ENERGY EFFICIENT FLUID POWER SYSTEM FOR MOBILE MACHINES WITH OPEN-CENTRE CHARACTERISTICS

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ABSTRACT

This paper presents a flexible and energy efficient system solution which mimics the behaviour of an open-centre system. An electro-hydraulic variable displacement pump and closed-centre valves are used. Instead of having a flow in the open-centre gallery, that flow is calculated using a pressure sensor and a valve model. The variable pump is then controlled in order to only deliver the flow that would go to the actual loads. It is also possible for the operator to decide how much load dependency there should be. The extreme case is not having any load dependency at all, resulting in a system where the pump displacement setting is controlled according to the sum of all requested load flows. It is thus possible to realize a system design with open-centre characteristics, a flow control system or something in between. Each operator can thereby get their optimal control characteristic while having high energy efficiency.

KEYWORDS

Mobile hydraulics, energy efficiency, dynamics, damping

NOMENCLATURE

\( A_c \) Cylinder area \( \text{m}^2 \)
\( A_{oc} \) Open-centre opening area \( \text{m}^2 \)
\( B_p \) Viscous friction coefficient \( \text{Ns/m} \)
\( C_L \) Capacitance of the load cylinder \( \text{m}^3/\text{Pa} \)
\( C_P \) Capacitance of the pump hose \( \text{m}^3/\text{Pa} \)
\( C_q \) Flow coefficient -
\( K_c \) Flow-pressure coefficient for the valve \( \text{m}^3/\text{Pa s} \)
\( K_{oc} \) Flow-pressure coefficient for the open-centre path \( \text{m}^3/\text{Pa s} \)
\( m_L \) Load mass \( \text{kg} \)
\( P_L \) Load pressure \( \text{Pa} \)
\( P_p \) Pump pressure \( \text{Pa} \)
\( P_{ref} \) Reference pump flow \( \text{m}^3/\text{s} \)
\( Q_{virtual} \) Virtual open-centre flow \( \text{m}^3/\text{s} \)
\( Q_{p} \) Pump flow \( \text{m}^3/\text{s} \)
\( Q_{oc} \) Open-centre transfer function
\( Q_{ref} \) Reference pump flow \( \text{m}^3/\text{s} \)
\( Q_{virtual} \) Virtual open-centre flow \( \text{m}^3/\text{s} \)
\( Q_L \) Load flow \( \text{m}^3/\text{s} \)
\( s \) Laplace variable \( 1/\text{s} \)
\( U \) Mechanical gear ratio -
\( x_p \) Cylinder position \( \text{m} \)
\( x_v \) Valve spool displacement \( \text{m} \)
\( \rho \) Density \( \text{kg/m}^3 \)
\( G_{oc} \) Open-centre transfer function
\( G_P \) Pump transfer function
\( G_v \) Valve transfer function
\( H_s \) Pump hose transfer function
\( Z_L \) Load transfer function
**INTRODUCTION**

The most common working hydraulic systems for mobile machinery are systems based on valve control. Common to these systems is that they can be supplied by one single pump, which gives a cost effective and compact system solution. Today, most hydraulic systems in mobile machines are of the open-centre type. In such systems, the directional valves are designed so that the entire pump flow is directed to tank when no valve is activated. These systems are designed for use with fixed displacement pumps, which give a simple and robust system solution. Another advantage with open-centre systems is that the flow is load dependent, giving the system a naturally high damping. Damping is a preferred property when handling large inertia loads, for example the swing function at a mobile crane.

A major drawback with open-centre systems is, however, poor energy efficiency. High energy losses occur when lifting heavy loads slowly. Most of the flow is then directed through the open-centre channel to tank with a high pressure drop, resulting in high energy losses. The demand for higher efficiency has led to an increase use of load sensing systems using variable displacement pumps and closed-centre valves. The pump pressure in such systems is continuously adapted according to the highest load, resulting in high energy efficiency although pressure and flow demands vary greatly over time and between different functions. However, the damping in load sensing systems is often poor due to the lack of load dependency [1] and its closed loop pressure control [2].

To improve the energy efficiency but still keep the load dependency and the high damping, load sensing systems based on open-centre valves have been developed by the Japanese excavator industry [3]. These systems use a variable displacement pump which is controlled in order to keep the flow through the open-centre path constant. The controllability is similar to open-centre systems, which means that the operator controls the system pressure when actuating a valve. This gives the system a smooth control with high damping. Power losses are generally higher than in closed-centre load sensing systems but not as high as in open-centre systems because of the variable pump. However, an open-centre load sensing system has power losses in neutral while closed-centre load sensing systems do not.

This paper proposes a novel system design with open-centre characteristics using an electro-hydraulic variable displacement pump and closed-centre valves. The open-centre flow is virtually reproduced by controlling the variable pump. By measuring the pump pressure and having a software model of the opening area in the open-centre gallery, it is possible to calculate the flow that would go through the open-centre channel. The pump displacement angle is then controlled accordingly to deliver only the flow rate that would go to the actual loads. For example, in a conventional open-centre system, the load flow would be reduced in case of an increase in pump pressure, no valve is actuated. In the proposed system, the pump would deactuate, compensating for the increased bleed-off flow and thus mimic the behaviour of the conventional open-centre system but without additional energy losses.

Since the open-centre flow only is a software model, it is possible to change its behaviour in the controller. Thus, the operator has the possibility to decide how much load dependency there should be. The extreme case is not having any load dependency at all, resulting in a system where the pump displacement setting is controlled according to the sum of all requested load flows. That system layout, referred here as flow control, has been given a lot of research interest, see for example [4], [5] and [6]. It is thus possible to realize a system design with open-centre characteristics, a flow control system or something in between. Similar commercial system designs are the VBO system from Bosch Rexroth [7] and the 3G valve from Nordhydraulic [8]. However, these systems use a pressure controlled pump and do not have the possibility to tune the load sensitivity online.

This paper gives an overview of desired system characteristics in mobile machines and describes the proposed system layout, including the pump controller. A dynamic analysis and simulation results demonstrate the capability of controlling a variable displacement pump in order to mimic the behaviour of an open-centre system. It is possible for each operator to get their optimal control characteristic while having high energy efficiency.

**MOBILE HYDRAULIC SYSTEMS**

Hydraulic systems have successfully been used in mobile machines for several decades. Because of the machines’ versatility, different hydraulic systems have been developed for different applications. Important properties for hydraulic systems are, among others, energy efficiency, controllability, damping and complexity.

**Open-centre**

Open-centre systems are used together with fixed displacement pumps and have a valve design with a channel in the centre position, directing all flow to tank when no valve is activated. When shifting a valve from its neutral position, the open-centre channel begins to close and the pump pressure increases. Figure 2 shows an example of the opening areas as a function of spool displacement. There will be a flow to the load when the pump pressure is higher than the load pressure. The rate of this flow is thus not only dependent on spool displacement, but also on load pressure. This load pressure sensitivity gives the
The pump in closed-centre load sensing systems is controlled in order to maintain the pump pressure at a certain level above the highest load pressure.

The pump in open-centre load sensing systems is controlled in order to maintain a constant pressure upstream the metering orifice in the open-centre path.

Figure 1: Pump controller layouts for closed-centre and open-centre load sensing systems.

(a) The pump in closed-centre load sensing systems is controlled in order to maintain the pump pressure at a certain level above the highest load pressure.

(b) The pump in open-centre load sensing systems is controlled in order to maintain a constant pressure upstream the metering orifice in the open-centre path.

Operator a pressure control, which means that he can control the acceleration of the load. This gives the system a naturally high damping. To obtain damping from a valve, the flow has to increase when the pressure drop across the valve increases and vice versa. A major drawback with open-centre systems is, however, poor energy efficiency due to the fixed displacement pump.

Closed-centre Load Sensing

Closed-centre load sensing systems improve the energy efficiency compared to open-centre systems by continuously adapting their pressure just above the highest load, see figure 1a. This means that a specific spool displacement results in a certain flow, independent of the load pressure. This pressure insensitivity make load sensing systems easy to operate for velocity or position control of low inertia loads. However, with high inertia loads, the operation becomes jerky because of the low damping. Furthermore, the closed-loop control mode for the pump might lead to instability issues [2].

Open-centre Load Sensing

To overcome the shortcomings in closed-centre load sensing systems, characterised by low damping and lack of pressure control, open-centre load sensing valves have been developed. It is a modification of the conventional and well accepted open-centre valve to work more efficiently with variable displacement pumps. A metering orifice downstream the open-centre path is added to the system. The pump is controlled in order to maintain a constant pressure upstream the metering orifice, see figure 1b. This will in turn keep the by-pass flow through the open-centre path constant. Activating an orifice will gradually close the by-pass orifice, creating a pressure drop in the by-pass flow, which is kept constant by the pump, and increasing the pump pressure. The spool displacement will thus determine the pump outlet pressure, similar to a conventional open-centre system, which gives the system a high damping. However, the efficiency is lower than in closed-centre load sensing systems because of the power losses in the open-centre gallery.
SYSTEM DESCRIPTION

The system design proposed in this paper has similar control characteristics as the open-centre system but without the power losses in the open-centre channel. This is done by using closed-centre valves, an electro-hydraulic variable displacement pump and a sensor measuring the pump pressure.

The pump controller is shown in figure 3 [9]. The operator sends a flow command to the electric controller and the pump is displaced accordingly. The displacement angle and the shaft speed are measured and the flow is controlled in a closed loop. To calculate the reference flow, the flow that would go through the open-centre path in a conventional open-centre system is calculated by measuring the pump pressure and having a model of the opening area in the open-centre channel as a function of spool displacement according to equation 1 and figure 2.

\[ q_{\text{virtual}} = C_d A_{oc} (x_v) \sqrt{\frac{2}{\rho} p_p} \]  

(1)

The virtual flow through the open centre path is then subtracted from the maximum flow rate of the pump and the result is the reference flow sent to the pump controller, see figure 4.

When no valve is activated, the reference flow will be zero. That can be compared with all flow going through the open-centre channel. Activating a valve will decrease the opening area of the open-centre channel and thus allowing a small flow to be sent by the pump, increasing the pump pressure. At a certain pressure level, the reference flow will find its equilibrium and then only compensating for its own leakage. Activating the valve more will continue to increase the pressure until the pump pressure becomes higher than the load pressure. Then there will be a flow to the load. Increasing the spool stroke further will decrease the opening area in the open-centre channel, which means increased flow from the pump. When the valve is completely opened, the pump will be at maximum displacement sending all flow to the load. A conventional open-centre system has exactly the same working principle, although the control is made hydraulically instead of electronically.

Since electronic control is used, it is possible to have an arbitrary model of the open-centre channel. For example, it would be possible to continuously decrease it in order to reduce the load dependency. In this paper, it is proposed to have a parameter, here called \( \xi \), which is multiplied with the virtual flow. At the same time, \( \xi \) will also change the input signal to the system. Instead of being the maximum flow rate, as in figure 4, the input signal will be dependent on the joystick command signal from the operator. The extreme case is when having no load dependency at all, \( \xi = 0 \), resulting in a system where the pump displacement setting is controlled according to the operator’s command signals, here referred to as flow control. That system layout has been analysed in, for example, [4], [5] and [6].

The final system design proposed in this paper can be seen in figure 4: Open-centre mode for the proposed system. The virtual flow going through the open-centre channel is calculated and subtracted from the maximum flow of the pump, resulting in a flow command signal sent to the electronic pump controller.
in figure 5. By only changing the value of $\xi$, it is possible to realize a system design with open-centre characteristics, a flow control system or something in between. The operator has the possibility to tune the value of $\xi$ in order to achieve optimal system characteristics for a specific application or duty cycle.

**DYNAMIC CHARACTERISTICS**

The dynamic behaviour of the proposed system design in this paper, see figure 6, can be described by equations (2)-(6). This results in the block diagram shown in figure 7a. The only difference compared to a conventional open-centre system is the pump controller, $G_p$. The pump controller consists of an electrically controlled valve controlling the displacement piston. If the flow balance, $Q_{ref} - Q_p$ is disturbed, the valve is displaced and the pump setting is then proportional to the integrated valve flow.

The system damping is proportional to the flow-pressure coefficient of the virtual open-centre path, $K_{oc}$. For small spool displacements, the opening area of the open-centre path will be large which gives high damping. The damping will then be reduced with increased spool displacement. Figure 8 shows the load pressure as a function of load flow for different spool positions. The damping contribution from the open-centre path is directly proportional to the slope of the curve, $-dq/dp$. A high damping is therefore obtained in a broad range of the working area, except for high flows. A system without any load dependency would only obtain damping from the inlet and outlet orifices in the directional valve, which in most cases results in a relatively low damping [10] [11]. Also, secondary effects such as leakage and viscous friction will contribute with damping to the system.

\[
G_p = \frac{Q_p}{Q_{ref}} 
\]

\[
G_{oc} = \frac{Q_{virtual}}{P_p} = K_{oc} 
\]

\[
H_s = \frac{P_p}{Q_p - Q_L} = \frac{1}{C_p s} 
\]

\[
G_v = \frac{Q_L}{P_p - P_L} = K_c 
\]

\[
Z_L = \frac{P_L}{Q_L} = \frac{U^2m_L s + B_p}{C_L U^2 m_L s^2 + C_s B_p s + A_c^2} 
\]
**SIMULATION RESULTS**

A non-linear dynamic simulation model has been built in Hopsan [12] [13] to illustrate some of the differences between different control modes for the proposed system design. The model consists of a displacement controlled pump, directional valves, an open-centre channel model and two cylinder loads.

In figure 9, directional valve 1 has a constant valve opening and a step is made in valve 2. It is shown how this disturbance affects the velocity of load 1. The valve step is made at 0, 1 and 2 seconds for $\xi = 1, 0.5$ and 0. It can be seen that a high value of $\xi$ decreases the tendency to oscillate. However, the load interaction decreases for small values of $\xi$. In flow control mode, the pump will increase its displacement when another load is activated and thus keep the velocity constant. In open-centre mode, the operator needs to increase the command signals in order to increase the system pressure and thereby keep the velocity constant.

At 3, 4 and 5 seconds a step is made in the external force at load 2. As can be seen in figure 9, more flow is then going to load 1 and the velocity increases. If this load interaction is an undesired property, it is possible to equip the valves with flow sharing pressure compensators. This has been studied in, for example, [5] and [14].

Figure 10 shows the load flow as a function of spool displacement for different load pressures. The open-centre mode has the same characteristics as a conventional open-centre system, see figure 10a. When decreasing the value of $\xi$, the load dependency will decrease according to fig-
The load dependency is high in open-centre mode, $\xi = 1$.

The load dependency decreases when having a combination of open-centre and flow control mode, $\xi = 0.5$.

It is no load dependency in flow control mode, $\xi = 0$.

Figure 10: Load flow as a function of spool displacement for different load pressures. When decreasing the value of $\xi$, the load dependency decreases.

Table 1: Comparison of different system characteristics.

<table>
<thead>
<tr>
<th>Open-centre</th>
<th>Closed-centre load sensing</th>
<th>Open-centre load sensing</th>
<th>Proposed system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity control</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Force control</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Efficiency</td>
<td>-</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Damping</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Complexity</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

In flow control mode there are no load dependency, see figure 10c.

**DISCUSSION**

Each hydraulic system has its pros and cons. A system design suitable for one application might be inappropriate for another. Table 1 summarizes the systems discussed in this paper in terms of important properties for mobile hydraulics. As can be seen, no system is optimal. Open-centre systems are a good choice if a simple system with high damping is preferred. Closed-centre load sensing systems improve the energy efficiency and velocity control but are poorly damped. Open-centre load sensing is a good compromise but lack the possibility of velocity control. The proposed system in this paper has high energy efficiency and some adaptable characteristics. It has force control and high damping in open-centre mode and velocity control in flow control mode. It is possible for the operator to tune the value of $\xi$ for optimal system characteristics. The drawback with the proposed system design is the complexity, more advanced components are needed, the system is sensor dependent an electronic control is needed.

**SUMMARY AND CONCLUSIONS**

A flexible system solution using a variable displacement pump and closed centre valves has been presented in this paper. The pump is electrically controlled and has sensors for pump pressure, shaft speed and displacement angle. This makes it possible to control the flow and also to calculate the flow rate that would go through the open-centre channel in a conventional open-centre system. By subtracting that flow from the maximum flow rate of the pump, it is possible to mimic the behaviour of an open-centre system.

It is also possible for the operator to change the system controller online. By decreasing the influence from the virtual open-centre channel, it is possible to realize a system where the pump displacement setting is controlled according to the sum of all requested load flows, and also something in between. The system characteristics could be adapted to take into account the dynamic characteristic of the studied function. For example, a sufficiently damped load can allow less load dependency and vice versa. Thus, it is possible to tune the controller to fit a specific application, function or working cycle.

If a specific control characteristic is better than another depends on the specific application and the type of load. But it is also operator dependent. For example, the load sensitivity of an open-centre system is said to give the operator a better feel of the machine. A skilled operator can use this information feedback from the system to their advantage and increase his controllability of the machine. However, a non-skilled operator might experiences this
pressure sensitivity as an inconsistency and it can then be regarded as a disturbance. With the proposed system layout, it is possible for each operator to get their optimal control characteristic with high energy efficiency.

REFERENCES


