Comparison of a Variable Displacement 3-Piston Inline Digital Pump Using Electrically and Mechanically Actuated Poppet Valves

James Marschand, Tyler Helmus, and John Lumkes

Purdue University, 225 S University St West Lafayette, Indiana 47907, United States
E-Mail: jmarsch@purdue.edu

Digital pumps using high speed on/off valves to control fluid entering and leaving the piston cylinder displacement chamber can increase efficiency by eliminating the leakage and friction associated with the port plate. Leakage scales with the displacement because the displacement chamber is only pressurized during a portion of the piston stroke. This work investigates the modeling, prototyping, and testing of two prototype digital pumps. The first prototype actuated on/off valves using electrical solenoids; the second configuration used mechanical cams. The mechanical actuation improved the repeatability and accuracy of the valves, matching or exceeding the performance of the electrically actuated prototype while eliminating all transducers and electronics. The mechanically actuated pump operated at 86% efficiency (full displacement) and 58% efficiency (25% displacement).

Keywords: Digital Hydraulics, Inline Piston Pump, Efficiency, Digital Pump/Motor

Target audience: Mobile Hydraulics, Digital Hydraulics, Piston Pumps

1 Introduction

A U.S. Department of Energy study reported that fluid power systems account for up to 5% of all energy transferred in the United States. Approximately 7-8% of the CO₂ emissions in the U.S. alone can be attributed to fluid power. During the time of this study, average fluid power system efficiency was 20%. Increasing this by just 5% would lead to savings of up to $20 billion and 90 million tons of CO₂ each year /1/. This is overwhelming motivation that supports the impact of improving system efficiency. Pumps are found in almost all fluid power systems and significantly influence system efficiency. As more efficient system architectures are being developed it is important that better pumps are available to support these advanced configurations /2/.

Digital hydraulics is one method of improving efficiency. Digital hydraulics systems are any systems “having discrete valued component(s) actively controlling system output” /3/. Digital hydraulics can be used at the system level or at the component level.

Improving pump efficiency will have a positive impact on reducing the energy losses in fluid power systems. State of the art pumps can be very efficient when operating at peak conditions, but when the pump displacement is lowered, efficiency can drop to as far as 30% /4/. Minimizing the drop in efficiency that comes from lowering operating displacement would greatly improve overall pump and system performance.

In order to improve pump efficiency at lower displacements, digital hydraulics is used to control the amount of fluid entering and leaving the pumping chamber for each piston. By placing a high speed on/off valve at the inlet and outlet port for each piston, the flow can be directed through either port as desired. Mechanical and electrical actuation of the valves were prototyped and tested. Operating strategies were developed to successfully allow for variable displacement operation.

2 Operating Strategies

When using high speed on/off valves there are multiple possibilities for controlling the displacement of pump/motors. All the methods described here, partial flow diverting (PFD), partial flow limiting (PFL), sequential flow diverting (SFD), and sequential flow limiting (SFL), control when the displacement chambers are connected to the pump/motor inlet and outlet, and do not vary the piston stroke. The piston stroke is always ‘full displacement’ and travels between maximum top and bottom range.

When operating as a pump using partial flow diverting (PFD), the inlet valve opens to let the pumping chamber fill with fluid as the piston travels to bottom dead center (BTC). While the piston makes its return towards top dead center (TDC), the inlet valve remains open allowing some flow to be diverted back into the low-pressure port. When the desired displacement volume is remaining in the pumping chamber, the inlet valve closes. After the fluid is pressurized, the outlet valve opens allowing this fluid to exit through the high-pressure port. This is shown in Figure 1.

![Figure 1: Partial flow diverting operating strategy /5/](image1.png)

For partial flow limiting pumping (PFL), the piston again starts at TDC with the inlet valve open. Shown in Figure 2, this valve only remains open until the desired flow volume is in the pumping chamber. Then the inlet valve closes and the piston continues to complete the entire intake stroke without allowing any more fluid to enter the chamber. At BDC there is a vapor void in the fluid and the piston begins the compression stroke towards TDC. Both valves remain closed until the fluid is pressurized. Once the chamber pressure reaches the same level as the system pressure the high pressure port opens and the fluid is pumped from the chamber into the system.

![Figure 2: Partial Flow Limiting /5/](image2.png)
Two separate valve blocks were created; one designed for electrical actuation and the other for mechanical actuation. Both valve blocks utilize the same base unit and on/off valves, only the actuation method is changed.

### 3.1 Electrically Actuated Valve Block

The electrically actuated valve (EAV) design utilizes solenoid operated valves to control both input and output ports. When an electrical signal is sent to the valves a magnetic coil opens the valve. The EAV block is comprised of two parts. The first part of the block bolts to the crankcase. It contains a low-pressure seal that prevents leakage to the exterior of the pump and a drainage port which returns any fluid to the case. The second part of the block houses the displacement chambers and the valves for each piston. Each displacement chamber has four internal connections shown in Figure 5.

**Figure 5: Schematic of internal ports of the EAV**

The EAV unit is controlled using the National Instruments Veristand software environment. A PXI-8108 controller runs a MATLAB Simulink model in the Veristand environment. The controller is responsible for opening and closing the on/off valves which in turn controls the output pressure and operating displacement. Adjustments to the operating conditions are all made through the controller and require the pressure transducers to be accurate and operational.

### Sequential Flow Diverting (SFD)

In Sequential Flow Diverting (SFD) pumping, individual pistons operate at either full or zero displacement during an entire stroke cycle (BDC-TDC-BDC); none of the displacement chambers are partially filled as in PFD or PFL. A discrete number of pistons associated with the overall desired displacement operate at full displacement (for example, using two pistons on a five piston unit would provide 40% displacement). The remainder of the pistons operate at zero displacement by directing the fluid as follows. The output valve remains closed throughout the entirety of the cycle to prevent any flow through the high pressure port. The input valve remains open for the entire cycle (Figure 3). Similar to the PFD strategy, only the desired amount of flow stays in the chamber to be pumped out of the high pressure port. Since the desired amount of flow for these pistons is zero, all of the fluid is pushed back out of the low pressure port.

**Figure 3: Sequential Flow Diverting**

Sequential Flow Limiting (SFL) is similar to SFD as it uses a predetermined number of pistons operating at full displacement with the rest operating at zero. For the pistons operating at zero displacement, the outlet valve is still kept closed for this strategy. The difference from SFD is that the inlet valve also remains closed in this strategy. Flow limiting allows only the desired amount of flow to be taken into the chamber. Since the desired amount of flow is zero, the inlet valve never opens. Each pumping chamber creates a suction during this operating mode.

### 3 Pump Design

In order to build a digital variable displacement pump that would be comparable to existing units, the prototype pump was designed using an off-the-shelf pump as a starting point. A CAT Model 1861 fixed displacement 3-piston inline pump was used as the base unit for this research. The rotation of the input shaft is converted into the linear motion of the pistons through a crank-slider mechanism that can be seen in Figure 4. The CAT pump was selected mainly because of its modularity and the seals used. The block assembly that contains the displacement chambers and valves is easily removed to be replaced with the modified valve block necessary for digital displacement control. Lip seals are used between the displacement chambers and the pistons which separates the chambers from the crank case eliminating the need for a lubricating gap.

**Figure 4: CAT Model 1861 Pump**

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**Figure 6: Cross section of the EAV attached to the CAT base pump**
Mechanically Actuated Valve Block

The mechanically actuated valve prototype (MAV) makes use of half masking cams to control the on/off valves at the displacement chambers. The half masking cams are two identical cams that are in the high state and low state 50% of the time. By rotating one cam relative to the other, the amount of time in the high state can range from 50%-100% and the amount of time in the low state ranges from 0%-50%. The MAV uses the same CAT pump and the same valve block. The actuation part of the valve block was redesigned for the MAV. Due to geometric constraints, on/off valves were not able to be placed at both ports. Instead, an on/off valve was placed at the inlet and a check valve was placed at the outlet. This limits, in this case, the operation to pumping only. In contrast to the EAV having four internal connections to the displacement chamber, the MAV has only three internal connections to the displacement chamber. Seen in Figure 7, the first connection is made to the on/off valve (1) at the chamber inlet. The second is the check valve at the outlet (2). Using a check valve at the outlet eliminates the need for the additional port used for a safety check valve in the EAV (3). The last connection to the displacement chamber is used for a pressure transducer that is used solely for data collection purposes; it is not needed for normal operation using the MAV.

Variable cam control is achieved by two parallel, dual-input, planetary gear systems. Each planetary set controls one half-mask of a variable cam. Figure 8 shows the gearing configuration. With this system, a self-locking worm gear can turn the ring of the planetary set allowing the sun gear to be phased relative to the rotation of the planetary carrier even while it is spinning. This is accomplished for both masks allowing them to be phased to any angle relative to each other and the pump shaft, which is tied to the planetary carrier, during operation. Due to the locations of the displacement chambers in this inline unit, three mechanically linked half-masking cams were used. In this system, one half-mask controls the displacement of the unit while the other can be adjusted to vary the valve timing and reclaim the maximum amount of compressed fluid energy from the pressurized fluid on the down stroke.

Experimental Testing

A regenerative test stand developed by Holland (2012) and Merrill (2012) was used to test both units. The necessary data acquisition equipment for both units was included on the test stand. Flow meters and pressure transducers were included on the stand at the inlet and outlet of the unit. Pressure transducers were also used in each of the displacement chambers in the valve block to monitor individual displacement chamber pressure. Both units were tested at 25%, 50%, 75%, and 100% displacement. Each displacement variation was tested at 34 bar and 103 bar at speeds of 300 and 500 rpm.

Results

The stock CAT pump was tested independently on the experimental test stand. The hydraulic efficiency was measured for the same operating conditions as the MAV and EAV with the exception of 300 rpm /4/. Since the unmodified configuration is a fixed displacement pump, data is only available at 100% displacement.

5.1 EAV Results

The EAV was tested in all four operating strategies for both pumping and motoring. The overall hydraulic efficiency for pumping is shown in Figure 9. Sequential flow limiting was the most efficient operating strategy followed by sequential flow diverting, partial flow limiting and then partial flow diverting. It is important to note that the baseline maximum efficiency of the unmodified check ball unit under similar conditions is 91%, shown by the red circle on the 100% displacement vertical axis. This efficiency is somewhat lower than conventional bent axis and swashplate units at full displacement since an extra set of seals separate the crankcase chamber from the pumping pistons. However, this does allow the unit to pump water and corrosive fluids as originally designed as a check ball pump for car washes.
5.2 MAV Results

The MAV was only tested using partial flow diverting for pumping because of the geometric constraints of the design. Figure 11 shows the overall hydraulic efficiency for pumping at 300 rpm for the mechanically actuated prototype at each pressure.

Figure 11: Overall hydraulic efficiency for pumping at 300rpm

The EAV was also tested as a motor but the results are not relevant in this comparison as the MAV, as configured, cannot be tested as a motor. The results for the EAV motoring tests can be found in Holland (2012).

The electrical power required for control of the valves was also monitored for the EAV. The total electrical energy requirements can be seen in Figure 10. The order of operating strategies to require the most power is the inverse of the order of most efficient.

Figure 10: Electrical Energy Requirements, pumping, 500rpm /6/
5.3 Comparison of Actuation Techniques

Because of the design of the mechanically actuated valve prototype, it was only operated in partial flow diverting for pumping. Figures 13 and 14 compare the overall hydraulic efficiency (electrical actuation energy for the EAV is not included) of the mechanical and electrically actuated prototypes using the partial flow diverting operation strategy. Data for the fixed displacement base CAT pump is included where it is available.

![Figure 13: Overall hydraulic efficiency for both prototypes, 300rpm, 34bar (left), 103bar (right)](image)

![Figure 14: Overall hydraulic efficiency for both prototypes, 500rpm, 34bar (left), 103bar (right)](image)

The efficiency shows the most variability at 50% displacement because this is the point where valve timing is the most critical. The valves must switch where the piston velocity and flow forces are at a maximum. This demonstrates the effects of the poor repeatability of the solenoid operated valves used on the EAV.

Besides the numerical data collected, there are many other ways to compare the two different actuation techniques. Both prototypes have different operating strategy capabilities. The EAV is able to operate using any four of the strategies and is able to actively switch between them. Thus it is capable of four quadrant operation. It can act as a pump or a motor independently in both CW and CCW. In the MAV prototype the outlet port is pressure actuated rather than controlled with an on-off valve like in the EAV. This eliminated the ability to use the sequential operating strategies. The half masking cams also limit the valves to being in either state a maximum of 50% of the time which eliminates partial flow limiting. This limits the MAV prototype to only partial flow diverting. Four quadrant operation can be enabled in the MAV by including an on-off valve at the outlet of each displacement chamber.

6 Conclusions

Mechanical actuation of the valves proved to be an attractive way to achieve high efficiency variable displacement units not requiring expensive sensors and electronics. The MAV achieved higher efficiency at 50% displacement and slightly higher efficiency at 75%. Although performance slightly dropped at 25% and 100%, the MAV unit performed almost as well or better than the EAV. The efficiency of the MAV could be increased by eliminating some of the gearing and not limiting the valves to be the same size as used in the EAV. The EAV, using solenoids, is more limited in valve size since actuation forces are relatively small compared to a mechanical cam system. In addition to the better performance, the mechanically actuated prototype was able to achieve variable displacement without the use of any electronics and the simple control of the turning of a knob. Additional improvements are possible by implementing this technology on a radial piston pump. Only one cam would be needed for each set of inlet and outlet valves, regardless of the number of pistons, and cam design (pressure angles) is easier with larger cam diameters.

7 Future Work

In the future, changing the piston orientation to a radial unit could provide multiple benefits. A radial unit would allow all valves to be controlled by a single central cam and would allow for a larger cam and less gearing. Improvements to solenoid operated valves would lead to greater success with the electrically actuated prototype. Faster valve transition time for larger valve areas would increase repeatability and allow for larger flows.

Nomenclature

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<tr>
<th>Variable</th>
<th>Description</th>
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<tbody>
<tr>
<td>TDC</td>
<td>Top Dead Center</td>
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<td>BDC</td>
<td>Bottom Dead Center</td>
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<td>PFD</td>
<td>Partial Flow Diverting</td>
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References


