CONTROL OF MOBILE HYDRAULIC CRANES

Marc E. MÜNZER
Aalborg University
Institute of Energy Technology,
Pontoppidanstræde 101
DK-9220 Aalborg, Denmark
Email: mmun@iet.auc.dk

The goal of the thesis described in this paper is to improve the control of mobile hydraulic cranes. The thesis is split into five parts: a requirements analysis, an analysis of the current systems and their problems, an analysis of different possibilities for system topologies, development of a new control system for the near future based on electro-hydraulic separate meter in / separate meter out valves, and finally an analysis of more advanced and complex solutions which can be applied in the more distant future. The work of the thesis will be done in cooperation with industry so the thesis will have more of an industrial focus than a purely theoretical focus.

Key words: Mobile Hydraulic Cranes, Control Strategies, Separate Meter-in/Separate Meter-out.

1 INTRODUCTION

The goal of the thesis described in this paper is to improve the control of mobile hydraulic cranes. A mobile hydraulic crane can be thought of as a large flexible mechanical structure which is moved by some sort of control system. The control system takes its input from a human operator and translates this command into the motion of actuators which move the mechanical structure.

The definition of this control system is purposely left vague in order not to impose any constraints on its design. The control system consists of actuators which move the mechanical structure, a means of controlling the actuators, a means of supplying power to the actuators, and a way of accepting inputs from the operator. It is this control system which is the target of this thesis. The goal is to analyze the requirements made on the control system and present guidelines for the design of new control systems.

The thesis will be split into five parts:

1. Analysis of the requirements of the control system, from the perspective of the operator, the mechanical system, efficiency, stability, and safety requirements.
2. Analysis of current control systems and what their problems are.

Proc. of 1st FPNI-PhD Symp. Hamburg 2000, pp. 475-483

3. Analysis of the different options for the control system: different types of actuators, different types of control strategies, and different ways of organizing components.
4. Presentation of a new type of control system, which is commercially implementable. A system that will meet the needs of industry in the near future.
5. Analysis of more optimized systems, with higher performance, better efficiency, more flexible control, etc. This will be less commercially applicable but will be a starting point for more research.

2 SECTIONS OF THE THESIS

2.1 Requirements Analysis of the Control System

Before starting detailed work on developing new control systems, it is important to analyze what the exact demands are on the control system. The control system is influenced by many factors. For example: the mechanical structure it is controlling, the human operator, efficiency, stability, and industry regulations.

Industry regulations are the first requirements that have to be addressed. Things like hose rupture protection and runaway load protection make a lot of demands on the control system. After regulations, stability is the next most important requirement; without stability the control system can't be used. Once stability has been assured, the performance requirements of the control system have to be set. They are determined by the mechanical structure of the crane and the human operator. The mechanical structure of a mobile hydraulic crane is a very large flexible structure which has very low natural frequencies. To prevent oscillations it is necessary to keep the speed of the control system below this natural frequency or to develop a control system which can increase this frequency. The human operator also imposes limits on the control system. If the control system is too slow or too fast then it is impossible for a human operator to give it proper inputs. And finally, once the regulations have been met, stability is assured, and the performance is at the right level, the power efficiency of the control system has to be optimized.

2.2 Analysis of Current Control Systems

Before designing a new control system it is good to analyze the current control systems to find out what their problems are. Current control systems are mainly hydraulic and can suffer from three main problems:

1. Instability
2. High cost
3. Inefficiency

2.2.1 Instability

Instability is a serious problem as it can cause injury to human operators or damage to equipment. When a system becomes unstable it usually starts to oscillate violently. To avoid instability in current systems, the designers either sacrifice certain functions which are desirable, or add complexity and cost. For example, in the crane shown in Figure 1, it would be desirable to have control over the speed. But due to the safety system that cranes are required to have, standard speed control is not stable. To add speed control requires a more complex and more expensive mechanical system.

The parameters of a hydraulic system, such as temperature or load force, also affect stability. A system that is stable with one set of parameters might be unstable with another set. To ensure stability over the entire operating range of the system, performance must sometimes be sacrificed at one end of the parameter range.

2.2.2 High cost

Current systems are purely hydraulic-mechanical, so if the user wants a certain function, the user buys a certain hydraulic-mechanical component. Because most users have different requirements, there are many different variations of the same basic component. This means that many specialized components must be manufactured rather than one standard product. This drives up the cost of components.

2.2.3 Inefficiency

One form of inefficiency in current systems is due to the link between the flows of the two ports of the cylinder. This is because most valves use a single spool to control the flow in both ports. Because of this link, it is impossible to set the pressure levels in the two sides of the cylinder independently. Therefore, the outlet side will develop a back pressure which acts in opposition to the direction of travel, which increases the pressure required on the inlet side to maintain motion. Since the force generated by the actuator is proportional to the pressure difference between the two sides, the actual pressures in the cylinder don't affect the action of the cylinder. For example, the action of the cylinder for 0psi/600 psi would be the same as 1000psi/1600psi. However, in the second case, the power supply would have to supply much more power. This extra power is wasted.

2.3 Different Options for Control Systems

Current control systems use hydraulic actuators with directional/proportional valves to control the movement. However there are many different options for controlling a cylinder. Options range from new high performance electro-hydraulic valves, to separate meter in / separate meter out (SMISMO) valves, to hydraulic bus systems, to intelligent actuators with built in power supplies, to pump based control strategies. These systems all have advantages and disadvantages which need to be analyzed if the most optimum solution is to be chosen.

2.4 Near Future Solution

It is expected that even if it is proven that a completely new system topology is the optimum configuration, the crane manufacturers and component manufacturers will not accept the new technology overnight. This will most likely take time, so an interim solution will be developed.

This solution will be made up of micro computer controlled Separate Meter In / Separate Meter Out (SMISMO) valves (Elfving, Palmberg 1997; Jansson, Palmberg, 1990; Mattila, Virvalo 1997). SMISMO valves will make it possible to implement new control strategies which are more efficient and stable. The micro computer will make it possible to introduce flexibility to valves. Variants can be programmed in software. This eliminates the need to manufacture hundreds of different variants. The crane manufacturer will be able to choose the exact functions he wants in his valve, while the component manufacturer will have to manufacture only one valve. This will lower the cost, even though the performance will have increased.

2.5 Analysis of Higher Performance Solutions

This analysis will depend on the results of the analysis of different topologies. If it is shown that pump based control is to be the way of the future for example, then analysis will be performed in this area. Another area which will also be explored, is tool position control.

3 LABORATORY FACILITIES

As the focus of this thesis is on developing control strategies that can be implemented on commercial machinery, much emphasis will be placed on experimental results. Experimental results will be obtained from two systems. The first, a simple one degree of freedom crane, was designed as an experimental platform. The second is a real crane which was donated to the University by Højbjerg Maskinfabrik (HMF) a Danish crane manufacturer. Refer to Figure 1.

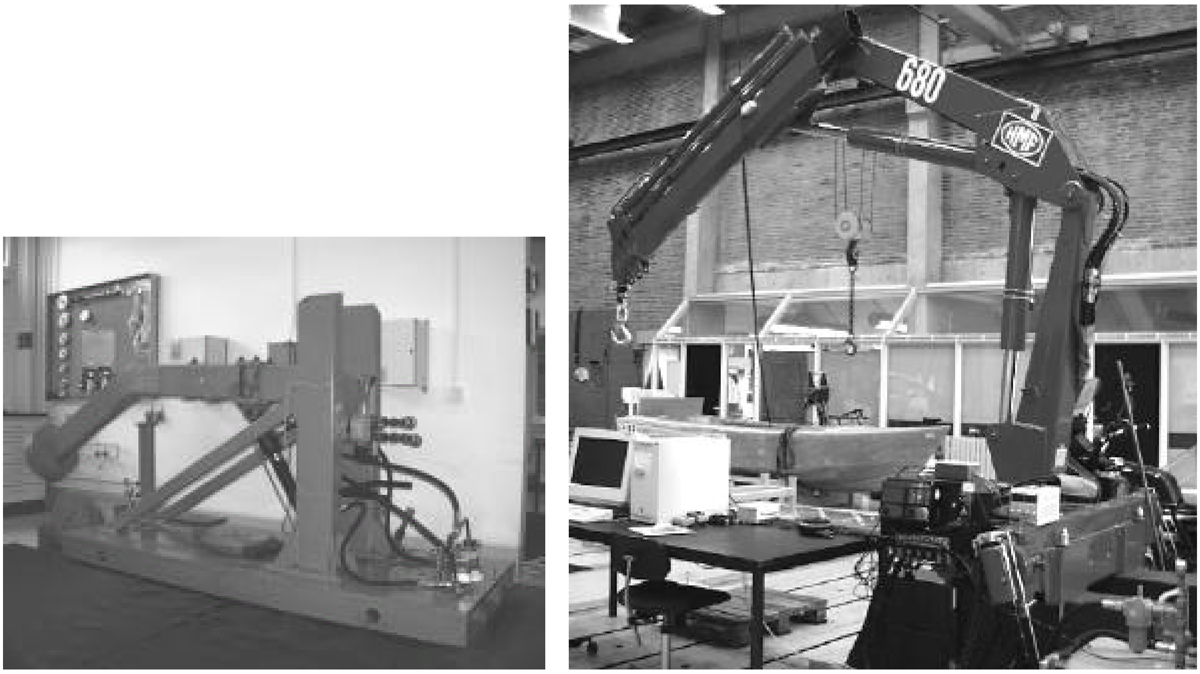

Figure 1 Experimental Systems in Laboratory. Left: One DOF crane model. Right: Real Mobile Hydraulic Crane

As there are currently no commercially available separate meter-in/separate meter-out valves, two separate valves will be used instead. A sample circuit of one cylinder is shown in Figure 2. The control algorithms which control the valves, will be programmed on a Digital Signal Processor (DSP)/Pentium dual processor system. The DSP will run the control code and the Pentium will do diagnostics and provide a graphical user interface.

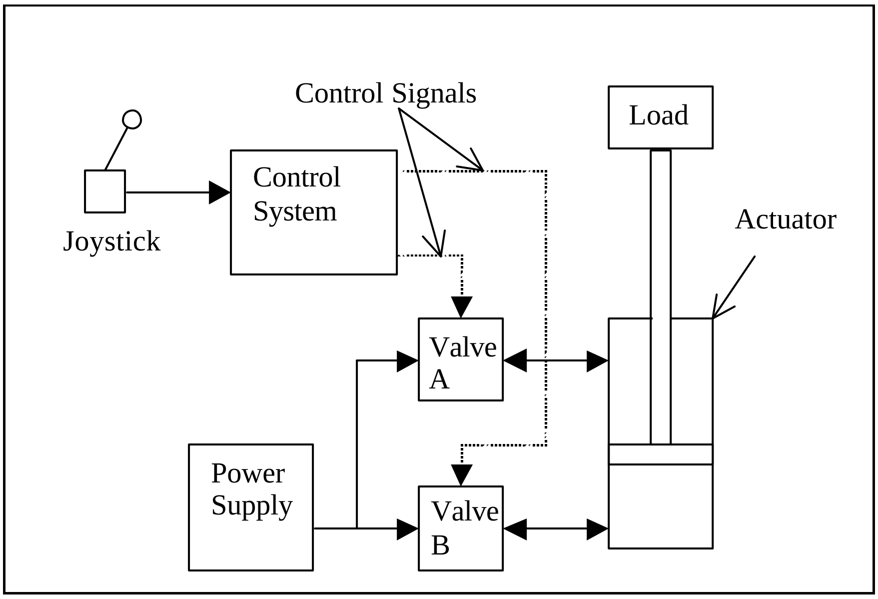

Figure 2 Separate Meter In / Separate Meter Out Setup

4 CURRENT WORK

4.1 Flow Control by Direct Actuation of the Spool

Most flow control valves on the market today work with a pressure compensator (Andersen; Ayres 1997). The pressure compensator keeps a constant pressure drop across the main spool of the valve, which keeps the flow constant. However, the addition of a pressure compensator makes the valve more complicated than a simple single spool valve. Another way of doing flow control is to measure the pressure drop across the valve and adjust the spool position to account for this (Backé; Feigel 1990). This is not a new idea but has not been implemented commercially because of the high cost of pressure transducers and micro controllers. However, with the current drop in cost of micro controllers and pressure transducers this idea is now commercially feasible.

The concept is very simple, spool position is calculated from the Bernoulli equation using the pressure drop across the spool and a reference flow.

$$x = \frac{q_{ref}}{K\sqrt{\Delta P}} \tag{1}$$

Even though this is a simple equation, it is not easy to implement. The accuracy of the flow control is dependent on the precision of the position sensors and of the pressure transducers. Noise on the pressure or the position signals can cause stability problems. Filtering the noise, introduces delays in the control which can also affect stability. In addition the Bernoulli equation is not followed exactly over the entire operating range of the valve, so it may be necessary to store the valve characteristics as a data table or develop a more complex equation.

4.2 Cylinder Control Strategy

To control a hydraulic cylinder, the strategy has to be able to handle four different situations depending on the directions of the load and the velocity of the cylinder. Refer to Figure 3.

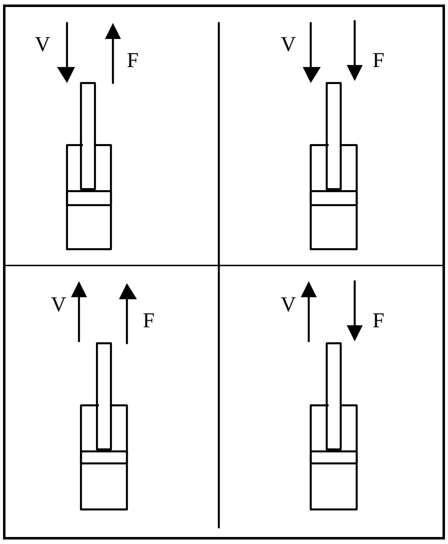

Figure 3 Different Situations in Crane Operation

The control strategies that have appeared in the literature are usually quite complex and depend on measurements of the cylinder position and velocity (Elfving, Palmberg 1997; Mattila; Virvalo 1997). They are also based on rather complex control algorithms. It is the goal of this thesis to start with a control strategy which is based on simple PI controllers and makes no demands for position and velocity of the cylinder. The performance of this system will be lower than a complex control strategy, but it may be easier to implement commercially because it has no need for special sensors and is easier to understand for the average engineer.

Another feature which needs to be acknowledged when designing a control strategy, is the type of valve used. Mobile hydraulic valves demand low leakage and since most mobile valves are spool valves, they usually have large overlaps. In addition, to make the cost of the valve acceptable to industry, the actuation stage on the spool is usually quite slow. This combination of large overlap and slow actuation makes it hard to implement many of the strategies that have been presented. Pressure control especially becomes difficult when there is an overlap and a slow actuator.

One example of a new strategy which is simple and robust is described as follows. Flow control is implemented on the inlet side and pressure control is implemented on the outlet side. The flow control is based on the Bernoulli equation. Pressure control is done by a PI controller which maintains a low constant pressure to increase the efficiency and prevent cavitation. To work around large overlaps and slow actuation stage, the pressure controller only does meter out control. This means that if the controller wishes to raise the pressure, it can’t add flow to the cylinder, it can only decrease the opening of the meter out port. The benefit of this is that the only time that the spool has to cross the zero position is when the operator wishes to change the direction of motion of the cylinder. For the case where the load force and the velocity are in the same direction, this strategy has to be modified. In this case, the pressure reference of the pressure controller at the outlet is increased to a value which opposes the load force. The pressure reference is increased when it is noticed that the pressure of the inlet side is dropping. The pressure reference is also controlled by a PI controller. A schematic model of the controller system for the load lowering case is shown in Figure 4.

At the time of writing this paper the initial experimental tests had been performed on the real crane shown in Figure 1. Stability was not achieved because the crane is equipped with a load holding valve. However, the load holding valve will be replaced with a pilot operated check valve, which should make it possible to stabilize the system. In current systems, the load holding valve serves two functions, load holding and runaway load protection. Due to the use of a SMISMO valve setup, the runaway load protection is built into the control strategy, therefore the only function which is necessary for the load holding valve to perform is load holding. A pilot operated check valve will be able to do this, without adding complex dynamics which upset the stability of the system.

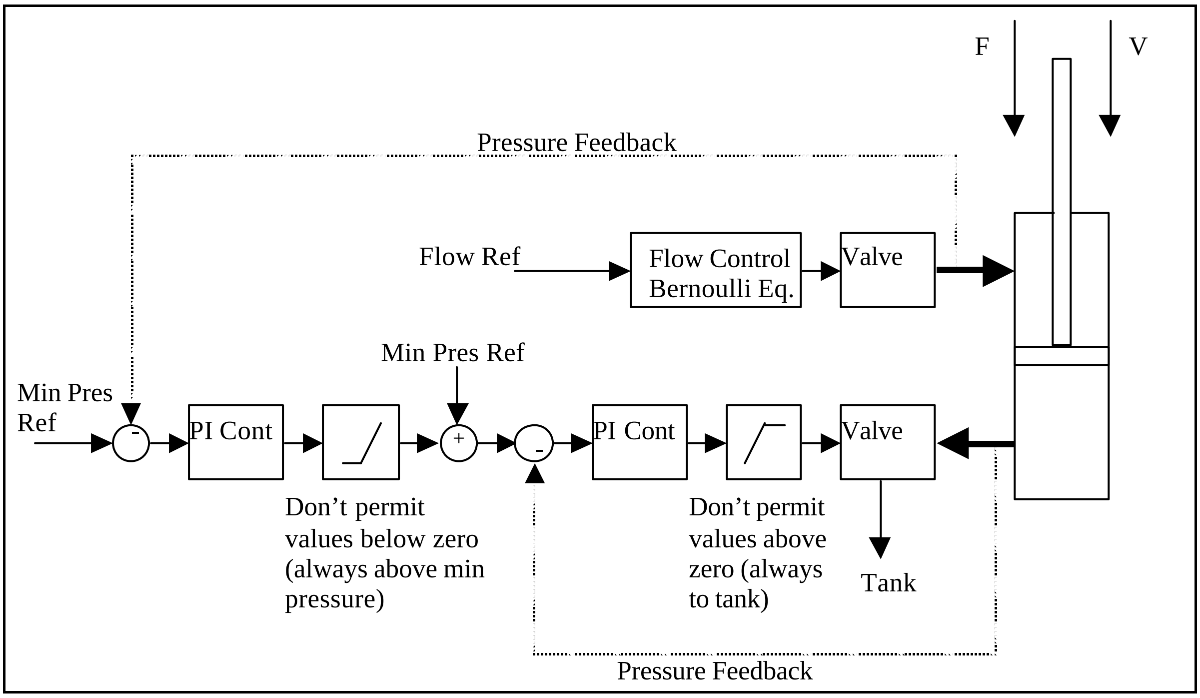

Figure 4 Controller Strategy for Lowering of Load

5 CONCLUSION

Even though not much experimental work has been finished, a good start has been made and initial tests have been promising. The outline of the thesis has been developed and organized in a logical manner. The work is split into five parts, requirements analysis, analysis of current systems, analysis of different topologies, development of a near future solution, and development of a more optimum solution. At the end of the thesis, the control of mobile hydraulic cranes will have been improved.

6 ACKNOWLEDGEMENTS

This project is being funded in part by Danfoss Fluid Power A/S. The author would also like to thank Højbjerg Maskinfabrik (HMF) A/S for the donation of the test crane.

7 REFERENCES

Andersen, B. R.; Ayres, J. L. (1997). Load Sensing Directional Valves, Current Technology and Future Development, *The Fifth Scandinavian International Conference on Fluid Power*

Backé, W.; Feigel, H. (1990). Neue Möglichkeiten Beim Elektrohydraulischen Load-Sensing, *O+P Ölhydraulik und Pneumatik 34*

Elfving, M.; Palmberg, J. O. (1997). Distributed Control of Fluid Power Actuators - Experimental Verification of a Decoupled Chamber Pressure Controlled Cylinder, *4th International Conference on Fluid Power*

Jansson, A.; Palmberg, J. O. (1990). Separate Controls of Meter-in and Meter-Out Orifices in Mobile Hydraulic Systems, *International Off-Highway and Powerplant Congress and Exposition*

Mattila, J.; Virvalo, T. (1997). Computed Force Control of Hydraulic Manipulators, *5th Scandinavian International Conference On Fluid Power*