ²]
A_B	Cylinder area in chamber B	[m ²]
A_{diff}	Effective cylinder area in differential mode	[m ²]
β_e	Effectiv fluid bulk modulus	[Pa]
Δp	Pressure difference	[Pa]
Δp_{load}	Pressure difference between loads	[Pa]
Δp_{MO}	Pressure difference over meter out orifice	[Pa]
E_{el}	Energy in electrical form	[J]
E_{hyd}	Energy in hydraulic form	[J]
E_{mech}	Energy in mechanical form	[J]
F	Force	[N]
F_d^*	Force limit in differential mode	[N]
F_n^*	Force limit in normal mode	[N]
F_{ref}	Force reference	[N]
$F_{\text{ss,ref}}$	Steady-state force reference	[N]
p	Hydraulic Pressure	[Pa]
p_A	Pressure in cylinder chamber A	[Pa]
p_B	Pressure in cylinder chamber B	[Pa]
p_C	Pressure in cylinder chamber C	[Pa]
p_D	Pressure in cylinder chamber D	[Pa]
p_{diff}	Pressure in differential mode	[Pa]

p_{CRS}	Pressures acting on recovery motor	[Pa]
p_{load}	Load pressure	[Pa]
p_{max}	Maximum allowed pressure	[Pa]
p_{s}	Supply pressure	[Pa]
p_0	Tank pressure	[Pa]
P	Power	[W]
P_{CRS}	Power generated by recovery motor	[W]
q_{A}	Flow cylinder chamber A	[m ³ /s]
q_{B}	Flow cylinder chamber B	[m ³ /s]
q_{max}	Maximum flow	[m ³ /s]
q_{MI}	Meter-in flow	[m ³ /s]
q_{MO}	Meter-out flow	[m ³ /s]
q_{s}	Supply flow	[m ³ /s]
v	Velocity	[m/s]
v_{d}^*	Velocity limit in differential mode	[m/s]
v_{n}^*	Velocity limit in normal mode	[m/s]
V_{A}	Volume of cylinder chamber A	[m ³]
V_{B}	Volume of cylinder chamber B	[m ³]
V_{diff}	Effective volume in differential mode	[m ³]
x_{p}	Piston stroke	[m]

Papers

THE FOLLOWING SIX papers are appended to the thesis and will be referred to by their Roman numerals. The papers are printed in their originally published or submitted state with the exception of correction of minor errata and changes in text and figures to maintain consistency throughout the thesis. In Chapter 5 a short review of the papers are provided where also the contribution of each author is clarified.

- [I] Kim Heybroek and Jan-Ove Palmberg. “Applied Control Strategies for a Pump Controlled Open Circuit Solution”. In: *Proceedings of the 6th International Fluid Power Conference Dresden, IFK’08*. Dresden, Germany, Mar. 2008, pp. 39–52. eprint: <http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-16073>.
- [II] Anton Hugo, Karl Pettersson, Kim Heybroek, and Petter Krus. “Modelling and Control of a Complementary Energy Recuperation System for Mobile Working Machines”. In: *Proceedings of the 13th Scandinavian International Conference on Fluid Power, SICFP’13*. Linköping, Sweden, June 2013, pp. 21–30. eprint: <http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-100142>.
- [III] Kim Heybroek, Georges E M Vael, and Jan-Ove Palmberg. “Towards Resistance-free Hydraulics in Construction Machinery”. In: *Proceedings of the 8th International Fluid Power Conference, IFK’8*. Dresden, Germany, Mar. 2012. eprint: <http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-132927>.
- [IV] Karl Pettersson, Kim Heybroek, Per Mattsson, and Petter Krus. “A novel Hydromechanical Hybrid Motion System for Construction Machines”. In: *International Journal of Fluid Power* 18.1 (2017), pp. 17–28. ISSN: 1439-9776. eprint: <http://dx.doi.org/10.1080/14399776.2016.1210423>.

- [V] Kim Heybroek and Johan Sjöberg. “Model Predictive Control of a Hydraulic Multi-Chamber Actuator: A Feasibility Study”. Submitted for publication in: IEEE / ASME Transactions on Mechatronics. Latest revision submitted in Oct.11, 2017.
- [VI] Kim Heybroek and Mika Sahlman. “A Hydraulic Hybrid Excavator based on Multi-Chamber Cylinders and Secondary Control: Design and Experimental Validation”. Submitted in August 2017 for publication in: International Journal of Fluid Power.

Other publications

The following papers are not included in the thesis, but constitute part of the background. Most of the ideas and results expressed in these papers are covered by the appended papers or in the extended summary of this thesis.

- [VII] Kim Heybroek. “Open Circuit Solution for Pump Controlled Actuators”. Master Thesis. FluMeS, IKP: Linköping, Sweden, 2006.
- [VIII] Kim Heybroek, Jonas Larsson, and Jan-Ove Palmberg. “Open Circuit Solution for Pump Controlled Actuators”. In: *The 4th FPNI - PhD Symposium Sarasota 2006*. Sarasota FL, USA, 2006, pp. 27–40. eprint: <http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-36910>.
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- [XI] Kim Heybroek. “Saving Energy in Construction Machinery using Displacement Control Hydraulics”. Licentiate thesis. Linköping University, 2008. ISBN: 9789173938600. eprint: <http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-15588>.
- [XII] Kim Heybroek, Jonas Larsson, and Jan-Ove Palmberg. “Mode Switching and Energy Recuperation in Open-Circuit Pump Control”. In: *VENTIL: Revija za Fluidno Tehniko in Avtomatizacijo* 15.2 (2009), pp. 134–143. ISSN: 1318 – 7279. eprint: <http://www.revija-ventil.si/arhiv/ventil-letnik-2009/>.

- [XIII] Kim Heybroek, Jonas Larsson, and Jan-Ove Palmberg. “The Potential of Energy Recuperation in Valve Controlled Mobile Hydraulic Systems”. In: *Proceedings of the 11th Scandinavian International Conference on Fluid Power, SICFP’09*. Vol. 1. Linköping, Sweden, June 2009. eprint: <http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-139848>.
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- [XVII] Kim Heybroek and Erik Norlin. “Hydraulic Multi-Chamber Cylinders in Construction Machinery”. In: *Hydraulikdagarna*. March 2015. Linköping, Sweden, 2015.

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1

Introduction

HYDRAULIC SYSTEMS are used in a wide variety of applications, mobile as well as stationary. Typical mobile applications are construction machines, forestry machines and agricultural machines. For these machines, hydraulics are in many cases used for both propulsion and various work functions and is thus often a major consumer of energy. With growing concerns over declining fossile fuel supplies and legislation on greenhouse gas emissions, the manufacturers of mobile machines are challenged to find new technical solutions to improve the energy efficiency of their products, including their hydraulic systems.

The energy efficiency of today's mobile hydraulic systems is typically in the range 30-50%. This low efficiency should however, be put in the context of how the systems have evolved in an environment where several other competing design aspects are weighed in. For many years a strong driving force has been to minimize system cost, where the resistance based valve-control has proved to be a winning concept. Relative to competing technologies, hydraulic systems are very robust against heat generation, since the oil is effectively transporting heat away from where it is generated. For the cost optimized hydraulic system, this feature means that hundreds of kilowatt power, is easily managed by resistive control, for instance in the lowering of a heavy boom of a large excavator. However, in a different setting, where the cost of energy has become of increasing importance to the end-users, alternative designs are required.

1.1 Outline

This dissertation is a so-called thesis by publication, which means it is a collection of research papers introduced by an extended summary that aims to place the scope and results of the papers in a wider context. The study is based on the submitted or published papers listed on pages xi-xii.

The current chapter, Chapter 1, describes the aims and scope of the dissertation and gives a description of the methods and tools used in research. Chapter 2 provides a general description of mobile hydraulic systems and describes the specific problems addressed in this research. Chapter 3 provides an overview of the hydraulic system concepts where research has been focused. In Chapter 4 use cases and experiments carried out in the studies are explained. This extended summary is followed by the main part of the dissertation, which consists of six papers.

1.2 Aim and scope

The overall aim of this dissertation is to investigate the energy efficiency aspect of mobile hydraulic systems and to propose how modern system architectures and control techniques are useful in the design of systems with an increased efficiency. More specific aims are to investigate energy efficiency, dynamic properties and control aspects of the following three system categories:

- Pump-controlled systems
- Complementary recuperation systems
- Common pressure rail systems

where the focus is on investigating how energy recovery and energy storage may be used to improve the efficiency of mobile machinery. A target is to test and demonstrate proposed systems in a laboratory environment and in full-scale mobile machine demonstrators to validate theoretical models and presented hypotheses.

As the main title suggests, hydraulic systems for mobile machines is of principal interest, as opposed to non-mobile applications such as stationary industrial applications. The study is mainly concerned with linear drive systems. However, as many mobile machines often rely on both linear and rotary drives, and the complete machine rely on all systems working together, questions concerning compatibility with rotary drives are nonetheless considered, although only to a limited extent.

Since the industrial partner in this research is a global manufacturer of construction machines, the examples and case studies will typically concern construction machines, but the main contributions from this work still target a broader field of use. However, the study mainly concern off-highway applications even if some of the results may still be applicable to on-highway vehicles. A number of system concepts are studied, but seldom based on the same machine application or duty cycle. It is therefore difficult to make side-by-side comparisons between the different concepts and instead the author has focused on qualitative assessments of the investigated systems.

1.3 Research questions

Based on the background, aims and scope, one main research question is formulated:

RQ: How can energy-efficient hydraulic linear actuation be realized in mobile applications?

The main research question is broken down into three sub-questions.

RQ1: Which are the main challenges in the realization of energy-efficient mobile hydraulic systems?

RQ2: Which are the enabling technologies in the design of efficient linear actuation systems for mobile applications?

RQ3: What are viable system architectures for energy-efficient linear actuation in mobile applications?

Answers to the research questions are provided in Chapter 7.

1.4 Research method

The workflow used in this research is aligned with the Design Research Methodologies (DRMs) as proposed in [1]. Even though this methodology was not explicitly selected from the start of the project, as DRM emerged as a guide in the research, the work was matched to its processes. DRM is suitable when dealing with research in industrial product development where projects are typically “one-off” and repeated design studies are hard to perform.

In short, the DRM comprises four stages where the first is the Research Clarification (RC) stage. The main focus in this stage is for the researcher to identify evidence or at least indications that support an assumption that can serve as the grounds on which to formulate a research goal and a suitable research plan. Second, the Descriptive Study-I (DS-I) is the stage in which the researcher develops and demonstrates factors that are detailed enough to describe the current situation and to be used in the coming stage. This knowledge is based on literature reviews, observations and interviews in an iterative process. Third, in the Prescriptive Study (PS) stage the researcher uses his or her increased understanding from DS-I to describe key factors to be addressed and to develop research support tools. Fourth, Descriptive Study-II (DS-II) is the final stage. In this stage, the previously developed support tools from the PS-stage are evaluated.

With reference to the papers published and their respective technical focus areas, Figure 1.1 maps the studies in relation to the general stages of DRM.

Important to point out is that the work-flow within the DRM framework is not linear. This means that findings from one stage can influence the others.

Figure 1.1 Mapping of the different stages in DRM to the publications and their respective technology focus area.

For example, a finding from the prescriptive study might help to reformulate the research questions and goals. It also means that such stages might overlap or be run in parallel. The increase in knowledge gained from one phase might lead to another loop in the DRM, where further empirical studies or literature review are needed. In addition, each stage is generally adaptable to a constantly evolving environment, where developments outside one's own research project may influence the directions taken, justifying a restart. Putting this in the context of this research project, the research project was performed over a ten-year period, with the author spending the first two years at Linköping University and thereafter with Volvo Construction Equipment (Volvo CE) in Eskilstuna, Sweden. At first, a clear focus was on the wheel loader application and the topic of pump-controlled actuators, reflected in Papers [I],[VIII],[IX] and [X]. As the author moved over to industry, influenced by insights gained from working close to product development the focus shifted towards solutions for energy recovery in valve-controlled systems, reflected in Paper [XIII]. From there the research homed in on hydraulic transformers and hydraulic energy storage, in Paper [II] and [XV], leading on to the topic of secondary-controlled hydraulics. Inspired by concurrent research the studies eventually ended up in the topic of secondary-controlled multi-chamber cylinders, resulting in Papers [IV], [V], [VI], and [XVII].

Simulation and experiments

The main research tools used are physical modelling, simulation and experimental testing. Since the energy aspects of hydraulic systems are at the core of this research, a central purpose of modelling and simulation has been to identify and quantify energy dissipation in existing and new system topologies. In the early stages of concept evaluation, the models are kept simple, focusing only

on the energy flow through the hydraulic system to quantify the dominating losses and system efficiency, as done in Papers [XIII] and [VIII]. In later stages, the models are expanded to also consider dynamic aspects, for instance in the development of new control strategies as in Papers [II] and [V]. Also complete machine models are developed to understand how the investigated hydraulic system will perform together with other sub-systems and to develop control strategies. Also in this case, the model fidelity varies depending on the topic of interest. In Paper [IV] and [XIV], a so-called backward-facing simulation approach is taken where both operator input signals and load trajectories are considered input signals. The dynamic effects are here kept to a minimum to allow quick simulation runs and the models are kept simple, but still with consideration to the main power losses to be able to assess the complete system's energy efficiency. In Paper [VI] the controllability aspects of an actuator were of main concern, why instead a forward-facing simulation technique is used.

In this research, experiments are carried out in all stages of the DRM. In the early stages, experiments start with isolated tests in laboratory test-rigs, as shown in Papers [II], [VIII] and [XVII]. Then, in later stages, depending on the results from the laboratory tests, they move on to full-scale mobile machines, as shown in Papers [X] and [VI]. The main reason for experimenting in the early stages is to gain new insights into how isolated parts of a system work, used to improve simulation models and develop control methods. The main purpose of experiments in later stages is to validate theories based on simulation results achieved in earlier stages.

1.5 Contributions

The main contributions of this dissertation can be summarized as follows:

1. Design principles and methods for discrete-mode control of hydraulic cylinders demonstrated in simulation and in practical applications for both pump-controlled systems and common pressure rail systems.
2. Control principles and a description to how hydraulic transformers (IHT type) are adapted for use in a 4-quadrant mobile application.
3. A first approach to model predictive control of hydraulic multi-chamber cylinders, including an optimal control formulation that captures the competing aspects of controllability and energy efficiency.
4. A general examination and description of problems and challenges encountered in the realization of both pump-controlled systems and common pressure rail systems.

2

Mobile hydraulic systems

BEFORE HYDRAULICS were used in mobile machines, it was common to drive the work functions with steel wires, for instance in excavators as shown in Figure 2.1. As hydraulics entered the arena, the machine manufacturers saw benefits in the hydraulic cylinder, with its double-acting capability and high power density. With high power easily routed through flexible hoses, more slender and cost-efficient machine designs could be realized. Since hydraulics also have the feature of built-in heat conveyance, very simple proportional valves could be used as a cost-efficient solution. The consequence was naturally heat generation due to the resistive losses in the valves, which at that time was subordinate to the importance of low system cost. When fuel efficiency became an increasingly important sales argument, the valve systems had to be improved through increased efficiency. Today, despite decades of incremental

(a) Rope-wire excavator

(b) Hydraulic excavator

Figure 2.1 A rope wire excavator from the late 50s beside a modern hydraulic excavator. Photo courtesy of: (a) Patrik Öhman, (b) Volvo CE

improvements to the valve systems, it is not uncommon that more than half of the energy supplied to the hydraulic system is wasted as heat in an average work cycle. In this section we describe to how mobile hydraulic systems are used, why energy losses are so high and possible solutions to increase the energy efficiency.

2.1 Machine applications

Mobile hydraulics are used in a variety of machine types used in many different segments, for example construction, agricultural, forestry and mining. Common to all these different machines is that they are used as tools to carry out various kinds of work. In this dissertation, we therefore refer to all these machines as ‘working machines’.

The hydraulic systems are used in the actuation of various work functions and auxiliary functions. In some working machines, hydraulics are used as the main power transmission system for motion control, while in other cases they are just one of several other systems used for motion control. Other motion control systems are for instance mechanical or electrical drive transmissions used for propulsion. However, even in these systems, hydraulics are often used as an integral part, for instance for gear shifting in mechanical transmissions. In most machines the hydraulic pumps are driven by a combustion engine, but with the trend of electrification of machines and vehicles also electrically driven pumps are beginning to become more common. The importance of hydraulics to a specific machine thus varies, both with regards to functionality and to energy consumption depending on application.

Example: wheel loaders

To give one example relevant to the studies in this dissertation a wheel loader is considered. In the study of hydraulic systems, the wheel loader is a good example that, due to its versatility, is also representative of many other machine types. The wheel loader contains both work functions and a propulsion system that are typically used simultaneously during work tasks, posing special challenges in the design of the individual subsystems as regards achieving an overall well-performing machine.

For the propulsion system closed-circuit hydrostatic drives and hydrodynamic torque converter solutions are the most common. Other solutions found on the market are based on diesel-electric transmissions or various power-split solutions. For the work functions, so-called load-sensing hydraulic systems are today considered state-of-the-art, even if other solutions exist, particularly in cost-sensitive markets.

As for most working machines, the aspects of total cost of ownership, availability, safety and legislation compliance are critical. The main performance-related properties of value to the wheel loader user/owner are productivity

(typically expressed in tons/hour), fuel efficiency (expressed in tons/litre or tons/kWh) and operability.

In Figure 2.2, one of the more common work cycles for wheel loaders is shown, referred to as a short loading cycle, or Y-cycle. In this cycle, approximately 50% of the energy produced by the combustion engine is consumed by the hydraulic system, while the rest of the energy goes to the propulsion system, as illustrated in Figure 2.2a. In most parts of the cycle both work hydraulics and propulsion are used together to carry out the work task, which is to fill a load receiver with material lifted from the ground. During the bucket filling phase, almost the full engine power is used and this is thus the phase where the energy consumption is highest.

Figure 2.2 Power distribution in a typical wheel loader duty cycle [2].

It should be emphasized that this is only one of several possible usages of a highly versatile machine. In general, the design of new motion systems requires good application knowledge and access to recorded load data from all sorts of use cases. Without this information, designs are likely to become sub-optimal as only sub-sets of the overall usage requirements are considered.

Operators and operability

Most often there is a human operator involved in the control of working machines, even if autonomous operation has increased in popularity over the last couple of years. The operator typically manoeuvres propulsion and/or work functions via buttons, joysticks and pedals. With a work task at hand, the operator controls the machine on a task oriented basis. This means that his or her inputs depend on the system output in a closed loop fashion. This ‘man-machine’ system is highly complex and very important to understand in the evaluation of new machine concepts [2]. As working machines generally have

several degrees of freedom in motion, they put a high mental workload on the operator. The output performance therefore depends largely on the skill level of the operator. This was shown in [3], where the spread in performance of 80 operators was assessed. In Figure 2.3 the result in terms of average fuel efficiency over their respective average productivity is shown. The best-performing operator with regard to fuel efficiency has been chosen as ‘Shadow operator’ (i.e. the one to compare with). It can be seen that the operators’ performance varies substantially, which is largely explained by the span in experience and skill level between the different operators. However, as described in [3] the variation for one individual operator also varies greatly.

Figure 2.3 *The spread in cycle productivity and fuel efficiency between, with courtesy of [4]*

Operability is the ease with which the user can operate the machine as intended. As the operators are essential to the performance of the machine, operability is important. Which motion control behaviour is desired to achieve good operability is often situational, even in one and the same machine type. For instance, force control could be desirable in one part of a work task, while in another part velocity control is of greater importance. Present hydraulic systems have been developed over decades to achieve the desired control behaviour.

Furthermore, to achieve good operability the hydraulic system must not only work well in itself, it must also be harmonized with other sub-systems in the machine. If for instance, the power available for a specific work function is increased, it may also require higher power availability to other functions, or the machine will be perceived as slower than before. This in turn can lead to overall lower operability even though performance for certain functions is improved. Another example is the importance of power limitations to the hydraulic system relative to other sub-systems. This was experienced in [5], where the power take-out of an over-powered hydraulic system had not yet been harmonized with the propulsion system. The operator was happy with the added hydraulic power, but had difficulties balancing the available engine

power between the two sub-systems, resulting in lower productivity and lower fuel efficiency.

Consequently, when developing new motion systems and machine concepts it is of high importance to consider how the operator behaviour is influenced by the new system and which effects it has on machine performance. As to achieve good operability it is of critical importance to get feedback from real operators in the system tuning process.

2.2 Motion control

Mobile hydraulic systems often contain several different actuators. In many cases, to reduce system cost, one pump is shared by several actuators. To distribute the power provided by the pump to the actuators, hydraulic valves are used. The typical hydraulic actuator has two working ports to which flow and pressure are controlled by a valve.

2.2.1 Conventional valve-controlled systems

There are different types of valve systems, with function based on different pressure and flow control principles. The most simple, and probably still the most common system, is based on so-called open-centre valves and fixed displacement pumps. The more efficient, but slightly more complex, open-centre system uses a variable-displacement pump that allows flow to be controlled based on an actuator command. Another category, instead uses so-called closed-centre valves together with a variable-displacement, pressure-compensated pump. In its simplest form, the pump pressure is set to a constant level, while in a more sophisticated version the pressure is controlled by an external signal. In Load-Sensing (LS) systems, the pump pressure is determined by a feedback signal from the load pressure. In the case where several actuators share the same pump, typically the highest pressure is sensed by the pump controller which regulates the pump discharge pressure to a fixed margin above the sensed pressure. The margin is set sufficiently high to overcome the pressure drop over the inlet orifice for a required flow. In a recent study [6], an excellent overview of energy saving valve technologies suitable for mobile machines is presented.

2.2.2 Independent metering

Another more sophisticated approach to valve control is based on Independent Metering Valves (IMVs). In contrast to the valve arrangement using spool valves the meter-in and meter-out orifices are no longer mechanically coupled. This concept provides a higher degree of freedom in control as flow and pressure at separate work ports are controlled individually. The main advantages of independent metering system are:

Throttle loss reduction As meter-in and meter-out orifices are controlled separately, many of the compromises found in conventional solutions can be avoided. For instance, the meter-out orifice can be opened fully while the meter-in orifice controls the flow.

Dynamic characteristics As there are more input signals, the architecture allows a higher degree of freedom in control, useful for instance to control the hydraulic damping depending on load condition.

Customizable characteristics Unlike conventional spool valve solutions, which have to be mechanically adjusted until the desired characteristics are achieved, the hardware in individual metering systems is made more general and characteristics are to a greater extent defined by software settings.

Historically, great efforts have been made to develop the IMV technology, both in academia and industry. In several studies, for instance [7–10], emphasis is placed on the efficiency aspects of IMV systems. When the appropriate hardware is combined with sophisticated control strategies, these systems can save a considerable amount of energy in mobile machines. The state-of-the-art systems in this field of research not only minimize the metering losses but also enable flow regeneration, which refers to letting back pressurized flow to the supply line to be shared by other functions in the system.

2.2.3 Digital hydraulic valves

Digital hydraulics, also called discrete fluid power technology, is characterized by hydraulic control being carried by the use of discrete valued components [11]. The research in this field is mainly focused on the design of energy efficient hydraulic system design, but strengths in the technology are typically also found in high control accuracy. Within this field, valve control is one main topic. In digital hydraulics, one metering-edge is comprises several parallel connected on/off valves that are controlled in a discrete manner to achieve a stepwise variable opening area. The solution is referred to as a Digital Flow Control Unit (DFCU). Depending on the number of valves used and which area coding is used for individual orifices within the DFCU, different resolutions in area opening are achieved. The use of DFCUs as part of IMV systems has been proven useful, for instance in [12] and [13]. The benefits are mainly found in the switching between different operational modes.

2.3 Energy efficiency and losses

On a general level, the term energy efficiency describes the ratio of ‘useful output’ to ‘total input’, where the ‘total input’ is greater than the ‘useful output’ with the difference between the two being losses. Energy efficiency is a

dimensionless number in the range zero to one which can be calculated either momentarily or over time. As the general definition includes a notion of ‘usefulness’, what should be included in the respective terms becomes somewhat subjective where different aspects of usability may be considered. There are several ways of defining energy efficiency, useful for different situations depending on perspective. For this reason, it is in many cases better to talk about energy in absolute terms, i.e. energy consumption or energy losses. Energy losses exist in every component of a hydraulic system. A majority of the losses are typically found in hydraulic pumps and control valves described next.

2.3.1 Pumps and motors

The energy efficiency of pumps and motors is frequently addressed in literature and industry, where sophisticated simulation models and extensive measurement are the tools used to isolate and optimize all parts of this highly important component. According to [14] there are two main approaches to model losses of hydraulic pumps and motors. The first approach is to base the models on prior generalized experience expressed by physical laws. The second approach is to develop empirical models based on the use of experimental data. One of the first to develop a model that explains the governing physical laws for flow and torque in hydrostatic units was [15], whose work was later extended by [16] and [17]. Another extension, based on polynomial expressions is suggested in [18]. And more recently [19] proposed is one method, called Polymod, which according to [20] provides high accuracy, reliability and ease of implementation.

The losses found in displacement controlled hydraulic pumps and motors are commonly divided into two categories summarized as follows:

Hydromechanical losses have an influence on torque/pressure. The rotation of pumps causes losses due to friction in seals and bearings. Friction is also found in sliding surfaces, such as between pistons and barrels and between barrel and valve plate. Furthermore, since the pump housing is typically filled with oil the rotating parts causes hydrodynamic losses due to churning of oil.

Volumetric losses are the part of losses that influence flow/speed. Leakage from the high-pressure control volume within the machine leads to less output flow. The compressibility of oil also causes losses in the commutation from high pressure to low pressure.

There are also losses related to the control mechanism used to vary the displacement, which can have a significant impact on energy efficiency, especially at lower displacement settings [21].

In mobile machines, ‘inline-pumps’ are commonly used to drive the work hydraulics. Relative to its alternatives, the inline pumps are considered cost

efficient and have the advantage of being stackable, enabling compact installations. In hydrostatic drivetrains the ‘bent-axis machine’ is commonly used as a motor. Its design typically offers higher performance in terms of power density and efficiency relative to its counterparts in other designs. It is, however, not stackable and its physical shape can complicate installation. Both these pump types have existed as commercial products for more than 50 years. Even though improvement areas are still found, the overall products are considered mature.

With the increasing demand for higher energy efficiency and emerging electric alternatives, new technical solutions are being developed. One example of a promising development is the ‘digital displacement’ technology, researched for more than 20 years [22] and now in a beta build stage for several applications [23–25]. Another promising development is the Floating Cup Technology, also under constant refinement since its introduction over 10 years ago [26, 27].

2.3.2 Control Valves

As mentioned earlier, in current mobile hydraulic system one pump is typically shared by several work functions. Since the pump can only adapt its pressure to one of the functions at a time, cases where several loads are operated simultaneously will in most cases result in pressure losses over some of the valve sections, here referred to as pressure-compensation losses. Depending on the loading conditions in a specific duty cycle and how the actuators are dimensioned, these losses have different significance for the cycle efficiency. The problem with pressure-compensation losses is illustrated in Figure 2.4. For the manufacturers of mobile machines, this problem is well known and compensated for by dimensioning the cylinder drives to minimize the power loss for a given duty cycle.

Figure 2.4 Simplified hydraulic schematic to describe losses related to parallel operation in a conventional load sensing system.

With a penalty on increased system cost, this loss may naturally be avoided by adding more pumps to the system, separating the functions as shown in Figure 2.5. One thing to keep in mind, however, is that this approach may introduce increased energy losses in the pumps. As the peak flow demand for

one function may still determine the required flow capacity of the pump it will more often be operated at part load displacement where it is less efficient, compared to the case where one pump is shared amongst several drives resulting in high displacement settings.

Figure 2.5 Simplified hydraulic schematic describing how separated pumps are used to eliminate losses in parallel operation.

The use of IMV could also improve the situation by means of driving the cylinder in a so-called ‘flow regeneration mode’, thus using the asymmetrical cylinder as a discrete transformer having the effect shown in Figure 2.6. This control principle is investigated in several studies, e.g. [28–30]. More information about this will follow in coming chapters, as the principle is also frequently addressed in our studies.

Figure 2.6 Simplified hydraulic schematic describing how IMV are used to drive the cylinder regenerative thus reducing the losses in parallel operation.

Another major problem in conventional hydraulic systems is the inability to recuperate potential energy stored in loads as they are lowered by gravity, a load case which we refer to as an over-running load. When loads are lowered towards the ground, the stored potential energy is converted to heat in a meter-out orifice leading the flow back to tank, which typically means a substantial power loss.

Coming back to the wheel loader example, operated in the short loading cycle described earlier, Figure 2.7 shows the duty cycle from a hydraulic load

perspective. The system consists of three hydraulic driven functions; boom, bucket and steering. As seen from the figure, the majority of positive work is carried out when the boom function is used for lifting the bucket filled with gravel. In the bucket emptying phase, a negative mechanical work is carried out by the bucket cylinder and later also by the boom cylinders as the empty bucket is lowered back to ground level. The negative work, circled in the figure, makes up about 40% of the positive work. The difference between positive and negative work is referred to as net work. The majority of the net-work is work spent in the digging phase filling the bucket, which is mainly due to friction between the bucket and the gravel pile. The other part of the net work is the potential energy required for lifting the material from ground level to the load receiver. A small amount of work also goes to overcome ground friction with the steering function.

Figure 2.7 Load power for the tilt, lift and steering actuators of a wheel loader operated in the short loading cycle, circled over-running load cases

2.4 Hybrid technologies

A hybrid vehicle such as a passenger car uses more than one power source for propulsion, often by accompanying a combustion engine (which uses fuel) with means for storing surplus energy. By finding the right way of how and when to combine both power sources, large gains in terms of energy efficiency can be achieved. This is also true for off-road working machines, which however are more complex since these also have motion systems for work functions, which in many cases have power demands exceeding those of the propulsion system. Significant differences to automotive application are:

Multiple degrees of freedom in their motion system, due to extra work functions besides a propulsion systems, each of which has its unique features and requires a power management strategy of its own.

Transient load cycles are common in both work functions and propulsion systems. The energy storage must endure high power fluctuations.

Repetitive duty cycles where the same or similar work tasks are carried out over and over again. This means possibilities to utilize predictive control strategies.

Harsh working environment as the machines are operated in rough terrain or in extreme weather conditions, which for instance means all systems has to withstand severe vibration and a large span in working temperature.

Many different classifications of hybrid system solutions exist, most having their origin in the automotive industry. A first classification is based simply on which type of technology is used in the energy storage (electric, hydraulic, mechanical). A second, more subjective, classification concerns the degree of hybridization, expressed in terms such as ‘micro-hybrid’, ‘mild-hybrid’ or ‘full-hybrid’, referring to the power/energy levels used in the hybrid system. The third, and probably most common, classification is based on system topology. The most classical topology categories are ‘parallel hybrid’ and ‘series hybrid’, referring to how the additional energy source is arranged relative to the main energy source. In working machines, the hybrid systems that concern only parts of the total motion systems would typically be referred to as ‘micro-’ or ‘mild-hybrids’, while hybrid systems that have significant impact across all motion systems would be referred to as ‘full-hybrids’. The classification based on system topology is also applicable, although the term is somewhat ambiguous in the case of working machines with several drive systems. As an example, in one drive system the hybrid energy storage could act ‘in series’ with the primary energy source, while in another the energy storage provides energy in parallel with the primary source. The machine is thus both a parallel hybrid and a series hybrid in different parts of the system. No new hybrid definition will be provided here, since there are far too many already. What is more important are the technical solutions and possible benefits of hybridization, described next.

2.4.1 Hybridization benefits

Depending on the power and energy capacity of the hybrid system, different efficiency-improving strategies can be executed. For some hybrid architectures, it could be only one basic function that is concerned while in other cases all functions of a machine are affected. Examples of features that are sought in the hybridization of working machine are the following:

Kinetic energy recuperation - Recovery and reuse of energy from deceleration of high inertia loads.

Potential energy recuperation - Recovery and reuse of energy stored in loads being lowered with gravity.

Function/system decoupling - Reduce the stiffness in systems, making components operate more independently from each other, allowing them to be optimized separately.

Power boost functionality - To relieve the primary energy source of peak power demands, which in some cases can lead to downsizing. Alternatively, increase the output power for a limited time period to increase productivity.

Electrification of on-road vehicles is an apparent trend in society, as it is for working machines where most of the larger machine manufacturers have developed and demonstrated electric hybrids. In for example the construction equipment industry a few example can be named [31–34], where the claimed reduction in fuel consumption is usually in the range 15-30%, varying with technical solution and application. A parallel development, central to this dissertation, concerns hybridization using hydraulic technology.

2.4.2 Hydraulic hybrids

In hydraulic hybrids, hydro-pneumatic accumulators are used as energy storage. The research and development of hydraulic hybrids solutions go back a long time and concern both on- and off-road applications. In on-road applications, the most prominent examples are found among heavy-duty vehicles with transient and cyclic driving patterns such as buses, delivery trucks and refuse trucks. An overview of challenges and opportunities in this field is found in [35]. The United States Environmental Protection Agency (EPA) recently completed a comprehensive evaluation of several different hydraulic hybrid drivetrains [36]. The results from the study demonstrate significant energy savings and indicate that hydraulic hybrids render a cost-effective solution in heavy duty-vehicles.

In working machines, hydraulics are already an integral part of the machine design and all the main components needed to make a hydraulic hybrid system are therefore well known by the manufacturers, and can thus be considered proven technology. Hydraulic accumulators have been used for decades, where safety standards are well developed [37]. It is also from many aspects a very simple and robust component, attributes attractive in working machines where up-time and durability are critical. The accumulator has its stronghold in duty cycles where transient high-power take-out is required, but has a relatively low energy density [38, 39]. This provides a good match with the energy/power characteristics of the duty cycles of working machines, which generally entail a low energy content.

Hydraulic hybrids in working machines have been studied in academia and a few solutions have reached the commercial market. Already in [40] accumulators were used in a system for recovery of potential energy in a large excavator. More recently a commercially available excavator uses hydraulic accumulators to recover energy from the swing function [41]. Also in the literature excavators

are frequently addressed as a suitable application for hydraulic hybridization, where [42, 43] provide recent examples.

In [44] technologies concerned with improving energy efficiency in mobile machines were introduced and summarized as follows:

1. LS Power Supply with LS-Controlled Valves
2. Electro-hydraulic Power Supply
3. Secondary Control Technologies
4. Hydraulic Transformers
5. Pump-Controlled Actuators
6. Independent Metering Valve Technology
7. Optimized Motion Control
8. Energy Regeneration Technologies

The list of technologies is to a large extent still valid today, not least in the design of efficient hybrid systems. However, as will be discussed in this dissertation, at least the following two items should be added to the list

9. Multi-chamber cylinders
10. Digital/discrete fluid power control

3

Investigated system concepts

THIS CHAPTER provides an overview of the three hydraulic systems' architectures considered in this dissertation, with reference to the state of the art.

3.1 Pump-controlled systems (PCS)

In Pump-controlled systems (PCSs) each load is driven by a separate pump. Available solutions can principally be separated into two different configurations, either with the hydraulic machine arranged in a closed circuit or in an open circuit, schematically depicted in Figure 3.1. In an open circuit configuration, the pump has a predefined high and low pressure side in contrast to the closed circuit, where the side of pressurization depends on the actuator load quadrant.

Figure 3.1 Pump control in two principally different circuit configurations.

In working machines, asymmetrical cylinders are used almost exclusively due

to space considerations. In closed circuits, the unequal differential volume flows from the cylinder must be compensated for. Several different solutions to this are found in the literature, for instance in [45] a conventional hydrostatic circuit is complemented with two additional hydraulic machines with displacements adapted to the cylinder area ratio. The study was later continued in [46], where the focus was on increasing the resonance frequency of pump-controlled systems.

In the mid-90s a pump-controlled closed circuit system consisting of fewer components, capable of asymmetric cylinder actuation, in four-quadrants, was patented [47]. A few years later, a similar circuit was presented in [48], shown in Figure 3.2a. In this solution, the differential volume of the cylinder is balanced on the low pressure side by a charge pump and an accumulator and the coupling between the cylinder's low-pressure side and the charge line is solved hydro-mechanically using pilot-operated check valves.

Figure 3.2 Simplified schematic of a closed circuit solution and its region of operation.

In the adaption of this system for use in working machines shut-off valves are added in order to hold the load in emergency situations, such as engine failure [49]. If several drives are used, they can conveniently be coupled via the low pressure side, sharing the charge pump and the accumulator. The total number of components can consequently be kept relatively low. Just like a hydrostatic transmission circuit, the circuit supports four-quadrant actuation in a simple hydromechanical manner. Its feasible region of operation is shown in Figure 3.2b. The hydraulic machine works as pump or motor depending on the load condition, recuperating energy whenever possible. The recuperated energy is mechanically transferred to other drives via the common drive shaft. A drawback is the lack of functionality to manage load power greater than the installed hydraulic power on the supply side. Compared to a valve-controlled system where the meter-out orifice size is not really a cost issue, the pump-controlled system requires the pump to be dimensioned to handle the full lowering flow and bigger pumps are generally more expensive. On the

other hand, the closed circuit pumps can operate at comparatively high angular speeds since its suction side is boosted. In [50] a prototype of the closed circuit solution was implemented in a wheel loader that demonstrated 15% reduced fuel consumption compared to a wheel loader equipped with a conventional load sensing hydraulic system.

In pump-controlled systems the pumps are generally designed to manage the peak power of each function in all of its four load quadrants. As a consequence, the pumps will frequently operate in part load conditions. As the main system loss in pump-controlled systems is found in the pump itself, it is critical to use pumps which are optimized for use in part load conditions. There has been much research and development within the topic of pump efficiency, where as described earlier, new pump designs are constantly emerging.

The open-circuit solution

In our studies, a pump-controlled system in an open-circuit configuration was studied, described in appended Paper [I] and further in publications [VIII, IX, X, VII, XI, XII].

The main difference compared to the closed circuit is that the open circuit handles four-quadrant actuation by means of controlling four separate valves located between the pump and the cylinder. The valves make it possible to combine the advantages from individual metering valves with the advantages from displacement control. For example, the feature of controlling the cylinder in different ‘modes’ allows the system to cover a larger region of operation than that of a closed circuit solution, as shown in Figure 3.3. Inside this region, higher cylinder velocities can be achieved for the same pump flow.

Figure 3.3 Open circuit solution for one asymmetrical cylinder.

Cylinder mode-control

In the differential state the cylinder piston chamber is hydraulically connected to the piston rod chamber. Since the chambers are short-circuited the effective hydraulic area becomes that of the piston rod, as illustrated in Figure 3.4a. As concerns the power supplied to the actuator, the two different modes means a discrete transformation in flow and pressure, reflected on the mechanical side as two discrete sets of force and speed, as illustrated in Figure 3.4b. This illustration however shows an ideal transformation, where no losses exist. In practice, resistive losses in valves and hoses cause a decrease in force with increasing velocities.

Figure 3.4 A conceptual description of the differential state and how it is used to broaden the operating range of an asymmetrical cylinder.

Energy recuperation

As the open circuit solution is equipped with proportional valve, several opportunities exist in terms of controlling the load in different modes. A summary of the control modes applicable for a retracting drive which is subject to a compressive load force is shown in Figure 3.5, with the following as a brief description of the different modes.

- I. Non-differential retraction
- II. Non-differential retraction with meter-out flow control
- III. Differential retraction
- IV. Differential retraction with pressure limitation control
- V. Differential retraction with meter-out flow control
- VI. Differential retraction with meter-out flow control and pressure limitation control

Figure 3.5 Plausible control modes in the case of an over-running cylinder retraction.

Switching between the states while the load is in motion requires a greater control effort than making the same switch at zero velocity. However, how difficult this is depends on which mode transition is desired. For example, in the load quadrant shown in Figure 3.5, going from meter-out flow control in non-differential mode to differential mode usually requires a reduction in displacement and simultaneously an abrupt closure of the meter-out valve. This is of course achievable, but usually at the expense of operation comfort. Other authors have looked at alternative methods to solve this kind of mode switching in research on IMV systems, for instance [7] and [30].

One method includes the step of detecting the current load force by the use of pressure sensors and selecting the appropriate operating state based on that information. The easiest solution is to always have a preference for a certain state of operation when initiating a motion. If the preference is a differential state it is important that the maximum pressure is not exceeded during a stroke. This is solved by calculating what the pressure will be in the differential state,

given the piston area ratio and the pressure level in the non-differential state. If the calculated pressure exceeds the maximum allowed system pressure level, non-differential mode is used instead.

Dynamic considerations

In the differential state, the hydraulic resonance frequency ω_h is decreased. If fluid passes between the chambers without any major restriction the piston rod area is the effective hydraulic area and the control volume equals the complete cylinder volume. In Figure 3.6, the difference between the two states is visualized over a parameter range typical for construction machines in terms of cylinder area ratio and piston stroke. In the visualization, a cylinder stroke of 1m is used and the inner diameter of the cylinder is 0.1m and a dead volume of 1% of the total cylinder volume and a typical hydraulic bulk modulus of 1500×10^6 Pa.

Figure 3.6 Difference in resonance frequency for the two cylinder states.

From working machines, the lower resonance frequency is generally seen as a problem since as an operator often works close to the machine, and consequently will notice any rapid change in acceleration or increased oscillations. However, if active damping is applied, it is generally easier to dampen low frequency oscillations as a lower control bandwidth is required. Several studies in oscillation damping can be found in the literature, for instance in [51] and more recently in [52].

3.2 Complementary recuperation systems (CRS)

To improve the efficiency of a conventional valve-controlled system its predominant losses may be reduced by adding a system that provides support for energy recuperation, as shown in Figure 3.7. We refer to such systems as Complementary Recuperation Systems (CRSs). Compared to many of the other energy saving technologies presented in section 2.4, the main idea of using a CRS is to keep the valve-controlled system as a basis and by means of the added CRS achieve an incremental improvement in energy efficiency. For many applications, one CRS unit is enough to achieve energy recovery in several drives, which leads to a high utilization of added components relative to for instance a PCS.

Figure 3.7 The energy flow in a generic system equipped with a CRS.

In this dissertation a CRS that connect to the base system via a hydraulic interface is of main interest. Connection is made to the meter-out port of an arbitrary valve control system. The system is adaptable to load conditions by controlling the port pressure using a hydraulic motor, illustrated in Figure 3.8. To recover energy from over-running load cases the meter-out port pressure is controlled. The pressure is set to a level below the load pressure, sufficiently low to achieve the desired function velocity. To minimize throttle losses and maxi-

Figure 3.8 CRS recovery principle, connection to the meter-out port of a valve-controlled system.

mize the energy recuperation, the meter-out valve should be fully open during

recovery. As discussed in Paper [XIII], Independent Metering Valve systems are extra useful in this, due to their added degree of freedom in controlling meter-in and meter-out independently.

Another load case subject to energy recuperation is multi-function operation. In this case the target is to reduce the pressure compensation losses. In Figure 3.9 the principle is shown for two loads. By increasing the meter-out pressure the load pressure is equalized and the difference in load power is instead turned to useful mechanical power by the recovery motor. If more than two loads share one CRS, a prioritization among the loads is needed. The control challenge in this method are discussed in Paper [XIII] and in [53].

Figure 3.9 Principle of energy recovery during parallel operation. i) Shows the normal case with throttle losses over meter-in. ii) Shows the possibility to “move” the pressure losses to the meter-out orifice. iii) By controlling the meter-out port pressure with a motor, the difference in load power is converted to useful mechanical power.

3.2.1 Configurations

With a CRS installed in a working machine, there are several options for how energy generated by the hydraulic motor could be utilized. Energy can be fed back either directly as mechanical energy or after conversion to other forms of energy, such as electric or back to hydraulic. Combinations between the options are also possible. Several variants are illustrated in Figure 3.10, that are discussed in Paper [XIII].

Another option is to add an energy storage in the CRS, meaning recuperated hydraulic energy is converted in one or several steps to reach the form of energy used in the storage. The three main solutions to energy storage, and their

Figure 3.10 The three main types of energy conversion useful in the design of the CRSs and examples of combinations in-between.

respective conversion principles shown in Figure 3.11. When stored energy is needed, it is converted back to hydraulic energy, or taken out via other power branches in the CRS, marked with dashed lines in the figure.

Figure 3.11 The three main ways of including an energy storage in the CRS.

Central to this dissertation is the solution using hydraulic energy storage, but before looking closer that, a brief overview of the three alternative is given below.

In the electrical solution, an electrical motor and typically a battery are used. Such solutions are interesting since modern electrical machines have started to become competitive in terms of cost and power density due to intense developments in the automotive sector. Examples where such solutions are applied to working machines are found in e.g. [54–56]. In these studies, there

are typically also other electrical drives on the working machine that can use the generated electrical energy.

The mechanical energy storage system is based on high-speed flywheels. When driven by a hydraulic motor, a gearbox and a clutch are required to achieve a good match in rotational speed and enable disconnection while not in use. To re-engage connection, speed-synchronization is required. To achieve high rotational speeds, the flywheel is typically operated in a hermetically sealed vacuum compartment to minimize air drag. Commercial solutions exist, e.g. [57] shown on an excavator. Other solutions are found in patent applications, e.g. [58].

The third option is based on hydraulic storage and conversion using a hydraulic transformer. As described earlier the hydraulic accumulator is a simple and proven component. Even if it has a poor energy density compared to the mechanical and electrical solution, it is suitable for transient and high power duty cycles, typically found in linear drives of working machine. Challenges in this concept are mainly related to the hydraulic transformer, both with regards to energy efficiency and controllability. In our studies, a transformer is modelled and tested in hardware described in Chapter 4.2 and in appended Paper [II]. A related study in this field is presented in [59], where different system configurations and control challenges are highlighted. In the next section follows some background to hydraulic transformers.

3.2.2 Hydraulic transformers

On the highest level, two different approaches to realizing a hydraulic transformer are found in the literature. The first, sometimes referred to as the ‘hydraulic switching converter’, is based on an oscillating circuit utilizing the effects of fluid inertia and fast switching-valves, a field of research well summarized in [60, 61]. The other approach, more central to this thesis, is the so-called ‘hydro-mechanical transformer’, in which the power transformation is carried out via the mechanical domain.

One common way to build a hydro-mechanical transformer, described already in the 1980s [62, 63], is to combine two hydrostatic units, where at least one unit has a variable displacement.

However, the efficiency of this type of transformer is limited as it includes two piston units, of which, at most operating points, at least one of the machines will operate under a partial loading condition, resulting in decreased overall efficiency [64]. From the late 1990s up until today, research has continued on alternative principles where one machine may be used instead of two in an endeavour to make the component more energy-efficient and commercially viable. In [65] a transformer based on the floating-cup technology was proposed. Named after the founding company, the solution is referred to as the Innas Hydraulic Transformer (IHT). The IHT uses one fixed displacement axial piston unit containing a rotatable port plate with three kidneys, where the

transformation ratio is controlled by turning the port plate. The solution offers a compact design and higher energy efficiency compared to the two-machine solution.

Figure 3.12 Partial exploded view and cross section of the IHT. The figure in the upper left corner shows the range of the control angle [XIV].

Another hydraulic transformer concept is the so-called “Digital Hydraulic Transformer” [66], which is based on a linear reciprocating double acting multi-chamber cylinder controlled by switching-valve valves. A related digital hydraulic transformer concept was recently presented in [67].

3.3 Common pressure rail (CPR) systems

In a Common Pressure Rail (CPR) system, a pump supplies flow to a hydrostatic rail to which all of the loads are connected. The main difference compared to a standard hydrostatic system is that the common pressure rail has a significant energy storage connected to the rails. The additional system capacitance leads to a notion of a pressure coupling rather than a flow coupling between the supply and the load side. The hydraulic supply system is mainly concerned with controlling the rail pressure, while the loads are controlled by means of displacement control, directly at the load side, on the ‘secondary side’. This control principle is referred to as ‘secondary control’, a technique that was intensively studied and refined in the 1980s, for instance by [68–71] and more recently evaluated for mobile hydraulic systems [72, 73]. For rotary drives, the displacement of a variable hydraulic motor is the controlled variable to control load torque while angular speed and position are typically controlled in a closed loop, based on feedback signals from the load. The main advantages of CPR systems are [74]:

Modularity The pressure coupling effectively decouples the loads from the energy source and from each other. The capacitance of the energy storage inside the rail allows the supply system to be operated somewhat separately from the load demand, which enables the use of simple pumps and relatively low requirements on control time.

Energy efficiency The energy storage in the CPR can be designed to deal with peak power shaving for the supply system and deal with storage of recuperation energy from over-running loads. Consequently, a downsized supply system may be used since it can be laid out for the average cycle power rather than the peak power.

Controllability Due to the close proximity between the controlled element and the actual load, time delays due to capacitances in lines can be avoided. Furthermore, due to the hydraulic capacitance in the CPR, the dynamics of the energy source does not influence the load.

Despite the advantages, CPR systems and secondary control are today not widely used, but are found only in a few niche markets. One of the main obstacles to this technology being deployed on a wider scale is the difficulty to include linear drives [44]. To control cylinder force, either the hydraulic pressure or the cylinder area should be controlled. Throttle control using valves could be used to control pressure, but for varying high power loads the losses will become excessive. One way to reduce throttle losses to acceptable levels, as shown in recent studies, is to increase the number of pressure lines [75].

3.3.1 The transformer approach

One way to include linear drives in a CPR is to add a hydraulic transformer between the rail and the cylinder, as shown in Figure 3.13. The hydraulic transformer controls the load power by converting pressure and flow in a non-dissipative manner. Transformation goes in both ways and provides the opportunity for pressure amplification and energy recuperation.

Figure 3.13 Examples of hydraulic transformers used in CPR system, actuating a single-acting cylinder load (principle schematics).

In this dissertation the IHT solution is mainly considered for use with the CPR system. As for four-quadrant actuation of asymmetrical cylinder drives, several alternative circuit solutions exist. All solutions found in literature require additional valves as shown in [76, 77], where Figure 3.14a is one of the proposed solutions. In Paper [III], another solution is proposed, shown in Figure 3.14b. This solution broadens the actuator speed range for a given transformer size and works with similar control principles as the open-circuit PCS, described earlier.

Figure 3.14 Examples of transformer configurations that enable 4-quadrant actuation.

The IHT has been studied for use in CPR systems for both on-highway and off-highway applications, for instance in a forklift truck [78], then as part of

a passenger car transmission [79, 80] and in hydraulic excavators [81, 82]. In Paper [XIV] the proposed four-quadrant solution is applied to the linear drives of a wheel loader application, the results summarized in Section 4.3.

3.3.2 The multi chamber cylinder approach

Another option to include linear drives in a CPR architecture is to control the hydraulic cylinder area without prior pressure transformation. In [83] a solution to a “stepwise variable-area” was conceived based on a multi-chamber cylinder controlled by digital valves. The authors estimated a potential to reduce energy losses by 60% compared to a conventional load-sensing system. The control approach is inspired by the secondary-control principles normally applied to variable-displacement hydraulic motors. Based on this analogy, we refer to the solution as a Variable Displacement Linear Actuator (VDLA). There are many ways to design hydraulic cylinders with more than the normal two chambers. In Figure 3.15 three examples are shown.

Figure 3.15 *Different variants of multi-chamber cylinders.*

To control the cylinder a valve matrix is used that connects each port of the cylinder to the CPR via valves as show in Figure 3.16.

Since the introduction of the concept in 2009, it has been investigated and further refined for use in several industrial applications, ranging from material handling machines in [84] to aerospace applications in [85] and large-scale wave-energy converters in [86, 87]. In our studies in Papers [XVII] and [IV] the technology is suggested as a solution for wheel loaders. In [88, 89] followed by Papers [VI] and [V], the use in excavators is studied.

Control principles and losses

From a control perspective the VDLA poses challenges in both force control accuracy and energy efficiency. Since the actuator has many control inputs, there are numerous solutions to control of the system.

Figure 3.16 The VDLA, consisting of a valve matrix and a four-chamber cylinder.

A first simple approach is to consider the actuator a pure force control device with a finite set of force states. Velocity and position control are then possible by adding an outer control loop. By selectively connecting the chambers to either the high-pressure (HP) or the low-pressure (LP) rail, different steady-state pressures and force levels are achieved. For instance, when all four cylinder areas of the 4-chamber cylinder are unequally sized and two supply pressure levels are used, there are $2^4 = 16$ different control combinations, as shown in Table 3.1. The resulting force spectrum is illustrated in Figure 3.17. Alternative sizing patterns that yield different force spectra are described in [85, 87].

<i>idx</i>	A	B	C	D
1	LP	HP	LP	HP
2	LP	HP	LP	LP
3	LP	HP	HP	HP
4	LP	HP	HP	LP
5	LP	LP	LP	HP
6	LP	LP	LP	LP
7	LP	LP	HP	HP
8	LP	LP	HP	LP
9	HP	HP	LP	HP
10	HP	HP	LP	LP
11	HP	HP	HP	HP
12	HP	HP	HP	LP
13	HP	LP	LP	HP
14	HP	LP	LP	LP
15	HP	LP	HP	HP
16	HP	LP	HP	LP

Table 3.1 Force index and resulting pressure rail to connect to the respective cylinder chamber.

Figure 3.17 Force and pressure spectrum in steady state at cylinder standstill.

In this approach, the force index, *idx*, resulting in smallest force error is

selected and translated to valve commands where valves are commanded to either fully open or fully closed state. To avoid jittering when the reference is equally close to two forces, a hysteresis effect can for example be added [89], or a limit on how frequently switching is allowed [86]. Figure 3.18 shows a simulation result where discrete force state control is used. It can be observed how the pressure change between HP and LP at different rates among the chambers, resulting in an uncontrolled build-up in force, thus the spikes. The pressure rate depends on several factors, e.g. valve dynamics, oil bulk modulus, chamber volume and actuator speed, described in greater detail in the appended Paper [V].

Figure 3.18 Simulation result showing a typical force behaviour using discrete mode control with on/off valves. The problem with force spikes in transitions is circled in red.

To improve the force control accuracy, the idea of restriction control of a multi-chamber system was introduced in [90], where DFCUs are used to accurately control the opening area of valves within force states. The control principle combines secondary control with throttle control. By restricting the flow to the cylinder chambers, force is controlled within a given state. In [84], a similar approach to restriction control was taken, but instead using conventional proportional valves. In [91] and later also in [92], a mix of proportional valves and on/off valves is suggested. In this approach flow is only throttled on two of the chambers, while the rest are on/off controlled.

The main losses for the VDLA are resistive losses that arise in the valves controlling the cylinder. The losses are categorised based on which part in the control causes the losses:

Switching losses are due to both fluid pressure dynamics and valve dynamics.

Energy stored in hydraulic capacitance which is lost when the chamber switches from HP to LP and equally so when switching back again from LP to HP, a loss referred to as a compression loss. Compression losses are minimized by minimizing the hydraulic capacitance. If the piston is moving, the valve dynamics also cause switching losses as valves are partially open in a transition period when changing force states. These

‘transition losses’ are reduced by the use of valves with high frequency response.

Throttle control losses increase as restriction control is introduced. However, since restriction control can be used to avoid frequent switching, the additional throttle losses can sometimes be justified by reduced switching losses.

Internal leakage losses especially with regard to short-circuiting. Due to valve delays, a challenge is to control the system in ways that will avoid simultaneous opening of HP and LP valves. This problem is typically avoided by adding a time delay to the opening of valves.

In [83], the problem with switching losses is implicitly addressed by introducing a cost function, wherein ‘difficult’ mode switches are penalized and short-circuiting is avoided by introducing a time delay in valve opening relative to closing. In [86] the compression losses are explicitly calculated and considered in the cost function. In our studies in Paper [V], a model predictive controller is proposed as a solution to improve force control accuracy of the VDLA at a minimized expense of energy losses. The suggested approach also addresses the force spikes in mode switching, described earlier.

4

Case studies and experiments

AS A NATURAL STEP in concept design, systems are evaluated in software and hardware. During the research project, the investigated system concepts were simulated and/or physically demonstrated in laboratory environment and in mobile machines. In this chapter the experiments and application case studies are presented.

4.1 The pump-controlled wheel loader

After initial evaluations in a laboratory test bench [VII], the open-circuit pump-controlled system was implemented in a medium-size wheel loader, shown in Figure 4.1a. The prototype is based on a Volvo L60E, equipped with a 100 kW diesel engine, a hydrodynamic transmission for the drivetrain and an 85 cc pump for the working hydraulics. Changing from a valve-controlled system to a PCS requires most of the standard components for the working hydraulics to be replaced. Shown in the simplified hydraulic scheme in Figure 4.1b the lifting and tilting drive is equipped with the the new open circuit solution. The less energy intensive drives, such as the steering, the brakes and the auxiliary hydraulics, are still based on sensing hydraulics, using a down-scaled pump (56 cc).

A prototype open circuit over-centre electronically controlled pump with a displacement of 75 cc was used for each drive. Inside the pump, shown in Figure 4.2, pressure, displacement, temperature and shaft speed are measured. The integrated electrical pump controller is capable of flow and pressure control, where the pressure control is a feature primarily designed to function as a maximum pump pressure adjustment [93]. In the demonstrator, the pressure

(a) PCS demonstrator based on a Volvo L60E.

(b) Hydraulic schematics.

Figure 4.1 Demonstrator machine equipped with the pump-controlled hydraulic system.

control capability is used to re-establish the pressure required by the load prior to opening the valve holding the load. In the wheel loader the two pumps are mounted in a tandem configuration connected to the diesel engine via a fixed gear ratio. As regards the conceptual capabilities of energy recuperation, energy is mechanically transferred to all other power consuming systems powered by the diesel engine. Since the system contains no energy storage, the energy must immediately be converted to useful work or turned into losses otherwise the engine speed will increase causing traction on the wheel drive.

(a) The P1-IDEC pump.

(b) Pump schematic.

Figure 4.2 Electrical open circuit pump used in wheel loader (courtesy of Parker Hannifin Company, Ohio, USA.)

To meet the demands on mode switching, four seat valves of the Valvistor® type were designed and custom made for each cylinder drive in [VII]. For use in a PCS the standard Valvistor® originally presented by Andersson, B. [94], is modified to allow flow control in both directions. The manifolds containing the valves shown in Figure 4.3.

(a) Valve manifold.

(b) Manifold schematic.

Figure 4.3 Valve manifold for one drive, consisting of four valvistors.

The valvistor was chosen due to its great resistance against pressure distur-

bances, low leakage properties and its advantageous property of soft closing, useful in mode-switching. The valvistor inherently operates as a check valve or anti-cavitation valve if the slot is connected to the tank port. Moreover, pilot circuit of the valvistor can be complemented with additional functionality, such as a pressure relief or pressure compensation [95].

Cylinder mode control

To illustrate the usefulness of the mode control, Figure 4.4a shows the wheel loader is used in the short loading cycle. Heavy material is loaded and lifted slowly up to a truck, followed by rapid lowering in a differential mode. In Figure 4.4b the wheel loader is used for material handling. High elevation is reached rapidly and loaded material lowered carefully in a non-differential mode. In this example no modes involving throttling are used; for a real machine, the required modes of operation obviously depend on both the sizing of pumps and valves and the prescribed force and velocity characteristics of the duty cycle. If the maximum pump flow is not sufficient to meet the requirements

Figure 4.4 The optimum mode selection depends on the force and speed characteristics and thereby also on the field of application.

as regards a specified lowering speed this is compensated for by the use of the meter-out flow control modes. In such cases energy is not recuperated, but instead wasted as heat.

In the demonstrator no changes were made to the hydraulic cylinders, hence the system was not ideally designed for the use of mode-control. However, the Lowering of an empty bucket in the differential mode is not a problem, but no lifting motions were possible in this state, not for tilt and not for lift.

Test results

The demonstrator machine was benchmarked against a standard machine using a conventional load sensing hydraulic system, here referred to as LS-S. Fuel effi-

ciency was measured in the short loading cycle, with both machines operated by a professional operator. The measurement results are presented in Figure 4.5. The left staple pair shows a 9% reduction in consumed fuel volume per loaded mass of gravel, representing how the efficiency in pure Newtonian work is affected. The middle staple pair shows how the system saves 13% in fuel volume over time. The right staple pair shows a 2% longer average cycle time. The error bars on top of the staples show the maximum and minimum measurement value throughout the tests. The reduced variation in results observed in the measurements from the PCS indicates that the operability of the machine is at a good level. To highlight the impact of increased drag losses caused by the

Figure 4.5 Performance measures from the truck loading cycle.

added pumps a transportation test was performed on an oval test track. The engine speed was set to 1600 rpm and the gearbox was locked in fourth gear for both test objects. The measured difference in fuel consumption is presented in Figure 4.6.

Figure 4.6 Fuel consumption in a transportation driving test comparing the PCS prototype to the reference machine.

4.2 The transformer test bench

In Paper [XV] with a continuation in Paper [II] focus is on a two-machine transformer concept where the goal is to understand the challenges in control and propose solutions thereto. A central topic for these studies was controlling flow since that would make the transformer valuable component in the design of an CRS to a load sensing system. Figure 4.7 shows an example to how such an CRS could be added to a basic valve system.

Figure 4.7 An example of a CRS implemented in a valve-controlled system.

As a motivation for this experiment, the wheel loader was considered as a possible target application. Based on the systems intended functionality, the potentially recoverable energy is illustrated in Figure 4.8. The cycle presented is the short loading cycle, described in Section 2.1. The figure shows the losses categorised into such that occur in overrunning load cases and in parallel operation, as earlier described being the most predominant in today's system.

Figure 4.8 The targeted energy losses in a wheel loader operated in a short loading cycle. Losses occur during load lowering and in multi-function operation.

Hardware and controls

The test bench, shown in Figure 4.9, consists of two Bosch Rexroth (A4VG) variable displacement machines connected via a mechanical shaft. Each machine is equipped with a swash angle sensor and a rotational speed sensor. The work with building up hardware and testing developed control strategies was supported by the two master thesis studies [96, 97].

Figure 4.9 The pressures on the load side and the low-pressure side of the transformer are controlled by two separate pump systems and pressure relief valves. The flow sensors are used for validation and not for controlling.

The system is a Multiple Input Single Output (MISO) system, with the machine displacements as input and the load flow to the host system as output. A suitable angular velocity of the transformer must be maintained to avoid over-speeding and stick-slip effects at low speeds. The cross-couplings of the machine displacements, however, cause difficulties to intuitively build controllers in order to satisfy these demands. The system is stiff, with a small inertia which causes it to be sensitive to disturbances and pressure variations. There are also strong non-linearities, such as a high stiction torque during stand-still and at low angular speeds. This effect is crucial due to the low inertia, causing rapid accelerations and decelerations when rotating close to zero speed.

As part of the controller synthesis, the system is modelled as a rotating mass with inertia J , connected to the two displacement machines according to Figure 4.10a. The shaft torque on the transformer is generated from the pressure on the load and accumulator side, p_L and p_A , in reference to the low side pressure p_T . The relative displacement of the displacement machines are determined by the control signals ε_A and ε_L . The losses in flow and torque are modelled with separate efficiency models for the two machines. For the purpose of evaluating the developed controller prior to physical testing a simulation model was built up in the simulation software AMESim. The model, shown in Figure 4.10b includes efficiency maps for both hydraulic machines with respect

to pressure, speed and displacement. The net torque (ideal torque less torque

Figure 4.10 Modelling and simulation of the two machine transformer.

losses) affects the acceleration of the inertial load. The displacement control dynamics is modelled as a first order system. The load side flow is dependent on the rotational speed and the load side displacement. The loss modelling of the displacement machines is critical to the performance of the controller. The proposed model is based on Rydberg's models [18], with modifications to reduce the complexity of the expressions. Figure 4.11 shows a comparison between the difference in ideal torques produced by the two units running at a constant speed and the torque losses estimated by the the model. The result is for a validation data-set other than the data-set used for estimation.

Figure 4.11 Estimated and measured torque losses.

To further evaluate the model, the friction model with the calculated parameters was implemented in the simulation model in AMESim by modifying the components that were used in the model. Actual measurement data (relative displacement and pressure at both displacement machines) from a hardware test run was used as input to the model. See Figure 4.12 for an overview of the simulation model. The resulting transformer speed from the simulation

was then compared with the measured speed from the hardware test run. The result is visible in figure 19 together with the relative displacements and pressures. Even with a fairly advanced friction model like the one used here, it is clear that the non-linearity in the efficiency of the displacement machines makes it hard to get a good fit in the full working area of the transformer. Even small errors in the estimation of the torque losses causes large deviances between modelled and actual speed.

Figure 4.12 Validation of the friction model implemented in simulation by comparing the measured rotational speed with simulated rotational speed. Measured pressures and relative displacements are used as inputs to the simulation.

Results

The main test results from this experiment are shown in Papers [II] and [XV]. The control strategy is based on a non-linear feed forward link and a state feedback link that compensates for model-errors and disturbances. This combination allows good flow reference tracking and quick response time, given that the transformer is in motion. The forward link allows for good reference tracking, but it is highly dependent on correct estimations of the torque losses. Due to strong non-linearities in the friction between operating points, this is a major issue in the control problem. Another issue is the low inertia and slow control dynamics which poses challenges for the start-up process and difficulties when compensating for disturbances. Concerning the use of this solution in an CRS a main challenge is the round-trip efficiency in recovery and reuse of recuperated energy. With standard hydraulic machines, this configuration gives a poor efficiency since energy is converted twice in each loading/unloading direction.

4.3 The series hybrid wheel loader

Described in Paper [III] and [XIV], a series hybrid system based on CPR technology is designed and simulated for a wheel loader application. The proposed system uses IHT-type transformers for both the wheel drive and for all actuators in the work hydraulics. The principal system schematic is shown in Figure 4.13. The effectiveness of the proposed CPR system is assessed through simulation focusing on the short loading cycle. The 33 ton wheel loader, serving as a baseline in the study, uses a stepped mechanical transmission with torque converter and a load-sensing hydraulic system for lift, tilt and steering functions. In the proposed system the diesel engine only powers one single con-

Figure 4.13 Schematic of the simulated CPR system for the wheel loader.

stant displacement pump that delivers its power to the common pressure rail, including high- and low-pressure accumulators. To control the power supply a simple charging valve system is used to engage or disengage the flow supply. This means the torque load of the diesel engine is determined by the accumulator state-of-charge. For the propulsion a central drive unit is suggested where the mechanical gearbox and torque converter are replaced by two constant displacement motors controlled by a hydraulic transformer. The proposed solution yield three hydraulic gear states, where a transformer controls each of the motors individually or both combined. For the work hydraulics a set of 4 logic valves connects the transformers to the lift and the tilt cylinders. In similarity to the open-circuit PCS proposed in Section 3.1, this configuration enables ac-

tuation in different modes. The region of operation of the transformer system is illustrated by the three grey areas in the diagrams shown in Figure 4.14 and the energy consumed during the drive cycle is drawn as bubbles. In the

Figure 4.14 Operating points of the lift (a) and tilt (b) function. The size of the circles indicate the amount of energy usage for the various grid points. Also indicated are the operational areas and limits of the conventional load sensing system (pressure limit 240-260 bar) and the new CPR system with hydraulic transformers with 200 bar as a lower pressure limit for the CPR.

new CPR system, the engine is operated close to the best efficiency point and allows recuperation of energy from the drive and implement functions. The transformer system has different characteristics than the baseline system and therefore also different limitations in its working region. The selected sizes for this study yields an operating region which is more limited in the over-running load quadrants but has instead a much larger working region in the dissipative load quadrants. In addition, the valves between the transformer and the cylinder are also useful for load holding or a free-floating movement. In the short loading cycle, both the lift and the tilt functions have a considerable recuperation potential. As regards to the wheel drive, the amount of brake energy is not high, and the energy gained by recuperation is offset by the extra losses in the hydraulic transformers, valves, pumps, motors and accumulators.

Simulation results

The simulation is based on backward facing models where a recorded duty cycle is used as input to calculate the flow required from the CPR for each of the functions. The accumulator flows are calculated as the sum of flows from the supply and load side and the resulting pressure is derived based on a simple accumulator model. The supply system is controlled using a rule based strategy with a main objective to keep the state-of-charge within a certain limits. The resulting operation of the combustion engine is shown in Figure 4.15. The

Figure 4.15 *Simulated operating characteristics of the diesel engine for both systems. The size (i.e. area) of each circle represents the amount of fuel used at the corresponding engine speed and torque.*

resulting energy flow within the common pressure rail system is illustrated side-by-side to the energy flow of the baseline machine from which the load data was taken, in Figure 4.16. The result shows a reduction in energy consumption of 49%. When accounting also for the improved operation of the combustion

engine a further small gain is achieved resulting in a reduced fuel consumption of 51%.

Figure 4.16 Sankey-diagrams summarizing the energy flow found in the baseline wheel loader and the CPR based system. The work output are identical for both systems.

4.4 The excavator using multi-chamber cylinders

In this case study focus was on evaluating the secondary-controlled multi-chamber cylinder as a solution for linear actuation in a common pressure rail system. Tests are carried out on two separate test rigs, one stationary and one mobile. The stationary test rig was used for initial test, where focus was on gaining basic understanding of the control challenges.

4.4.1 Laboratory test bench

A test bench is built based on an excavator arm and boom structure from a mini-excavator. The hydraulic is depicted in Figure 4.17a. The 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 are dimensioned for a 3-pressure CPR system. The configuration yields 81 possible steady state force modes as visualized in Figure 4.17b. The manifold of each actuator contains 27 identical on/off valves, of which several are parallel connected allowing them to be used as DFCUs useful for investigating throttle control principles. The development of this test bench was done with support from the master thesis [88].

Figure 4.17 Test rig built up for initial evaluations of the VDLA concept.

A top view of the control structure is shown in Figure 4.18. The feed forward term consists of three parts: one dynamic part that calculates the force needed to accelerate the boom and the mass, one static part that calculates the force needed to lift the weight of the boom and the mass, and one term that calculates how much force is lost due the pressure drops over the valves.

Figure 4.18 High-level control structure used in the laboratory test bench.

The CPR pressures are used to construct a force matrix with all available forces. The control signal (desired force) is converted to the closest available force in force matrix and from there translated into a valve control signal for the individual valves. From the reference signal, velocity, the acceleration used in the dynamic feed-forward term is acquired by filtering the reference signal through a second order filter.

Figure 4.19 shows the result from one experiment where a score-based penalty system is used to avoid frequent switching of high amplitude pressure changes. High amplitude changes will have highest effect on the smoothness, especially if it occur on all chambers at the same time. A high amplitude change is rated high in score and a low amplitude change rated low. Due to constraints to how large loads could be applied to the test bench, test could only be carried out within a relatively narrow force range (approximately 10% of the full range). Given this constraint, the result in terms of force control was considered good enough to take the concept to a next level of evaluation, described next.

Figure 4.19 Operation of boom function within a narrow range ($\sim 10\%$) of the total force spectrum. Further test results are documented in [88].

4.4.2 Full-scale demonstrator

In this experiment a 30-ton class crawler excavator from Volvo CE is used as the host machine to evaluate the CPR architecture in full scale, including both secondary controlled rotary drives and linear drives based on multi-chamber cylinders. At the time of writing, this hydraulic hybrid demonstrator is still under development with a first publication provided in appended Paper [VI]. An overview of the prototype is shown in Figure 4.20 with a simplified schematic for the system shown in Figure 4.21.

Figure 4.20 Picture showing the demonstrator machine with brief description of the major changes relative to a standard machine of the same make.

Figure 4.21 An overview of the CPR system evaluated in the excavator.

Design and implementation

Compared to the baseline excavator, less pump capacity is needed due to the hydraulic accumulators proving the peak power. Accompanying the downsized pumps is a combustion engine rated at 30% lower peak power and 2x50L piston accumulators connected to each pressure rail. The supply side uses variable-displacement closed-circuit axial piston pumps with an integrated boost pump. The boost pump is used for charging the low pressure side at system start up. The installation on the excavator implement is simplified compared to a standard machine. Instead of using two separate pressure lines for each function, it is sufficient to have two lines in total, as shown in Figure 4.22. For the VDLAs, proportional valves are used to enable throttle control within the different force states, as described earlier.

Figure 4.22 VDLAs connected to the CPR on the excavator work implement.

With respect to force performance, the multi-chamber cylinders are sized for the worst case scenario, which is when HP-pressure is at its minimum and LP-pressure is at its maximum. Dimensioning of all components was carried out by the help from dynamic simulation as described in [VI].

The actuator uses feedback from integrated cylinder position sensors. For the swing drive a variable-displacement secondary-controlled axial piston motor is used. The angular speed of the machine upper carriage is measured and used in the control.

Control challenges

The challenges in control range from the lowest level in how individual valves are controlled to the highest machine level where power and energy management are central topics. The main insights to control, gained from practical testing can on a high level be summarized as:

VDLA controls To switch or not to switch, that is the question. As proportional valves are used, a force reference may be eliminated from any mode, but at different expense in throttle losses. The alternative is to switch to a different force state but with switching losses as a consequence. Switching losses consist of both transition losses and compression losses, where resistive losses due to partly open valves have turned out to be important.

Power/Energy management: Due to the accumulators on the CPR, the power availability is far greater than for a conventional system. If the

power take out is not actively controlled, all the energy stored in accumulators will quickly be drained as an operator gladly uses all power available to perform the work as fast as possible. When this happens the function speeds will be reduced as the common pressure supply becomes a flow supply, with a downsized flow source.

Secondary controlled swing is used on the machine. An angular position sensor is used in the feedback control of rotational speed. Given a relatively high upper carriage inertia a relatively slow dynamic response is required from the hydraulic pumps/motor to achieve acceptable control behaviour. The achieved overall performance is good, but challenges remains concerning controllability at low speeds. The main problems are due to mechanical play in a gearbox in which inertia is low, noticeable as mechanical noise and rough low speed control performance.

Test Results

The excavator demonstrator was extensively tested by four professional operators in tests side-by-side a standard excavator of the same make and weight class. The machine performance was evaluated in a digging and dumping cycle, where the excavator is used for loading gravel onto a load receiver. In the test, the machines are arranged so that the excavator has to slew 90 degrees from where it is digging to dump into the load receiver as shown in Figure 4.23. The test procedure is described in greater detail in Paper [VI].

(a) VDLAs visible on the boom, arm and bucket function.

(b) Accumulators installed outside the counterweight.

Figure 4.23 *Testing the demonstrator in the 90 degree digging and dumping cycle.*

To provide an overview of the results on a complete machine level, Figure 4.24 shows a comparison between the baseline and the demonstrator, referred to as ‘Hybrid’, with regards to fuel efficiency and productivity.

As to minimize the spread caused by differences in operator behaviour, four professional operators tested the machine. The results proves an improvement in fuel efficiency (ton/litre) in the range 34%-50% for all comparisons made in

Figure 4.24 Measurement results of fuel efficiency improvement over productivity improvement for four different operators.

the interquartile range, shown in distribution curves in Figure 4.25. In the 10th percentile of comparisons, the improvement is greater than 58%. The dispersion in results depends on the difference in operator behaviour and in which working mode of the baseline machine comparisons are made. The reduced fuel consumption is mainly due to reduced losses in the hydraulic system, and the main energy saving comes from energy recovery in boom down motions and swing deceleration. The productivity increase is a result of greater power availability, which enables faster multi-function operation.

Figure 4.25 Test result distribution shown as a histogram and as a cumulative function.

As demonstrated by these results, the potential of the common pressure rail solution in combination with VDLAs is very high. Worth pointing out is that the results shown so far are based on an early research prototype and there is still much room for efficiency improvements to be shown in future studies and publications on this technology.

5

Review of appended papers

This section provides a brief summary of each of the appended papers and its main contribution. Unless stated otherwise herein, the research leading to each paper and the writing of the paper itself are the work of the first author.

Paper I

“Applied Control Strategies for a Pump Controlled Open Circuit Solution”

The paper briefly introduces the open-circuit pump-controlled system’s hardware capabilities. It explains how the valve configuration inside the new system renders a solution versatile in control, allowing different discrete operational modes. The main concept studied in this paper was introduced by the authors in Papers [VIII, IX, VII] and validated in a practical application in Paper [X]. The main contributions of this paper are the increased knowledge of how different operational modes of an asymmetric cylinder affects the energy recuperation potential and a reasoning on the pressure matching in mode transitions.

Paper II

“Modelling and Control of a Complementary Energy Recuperation System for Mobile Working Machines”

This paper deals with an energy recuperation system based on a two-machine hydraulic transformer. Simulation and linear control theory are used to visualise the control challenge. A control method is proposed and validated in a

test bench where acceptable reference tracking is achieved. The main contribution of this paper is the demonstration of how a relatively simple control method can be used to control a hydraulic transformer despite its low inertia and non-linearities.

The main author wrote this paper as a follow-up to his master thesis on the same topic [97], wherein the second and third authors were the supervisors of the first author and assisted in controller design and testing. This paper is a continuation of the work carried out under Paper [XIII] and Paper [XV] supported by the master thesis study [96].

Paper III

“Towards Resistance-free Hydraulics in Construction Machinery”

In this paper a common pressure rail system is simulated. In the proposed hydraulic system, transformers of IHT type are applied to all functions of a wheel loader. A valve configuration enables multi-mode operation, making it possible to use smaller components. The main contribution of this paper is the proposed use of a hydraulic transformer for linear drives, where a valve configuration enables 4-quadrant operation. A second contribution is a methodology for how a transformer system could be dimensioned for a real application. This paper is associated to the studies carried out in Paper [XIV].

Paper IV

“A novel Hydromechanical Hybrid Motion System for Construction Machines”

This paper presents a simulation study where a common pressure rail system is applied to a wheel loader. For the propulsion system a hydromechanical power-split transmission is used and for the work hydraulics VDLAs based on multi-chamber cylinders are used. The system is modelled and simulated using an optimal energy management strategy based on dynamic programming.

The main contribution of this paper is a case study showing the benefits of a throttle-free bidirectional link between the machine’s subsystems and the energy storage, enabled by the CPR system.

The main author is responsible for the main part of writing the paper and the detailed design of the power split Continuously Variable Transmission (CVT) transmission. The second author was active in the concept generation phase that led to the proposed concept and in the definition and assisted in the description and inclusion of the linear actuation system.

Paper V

“Model Predictive Control of a Hydraulic Multi-Chamber Actuator: A Feasibility Study”

This paper presents a model predictive control strategy for a multi-chamber cylinder. The main objective is to achieve accurate force control with preserved energy efficiency. System modelling and simulation results are presented and the trade-off between energy efficiency and force tracking is discussed. The proposed controller is tested on a reference trajectory taken from a hydraulic excavator. The main contributions of this paper are a control framework along with new insights to the trade-off between the controllability and energy efficiency of a multi-chamber cylinder.

At the time of writing this dissertation, this paper is under review for publication in *‘IEEE Transactions on Mechatronics’*.

Paper VI

“A Hydraulic Hybrid Excavator based on Multi-Chamber Cylinders and Secondary Control: Design and Experimental Validation”

In this paper, a special type of multi-chamber cylinders and secondary controlled hydraulic motors are key components in the design of a highly efficient hydraulic hybrid system. The system is developed for and tested on a large hydraulic excavator. The evaluated system supports potential and kinetic energy recovery and storage using hydraulic accumulators. The study includes results from both simulation and real testing. The main contributions of this paper are the experimental results and a detailed description of energy flows within this novel hybrid system.

The main part of writing, conceptual design, practical tests and energy analysis is the work of the main author. However, the demonstrator machine was built as a joint project effort between the two companies Volvo CE and Norrhydro OY, where all the team members contributed to the results presented in this paper. The main author was the technical project leader at Volvo CE.

At the time of writing this dissertation, this paper is under review for publication in *‘International Journal of Fluid Power’*.

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Summary and discussion

Demands increasing for reduced energy consumption of machines and vehicles, a demand that will most likely continue. As for mobile machinery, where a significant part of the consumed energy often goes to drive hydraulic systems, focus will increase on making those systems more energy-efficient. As described in this dissertation, there is a great potential to improve the efficiency of today's systems and there are several approaches to how this can be achieved.

The valve-controlled system architectures used in mobile machines today have typically evolved through years of iterations with application-specific refinements. This means it can be both difficult and expensive to completely switch to new system architectures. As an alternative, for some time to come it is possible to continue to meet the demands by incremental updates to the valve system. Focus in such updates will be on reducing the dominating losses typically found in over-running loads and losses in multi-function operation. To some extent this can be managed by means of rather simple changes such as increasing the number of pumps to reduce pressure compensation losses, or simply reducing the resistive losses by using bigger valves, hoses and connectors. The use of more efficient pumps also has a direct impact on the energy efficiency. Further options, focused on in this dissertation are summarized below.

Pump controlled systems

The basic principle in pump controlled systems (PCS) is to use one pump for each load, where the pump displacement is used as the primary control element. Generally the PCS requires more pumps than a conventional valve-controlled system and the pumps needs to be electronically controlled and high dynamic response is required. The solution offers decoupling of individual

work functions, thus effectively avoids losses in multi-function operation. It also enables energy recuperation by the use of negative displacement in regenerative load cases. Pump-controlled systems are sometimes referred to as ‘valve-less solutions’. However, for use in mobile machinery our studies have shown that valves are useful to achieve a compact and energy-efficient solution. In the proposed ‘open-circuit solution’ applied to a wheel loader, valves are used for load holding and multi-mode operation of an asymmetrical cylinder.

Identified challenges for the open-circuit solution are mainly related to the synchronous control of pumps and valves required for seamless four-quadrant operation and even more so to fully utilize the multi-mode capabilities. When operated in its differential mode, the resonance frequency is significantly decreased and thereby more noticeable to an operator. Since the hydraulic damping of a PCS is lower than that of a conventional valve-controlled system, active damping of oscillations is likely needed for precision control applications. The open-circuit solution uses pressure sensors in its controls, which comes with both benefits and drawbacks. One benefit is that it enables features such as load weighing and various operator assistance functions. On the other hand, since the concept relies on pressure sensors to be fully functional, extra precaution must be taken to safety and durability/reliability aspects. To get the most efficiency out of this concept, pumps with good part-load efficiency are of major importance. Furthermore, the sizing of hydraulic cylinders is critical to fully utilize the benefits of the multi-mode functionality.

Energy recuperation systems

The proposed solution is a complementary system that connects to the meter-out port of a valve system. By controlling the port pressure with a hydraulic motor, the meter-out pressure drop is altered and energy is recuperated by the motor. Torque generated by the motor is used directly in a mechanical connection to the base system or further transformed to other domains. In our studies focus was on a solution based on a hydraulic transformer and a hydraulic accumulator. Simulations and experiments on a two-machine transformer indicate a poor round trip energy efficiency and significant control challenges. To consider the transformer a viable solution for use in an energy recovery system, a high energy efficiency of the rotary unit is essential. Also, to realize a compact and cost-efficient solution viable for use in mobile machines, higher power density is desirable than that offered by a two-machine transformer. A promising alternative to several of these problems is the IHT (Innas hydraulic transformer) or a transformer based on digital displacement machines.

Common pressure rail systems

As a third architecture studied in this dissertation, the common pressure rail (CPR) systems has shown the highest energy saving potential. This system topology differs significantly from both a valve-controlled system and a PCS,

thus requiring considerable changes in a complete machine platform if transitioning from one or the other. Once in place, the system offers a modular design approach where new functions are simply added to the two rails that includes hydraulic accumulators as energy storage. All functions in the system can take the role of either consumer or producer of energy to the common pressure rail. Due to the energy storage all functions work virtually without interference from each other and a downsized supply system is focused on energy management of the energy storage.

The major challenge in applying the CPR architecture to mobile machines is the incorporation of linear drives. In this dissertation, the both hydraulic transformers and variable displacement linear actuators (VDLA) are investigated.

The transformer concept was evaluated through simulation, as a feasibility study with primary focus on energy efficiency in a wheel loader application. The VDLA concept was taken further, to physical implementation and tests on an excavator. The test results shows a significant increase in fuel efficiency and an augmented work productivity. Since the VDLA concept was experimentally validated, while the hydraulic transformer was only simulated, the confidence in viability is higher for the VDLA concept. However, one identified benefit to the transformer concept in relation to the VDLA concept is that transformers allow for pressure amplification. As the pressure level in the CPR varies with accumulator charge, the pressure amplification would make it possible to use smaller hydraulic cylinders and most likely also smaller accumulators. The fact that standard 2-chamber cylinders are well proven technology, while 4-chamber cylinders are not, could also be considered a benefit to the transformer concept. However, the aspect of controllability is a concern which require further investigation.

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Conclusions

In this research three system architectures are proposed as feasible solutions to improve energy efficiency in mobile machines. Key features of the systems are energy recuperation, function decoupling and energy storage. In relation to valve-controlled systems, the applications that benefit the most from energy recuperation are those with a high degree of negative mechanical work. Function decoupling is mainly beneficial in machines where several functions are used simultaneously. Systems with energy storage capability are mainly useful when recovered energy cannot momentarily be used by other consumers. Energy storage is also an enabling technology for sub-system and function decoupling. Further and more detailed conclusions are drawn by revisiting the research questions stated in 1.3.

RQ: How can energy-efficient hydraulic linear actuation be realized in mobile applications?

A: On a high level, it is important to recognize the hydraulic system as part of a bigger system, a complete machine, that serves a purpose for a user. Understanding the user's needs is the key to realizing an energy-efficient system. On a machine level, it is important to understand how the hydraulic system works in relation to other sub-systems to avoid sub-optimization. It is also important to recognize the machine operator as a part of the system and understand that changes to the hydraulic system may influence his or her operating behaviour and thereby affect the energy efficiency. In this work, this aspect has been considered by the use of full-scale machine demonstrators tested by more and less experienced operators.

RQ1: Which are the main challenges in the realization of energy-efficient mobile hydraulic systems?

A1: Challenges exist on many levels, where on a high level several competing design aspects such as system cost, controllability and safety must

be considered. In today's mobile systems, an acceptable compromise between these aspects is achieved. In a different setting where energy efficiency is of increased importance, the resistive losses associated with throttling of valves must be reduced. The main challenge is to achieve this with preserved controllability, at a cost level justifiable by the decrease in energy consumption. Another challenge is to design decoupled systems that allow components and subsystem to be individually optimized before an overall optimization on complete machine level can be performed.

RQ2: Which are the enabling technologies in the design of efficient linear actuation systems for mobile applications?

A2: In mobile machines solutions that enable recovery of potential and kinetic energy are often most critical. Also important is the introduction of energy storage, allowing improved power and energy management due to the decoupling of components and subsystems. Discrete mode control of hydraulic cylinders enables efficient variable power transformations for linear motions. As an overall enabling technology, electronically controlled components and model-based control techniques are essential constituents.

RQ3: What are viable system architectures for energy-efficient linear actuation in mobile applications?

A3: In this study, three different system categories are proposed, viable depending on application and targeted energy saving:

Pump-controlled systems (PCS) configured in an open circuit require one pump for each major function. The architecture enables energy recuperation and function decoupling. The system was demonstrated in a full-scale wheel loader where 10% reduced fuel consumption in a complete machine level was achieved, which corresponds to a reduced hydraulic energy consumption in the order of 20-25%.

Energy recuperation systems (CRS) have a potential to improve the energy efficiency of conventional valve-controlled systems by adding the features of energy recuperation and energy storage. However, no specific conclusions regarding energy savings are drawn for this system category as the results mainly concern the control challenges for one selected system. Viability for the selected system, a parallel hybrid using a two-machine transformer connected to an accumulator, highly depends on the use of efficient hydraulic machines and sophisticated control.

Common pressure rail systems (CPR) would in most cases involve considerable changes compared to conventional systems with

consideration to both supply system and actuators. The architecture enables energy recuperation, function decoupling and energy storage and has a potential to reduce hydraulic energy consumption in the order of 40-50%. Two separate solutions are proposed for linear actuators. First, a four-quadrant transformer of IHT type is proposed, where simulation results indicate that a fuel saving of up to 50% is feasible for a wheel loader operated in a short loading cycle for a system where both propulsion and work hydraulics are driven by transformers. The second is a 4-chamber cylinder controlled by proportional valves. The concept is investigated with respect to energy efficiency and controllability, then validated in a real excavator application. The system has been proven feasible through extensive testing, with a reduced hydraulic input energy consumption of about 30% and an increased fuel efficiency in the order of 30-50%.

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Outlook

We are starting to see how technologies previously researched in the field of energy-efficient mobile hydraulics are now reaching the market as commercial products. Good examples are independent metering valve technology and a variety of hydraulic hybrid solutions.

Regarding the pump-controlled systems studied in this dissertation, we see a need for pumps with higher part-load efficiency, where the digital-displacement technology probably has an important role to play. We also see a need for further development of hydraulic transformers and multi-chamber cylinders as key components of the CPR architecture, which is considered a suitable solution for both traditional combustion-powered machines and electrically powered machines.

For the future, we foresee a speed-up in development in the field of hydraulic. One of the factors that will contribute to this is the rapid development of electrical drive systems. To accommodate this trend, we see an increasing need for hydraulic systems designed for use with electric drive systems, with pumps driven by electric motors.

Considering the linear drives, electro-mechanical actuators (EMA) are sometimes argued for as a replacement for hydraulics. We believe this could be a solution for some applications, but for use in working machines there are imminent challenges to be solved related to cost, robustness, safety and physical installation, in particular for high power drives. The fact that the electric motor and the roller/ball-screw of an EMA are not easily separable complicates installation as bulky components mean a setback in the design of slender, weight-optimized machine structures. Hydraulic systems offer a flexible power transmission where several linear loads can share the same pump through efficient solutions such as the CPR system, using proven and robust components.

It should be underlined that the use of efficient hydraulic drive systems is compatible with the development of electric drive systems, where the means of power transmission of a hydraulic system provides a higher flexibility than a mechanical solution, e.g. with roller/ball-screws.

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