Forestry Crane with Electrohydraulic Flow-on-Demand System

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Abstract

The major issue developing sophisticated hydraulic systems is to significantly improve the energy efficiency without sacrificing the ease of control and operability. The present paper illustrates the upgrade of a mobile forestry crane from a hydraulic-mechanical Load-Sensing system to an innovative electrohydraulical Flow-on-Demand system.

1. Introduction and Objectives

Compared to conventional hydraulic setups, electrohydraulic systems offer new possibilities regarding energy efficiency and operability. In this context, the paper extends previous research in Flow-on-Demand applications, as a rising number of sophisticated electrohydraulic components available from series production make Flow-on-Demand implementation feasible a lot easier than some year ago. At the Karlsruhe Institute of Technology (KIT), a public funded research project is conducted to investigate the benefits and usability of an electrohydraulic Flow-on-Demand control. The innovative system is applied to a forestry crane and compared to a conventional hydraulic-mechanical Load-Sensing (LS) system as technical reference in terms of energy efficiency and operability. In a first step, the system is represented using simulation methods, followed by extensive validation on a hydraulic test rig. The project will conclude with the buildup of a forestry machine prototype.

2. Flow-on-Demand Principle

Mobile working hydraulics mainly consist of linear actors that move all kinds of loads. Hereby the cylinder stokes are controlled by joystick signals that pose either a pressure *or*, more common, a flow demand from the operator. In state-of-the-art Load-Sensing systems, pressure compensators ensure the load independent velocity control, making them purely flow controlled. Nevertheless, using a hydraulic-mechanical pressure controller, the pump displacement remains pressure controlled in these systems. [1]

In contrast to that, Flow-on-Demand systems are entirely displacement or flow controlled. Initial considerations on aggregate flow controls by [2] were later refined by [3] and [4]. Rising interest among academia is displayed by the publications of [5], [1] and [6], entailing the need for a discussion on terminology, that can be found in [7].
The basic idea behind the Flow-on-Demand principle is to calculate the required oil flow through the consumer velocity inputs of the electronic joysticks, or by reading back the valve spool positions with integrated displacement sensors. The aggregate flow, delivered by an electrohydraulic variable displacement pump, is to match the single flow demands. The system pressure settles slightly above the highest load pressure (see Figure 2.1b) achieving significant energy efficiency advantages compared to LS systems (see Figure 2.1a), especially in partial load cases.

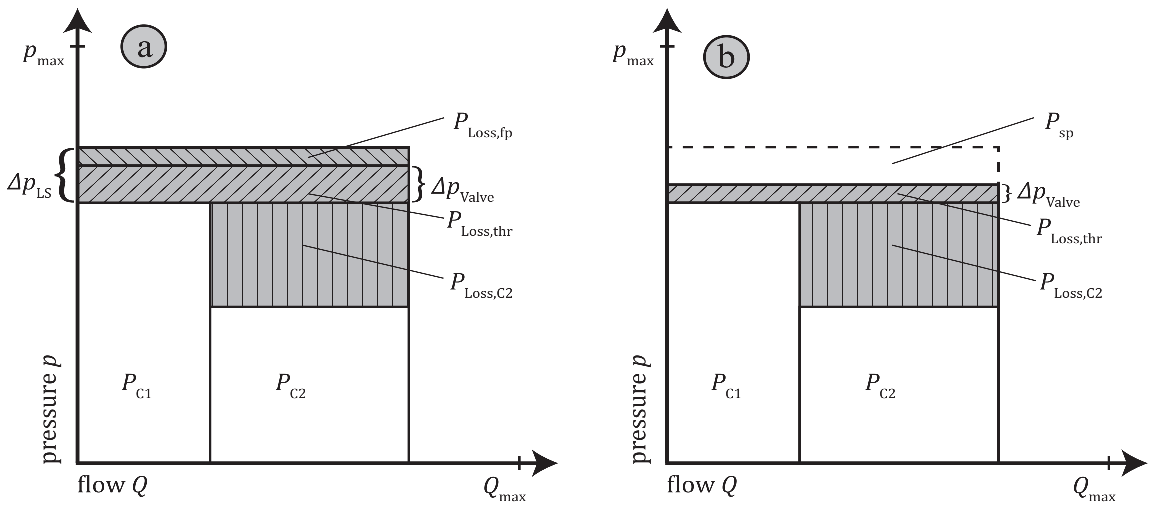

Figure 2.1: Power Consumption of Load-Sensing (a) and Flow-on-Demand (b) Systems

To avoid load interference, [3] and [4] studied system layouts with common pre compensators, later [5] proposed a setup with downstream flow sharing compensators. The actual flow matching is conducted via different control strategies with varying complexity in hard- and software, flow sharing precision and energy efficiency. Flow-on-Demand control concepts may be classified in closed or open loop controls, relying on a varying amount of sensor data [3]. The setup chosen for the project at KIT is shown in Figure 2.2, representing an easy but efficient Flow-on-Demand layout with open loop control architecture.
The simplified illustration dispenses with representing the consumers. The directional valve is displayed as adjustment meter-in orifice, the return flow is not shown. The variable

displacement pump is controlled electronically. It is additionally equipped with a pressure limiting hydraulic-mechanical controller to avoid pump damage in case of malfunctions.

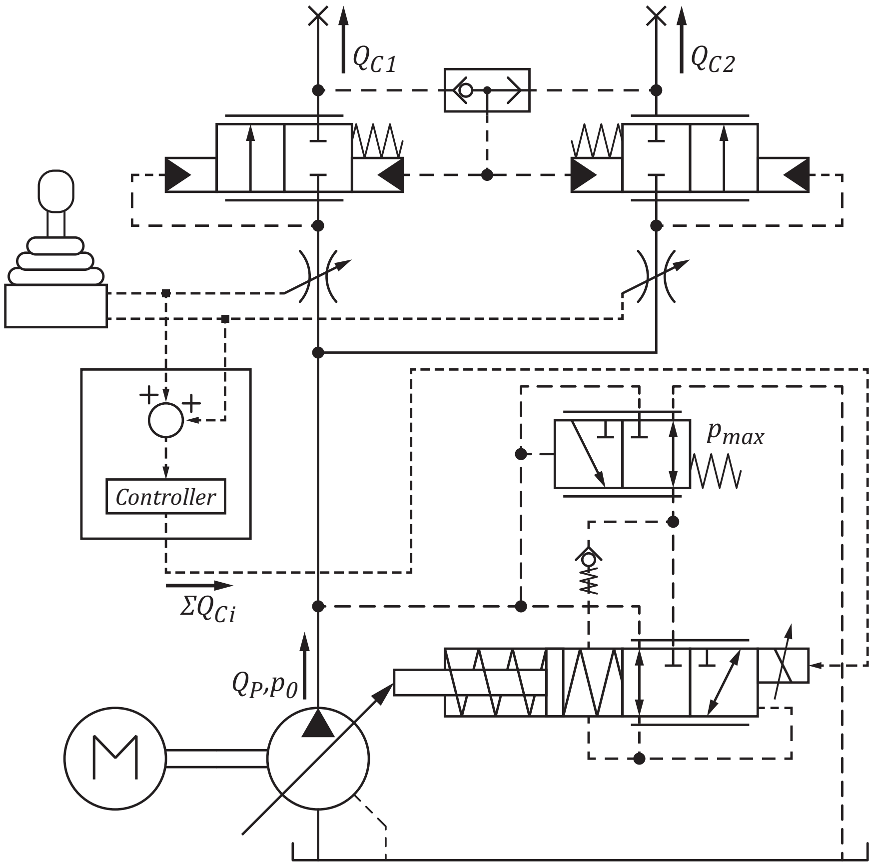

Figure 2.2: Flow-on-Demand hydraulic layout with post compensators

3. Advanced Flow-on-Demand Control Strategies

A novel control concept is being introduced to prevent flow oversupply in case of consumers reaching cylinder end stops. In this case the consumer velocity inputs and the actual consumer oil flows do not match any more. If the aggregate flow of the pump is solely calculated through addition of these consumer velocity inputs, the pump delivers too much oil into the systems, accelerating the residual consumers in an undesirable manner. To overcome the issue, the system may not stay sensorless. Thus, the project constraint to use off-the-shelf components remains valid by deciding on control valves

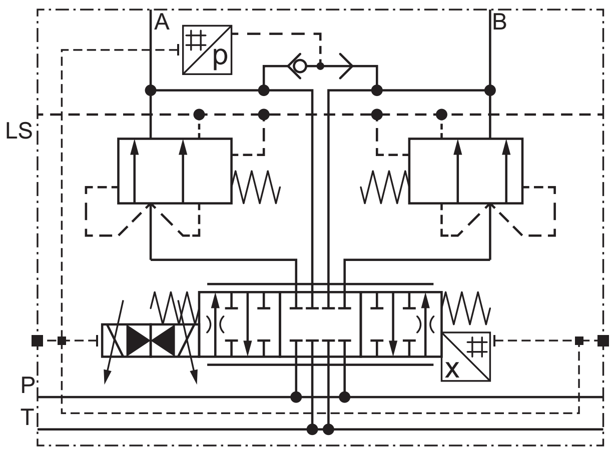

Figure 3.1: selected spool valve with post compensator and pressure transducer

that are equipped with additional, internal pressure transducers (see Figure 3.1) and implementing electronic pressure limiting functions. Reaching an end stop causes the consumer pressure to rise to its preset maximum. In turn, the related control valve switches from flow control mode to pressure control mode, ignoring the joystick input and controlling the pressure by reducing the control edge opening. The respective closed-loop control is displayed in Figure 3.2.

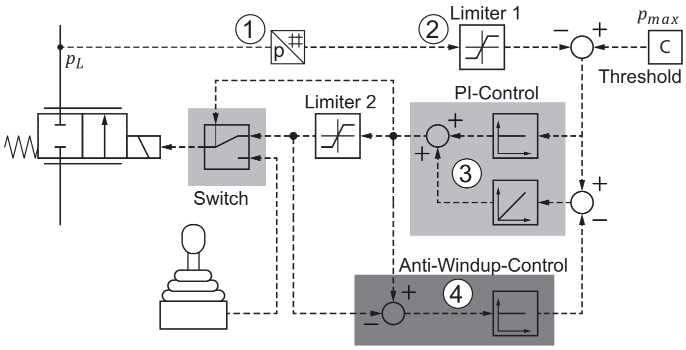

Figure 3.2: electronic pressure control

The load pressure p_L behind the valve is measured by a pressure transducer (1) and compared to a threshold. Due to a limiter (2), which sets the minimum value of the load pressure to the threshold, the comparator just passes a signal unequal to zero if the pressure is above the threshold. In this case, the error is conducted to a proportional-integral (PI) controller. This provides accurateness for the maximum pressure values. The value behind this controller switches, once it has reached a threshold, the command of the valve from the user to the pressure-control of the valve (3). Another limiter restricts the signal of the PI-controller, so the valve closes if the maximum pressure is reached. Due to the fact, that the valve is not constantly following the values of the PI-controller, the stability of the system requires an anti-windup controller (4). This anti-windup controller subtracts the difference of the values before and after the limiter from the value leading to the integral part of the PI-controller. Through the feedback of the anti-windup controller, the value of the integral part of the PI-controller will not grow through the limitation. To calculate the aggregate pump oil flow, no longer the velocity input is utilized but the flow corresponding to the valve spool position.

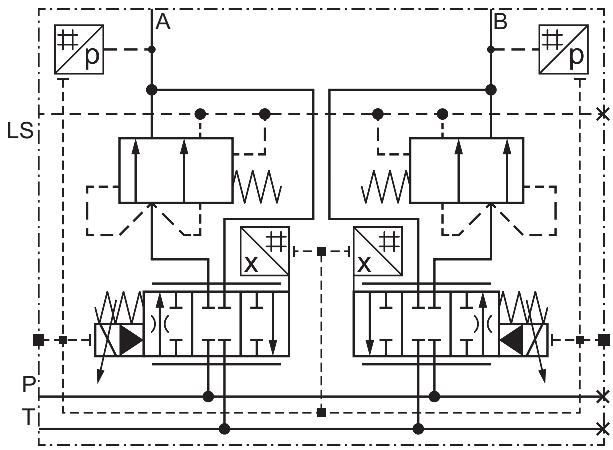

Figure 3.3: segmented spool valve

A further issue is the poor damping characteristic of a standard meter-out orifice, being firstly addressed by [1]. Especially concerning dragging loads, unwanted aftereffects may occur. As elaborated orifice design is the decisive factor, but not being detailed in the simulation models, the authors have included an innovative directional valve into the hydraulic test bench layout. The concerned device has a segmented valve spool, which allows for independent activation of the control edges P-A from B-T, respective P-B from A-T. The flow rate is calculated according to the meter-in orifice position, which is related directly to the desired consumer velocity. To avoid too fast consumer movement induced by dragging loads, the meter-out orifice may be used to throttle the outlet flow appropriately. Therefore the valve is equipped with two integrated pressure transducers. A closed-loop control shuts the meter-out orifice as narrow that negative pressure and thus cavitation on the inlet side are prevented.

4. Characteristic Forestry Crane Duty Cycle

The selected reference application, the feeder crane of a mobile log debarker is equipped with measurement technology to record hydraulic pressures and flow rates as well as cylinder strokes and velocities. The measurement results are used to parameterize and validate the simulation models, consisting of five main consumers, namely crane slewing, boom- and bucket cylinders, gripper and associated rotation unit. The consumers are divided into two decoupled hydraulic circuits with variable displacement pumps being powered by a diesel engine. Additionally the machine has several auxiliary consumers, e.g. the telescopic arm and the hydraulic outriggers, not taken into account for the derived characteristic duty cycle. The specific consumer movements, namely cylinder strokes and rotation angle, are displayed in Figure 4.1, the numbers (1 - 2 - 3 - 4 - 5 - 1) in the figure indicate the slewing position of the crane. The crane starts in position 1, grips the log a first time in position 2 and places it in position 3. Being gripped a second time in position 4, the log is fed to the debarker from position 5 on. The log is released, leaving the crane in its initial position 1, ready for the next cycle.

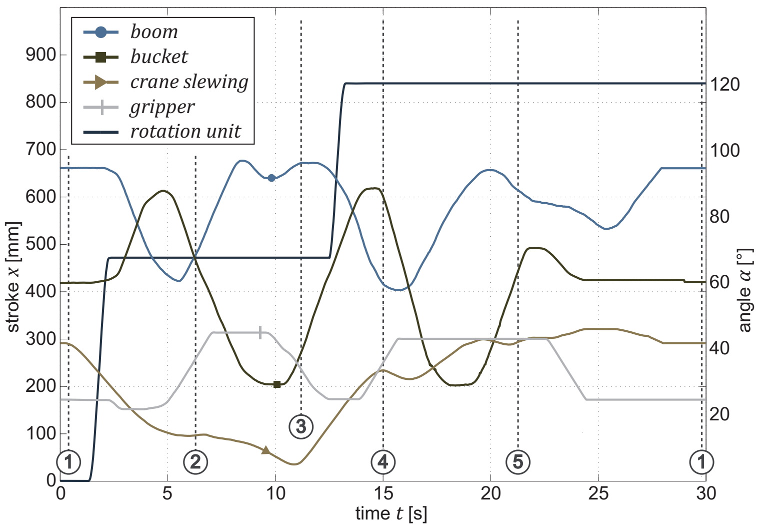

Figure 4.1: duty cycle - consumer movements

Selected by availability and moreover its high workload and daily hours of service, the sample application represents other forestry crane applications with similar duty cycles like timber transporters, forwarders and wood chippers, implicating potential energy savings in the same range, at least concerning their cranes. The duty cycle of a timber transporter crane is exactly the same, also having two pick-up points and two release points, only that the overall workload is wane due to major driving shares in the complete duty cycle of the transporter. Apart from usually only gripping a log once, duty cycles of forwarder and wood chipper cranes also correspond, despite the latter frequently using its telescopic arm to feed the chipper.

5. Dynamic Simulation Results

In the first instance, the real Load-Sensing reference application is remodelled in the simulation environment, followed by the buildup of the simulation model of the innovative Flow-on-Demand concept crane. Both systems are compared over the characteristic forestry crane duty cycle (cf. chap. 4). The simulation results reveal promising efficiency improvements of the Flow-on-Demand system. Figure 5.1 depicts the pressure histories of the two hydraulic pumps, clearly showing the pressure level of the flow-on-demand system lying always at least 10 bars beneath the LS-pump pressure.

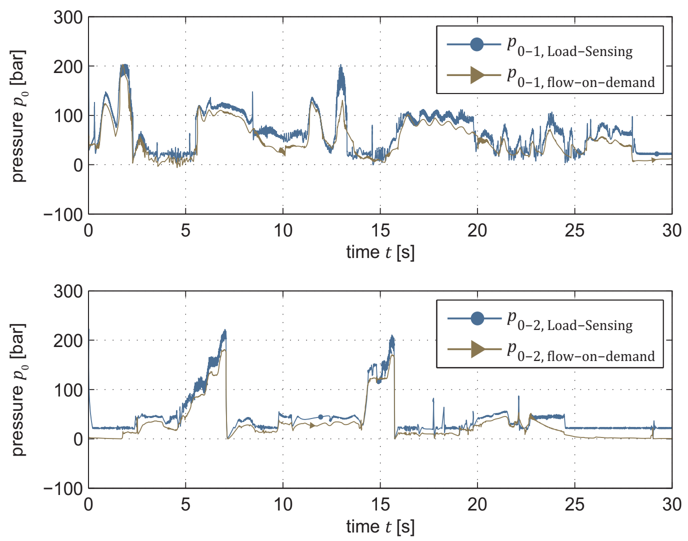

Figure 5.1: pressure history over duty cycle

Calculating the system power consumption via multiplication of pressures and flow rates allows for the integration of the energy saving potential, which simulation outputs reveal to be up to 15 percent.

6. Hydraulic Test Rig

The layout of the hydraulic test stand includes an electrohydraulic displacement pump and three hydraulic consumers. Namely a pressure adjustment orifice in bridge connection and two differential cylinders that may be coupled to imprint dragging loads.

The results of the first test runs are shown in Figure 6.1. The input is a constant flow rate demand over Valve 1 to the load bridge with parallel cylinder movements, followed by a ramped flow rate solely over Valve 1. On the left side (a), the pressure courses of the pump and the highest load are displayed. As expected, the pump pressure settles about 10 bars above the highest load pressure. The consumer flow rates on the right side (b) add up to the aggregate pump flow rate. The offset is explained by internal leakages and mainly by the pilot oil demand for the valve block.

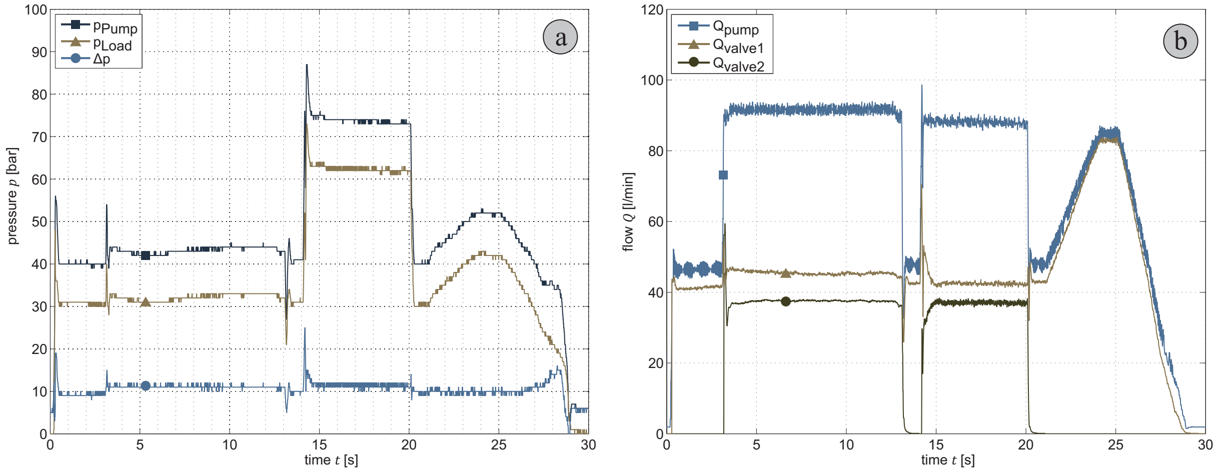

Figure 6.1: pressure courses (a) and flow rates (b) of test run with 2 consumers

The peaks in both pressure courses and flow rates come from the so far not optimally synchronized pump and valve controls. Nevertheless, these first results are promising, as the pressure level is significantly lower than in comparable Load-Sensing systems and the flow rate distribution works load independent and virtually without consumer cross interference.

7. Conclusion

In mobile machines the operator inputs usually depict velocity and thus flow demands. The idea to replace the pressure controlled flow supply with a completely flow controlled system is inherent in Flow-on-Demand hydraulic systems. The present paper displays the feasibility of applying such a Flow-on-Demand system to one of the most delicate applications in mobile hydraulics, namely a forestry crane.

8. Outlook

Being fine-tuned and intensively tested on the hydraulic test rig at the Chair of Mobile Machines, the transferal of the developed Flow-on-Demand system to a forestry crane prototype depicts the next project step. Scientifically, the combination of flow controlled systems with independent meter-in/meter-out valves calls for further research. Energy saving potentials through regenerative and recuperative operational modes are outlined in [1]. In the light of ample research activity concerning electrification of mobile machines, the combination of a fixed displacement pump with a speed controlled electric motor to adjust the pump flow rate of a Flow-on-Demand system may depict a cost efficient intermediate step towards direct driven electro hydraulic actuators.

9. Acknowledgements

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