INTERNATIONAL JOURNAL OF FLUID POWER, 2016
VOL. 17, NO. 1, 37–47
http://dx.doi.org/10.1080/14399776.2015.1120138

Taylor & Francis
Taylor & Francis Group

The impact of peak-and-hold and reverse current solenoid driving strategies on the dynamic performance of commercial cartridge valves in a digital pump/motor

Farid Breidi, Tyler Helmus and John Lumkes

Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN, USA

ABSTRACT

Valve dynamics play an important role in existing fluid power systems and are key enablers to a wide range of digital hydraulic systems. Varying the electrical input signal to the solenoids is used to improve the dynamic performance and response times of on–off valves by reducing the eddy currents and coil inductance. This work examines the effects of the peak-and-hold and reverse current driving strategies on the performance of two commercially available direct actuated valves, and the resulting impact on the efficiency of a digital pump/motor. An electric circuit was designed to execute the driving strategies and a single valve hydraulic test stand was assembled to perform the valve timing studies. The differential pressure across the valves was found by installing the valves between two high frequency pressure transducers, allowing the calculation of the transition and delay time of the valves. The durations of the peak and reverse voltage signals were varied over a range of 0–10 ms with a 1 ms increment. Peak voltages were between 50 and 55 V, followed by a holding voltage of 12 V. The optimum response was found at peak duration of 6–8 ms. A reverse current strategy was used to increase the decay rate of the eddy currents during a turn-off response, improving the response time. The modified peak-and-hold input signal was able to improve the turn-on response time of a commercially available valve from a range of 33–55 ms to a range of 7–9 ms, while the reverse current signal was able to improve the turn-off response time from around 130 ms to a range of 16–50 ms. These valves were then tested both in simulation and experimentally on a three-piston digital pump/motor to examine the improvement of the pump/motors efficiency resulting from the improvement of the valves switching times. The improvement in valve performance resulted in significant energy savings; up to 15 and 12% in the simulation model and digital pump/motor test stand respectively.

ARTICLE HISTORY
Received 28 August 2015
Accepted 11 November 2015

KEYWORDS
Digital hydraulics; High speed on/off valves; Pump/Motor; Peak and Hold; Valve driving strategies

Introduction

A study done by the Unites States Department of Energy found that hydraulic systems are generally inefficient, averaging less than 22% in overall efficiency in the United States, where these hydraulic losses total more than the energy produced by all the renewable energy sources combined (Love 2014). One of the main hydraulic losses is the valve throttling losses, which can account for up to 43% of the total energy consumed by an excavator (Love 2009). This is motivating the research of more efficient fluid power systems which include displacement controlled actuation, hydraulic transformers, and independent metering valves (Williamson and Ivantysynova 2007, Bishop 2010, Heikkila *et al*. 2010, Lumkes and Andruch 2011).

A valve is a component found in almost every conventional hydraulic system and various approaches using faster valves or new system architectures based on valves have been studied. These include virtually variable displacement pump/motors (Nieling *et al*. 2005, Lumkes *et al*. 2009), high speed mode selection control (Shenouda and Book 2008), hydraulic transformers (Scheidl *et al*. 2008, Merrill *et al*. 2010), high bandwidth control of pump/motor displacement (Long 2009), and pulse width modulation (PWM) system control (Long and Lumkes 2010). Valve based approaches rely on using valves with a fast response time and a large flow area to minimize valve throttling losses, providing motivation to develop higher performance valves.

Specific to this research, high performance valves are also essential in the development of four-quadrant digital pump/motors. A problem with commercially available on/off valves is slow and varying response time (Mikkola *et al*. 2007). The efficiency of a digital pump/motor is directly related to the reliable, rapid response of the valves being used. Figure 1 illustrates the importance of valve repeatability by showing the percentage of theoretical power lost if opening is different than expected.

CONTACT Farid Breidi breidi@purdue.edu

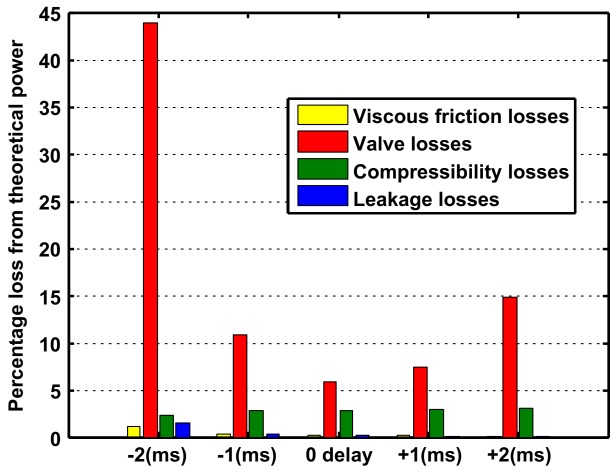

Figure 1. Simulation of seven-piston pump at 3000 rpm, 300 bar, 57% displacement (Merrill *et al.* 2013).

If the repeatability of the valves varies by even 2 ms, the throttling losses experienced can be significant (Merrill 2012, Merrill *et al.* 2013).

New valve configurations targeting improved performance have been proposed and reviewed in literature (Van de Ven and Katz 2011, Tu *et al.* 2012); some include new valve concepts such as using a rotational energy source (Tu *et al.* 2012, Skelton *et al.* 2013, 2014, Xiong and Lumkes 2014). However, most of these concepts rely on new valve architectures and are still in the prototype stage, which might not be a feasible solution for an end user who wants to buy a commercially available valve.

Additionally, Artemis units rely on a latching check valve to overcome the speed limitations of traditional valves though this configuration limits the quadrants of operation of this unit (Ehsan *et al.* 1996).

This work examines the impact of peak-and-hold and reverse current solenoid driving strategies and the resulting improvement in valve performance when applied to commercially available solenoid actuated cartridge valves. An electric circuit was designed to implement the driving strategies and a single valve hydraulic test stand was assembled to perform the valve timing studies; the valves were tested using identical operating conditions. The valves in this study were then also tested on a four quadrant digital pump/motor test stand to determine the pump/motor efficiency improvements realized by improved dynamic performance of the valves.

Background

To improve the opening of these normally-closed valves, a peak-and-hold driving strategy was implemented. This provides a high initial voltage to overcome inductance and eddy current lag while generating high flux levels across the air gap. After the magnetic field is established, a constant holding current is applied to the solenoid to keep the armature in place without expending undue energy to resistive heating. It should be noted that there is no performance benefit from a peak duration that is longer than optimal, and heat will build up in the coil reducing electrical efficiency and possibly damaging the coil. Figure 2 shows the peak-and-hold strategy implemented in this research.

The reverse current turn off method is more complex than the previous method. Valve closing lag is mainly due to lingering current in the solenoid and residual magnetism which opposes the closing force of the spring. The reverse current method decays these residual effects more quickly than a flyback diode (Batdorff 2010). Figure 3 shows the reverse current profile implemented in this research.

Batdorff developed a theoretical equation (Equation (1)) for the decay of the magnetic flux density (B) when a reverse current is applied (Batdorff 2010). Normal decay is proportional to the Zero Applied Magnetic Field and time; adding the reverse pulse adds the multiplier of one plus the magnitude of the Reversed Pulse, greatly reducing the decay time realized in the solenoid.

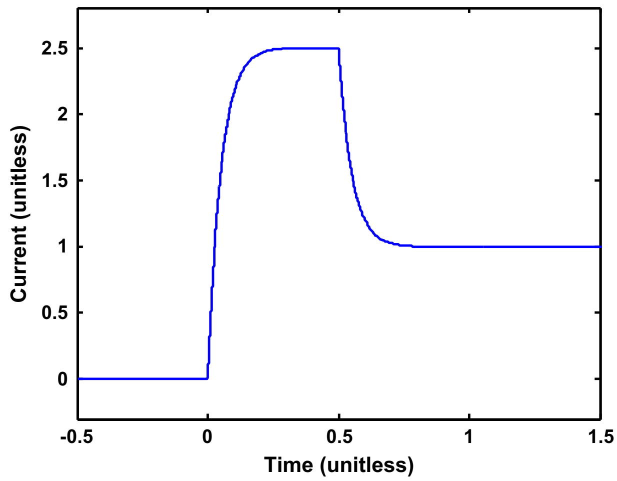

Figure 2. Peak-and-hold applied normalized current vs. normalized time.

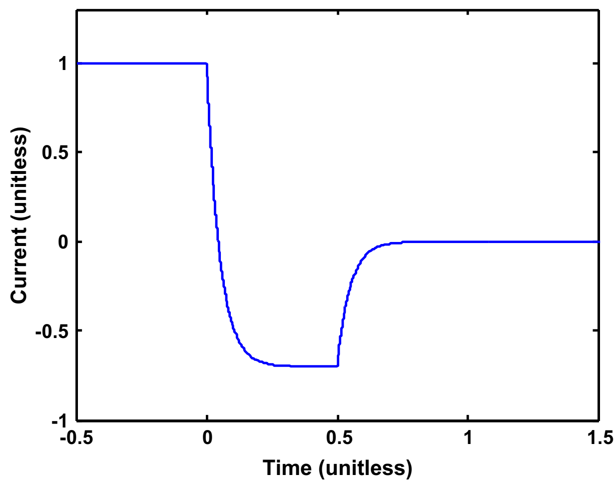

Figure 3. Reverse current applied normalized current vs. normalized time.

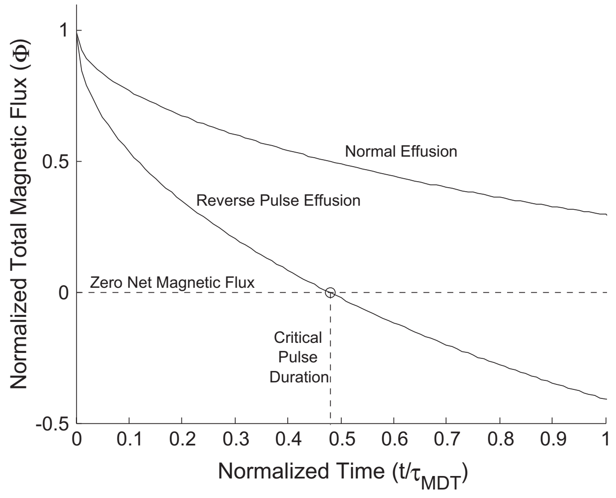

Figure 4. Comparison of dimensionless magnetic flux effusion (Batdorff 2010).

$$B(z,t) = \underbrace{1}_{\text{Initial Steady State}} \underbrace{-(1+m_r)\beta(z,t)\delta(t-0)}_{\text{Reversed Pulse}} + \underbrace{\beta(z,t)\delta(t-t_r)}_{\text{Zero Applied Magnetic Field}} \quad (1)$$

In this equation, z is the distance into the plate, t_r is the normalized duration of the Reversed Pulse and m_r is the relative normalized magnitude of the Reversed Pulse. δ is the unit step function which is 1 when the first term is greater than or equal to the second and is 0 otherwise. β is the diffusion of magnetic flux from one side into a plate in response to a step magnetic field intensity change. Figure 4 shows the theoretical normalized comparison of magnetic flux effusion and reverse current effusion.

An important factor that must be taken into account when using the reverse current method is that the magnetic field can be reestablished by the reverse current, resulting in an increase in transition time if the reverse current is applied longer than necessary to decay the residual magnetism. The proper length of the applied reverse current will first reduce the forward current and then counteract the lingering eddy currents and residual magnetism. This results in a critical pulse duration for optimal transition time of the valve beyond which the reverse current hinders valve closing transition time. This point and the reestablishment of the magnetic flux can be seen graphically in Figure 4. The critical pulse duration is a function of forward current, supply voltage, and material properties. This is dissimilar to the peak-and-hold strategy where the penalties for a longer than necessary peak duration are inefficiencies and possible damage to the coil from the increased voltage. While the extended peak-and-hold signal is undesireable, the opening transition time is not affected.

Electric circuit

An H-bridge circuit, shown in Figure 5, is needed to achieve both the peak-and-hold turn-on and reverse current turn-off strategies. Though the complexity of the H-bridge is not necessary for the peak-and-hold turn-on strategy, a full H-bridge is necessary for the reverse current valve turn-off strategy.

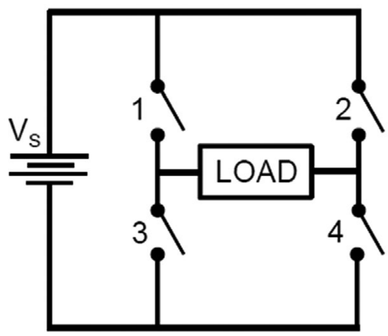

Figure 5. H-bridge circuit.

Table 1. H-bridge states.

	On		Off		
Switch	Forward	Reverse	Case 1	Case 2	Case 3
1	Closed	Open	Open	Open	Closed
2	Open	Closed	Open	Open	Closed
3	Open	Closed	Open	Closed	Open
4	Closed	Open	Open	Closed	Open

H-bridges have the ability to control the polarity of voltage and direction (DIR) of current with the use of four solid state switches (MOSFETs). The different states of an H-bridge are shown in Table 1. Forward current and voltage can be achieved by closing switches 1 and 4 and opening switches 2 and 3, while reverse current and voltage could be achieved by closing switches 2 and 3 and opening switches 1 and 4. Off states can be achieved by opening all switches, opening switches 1 and 2 and closing switches 3 and 4, or closing switches 1 and 2 and opening switched 3 and 4.

Holland describes implementing a valve power electronic circuit shown in Figure 6 (Holland 2012). A LMD18200 H-bridge was implemented to carry out the strategies described above. This H-bridge has 55 V and 3A limits allowing for peak-and-hold and reverse current strategies to be carried out for a 12 V valve coil. Batdorff (2010) goes into greater detail about the effects of peak voltage on the valve response; he concluded that increasing the voltage results in diminishing returns. 55 V is a good compromise between power consumption and valve response. The H-bridge also features built-in logic and current sense output. High speed optocouplers isolate the logic circuits from the high voltage actuation circuit. A 74LS04 hex inverter was used to return the signal to its original states as optocouplers invert the input signal.

Peak, hold, reverse current, and off states were achieved with control of the PWM and DIR pins. Table 2 shows the control inputs for the H-bridge to function in the desired states. For the peak state, a high input signal at the PWM pin allows the full supply voltage

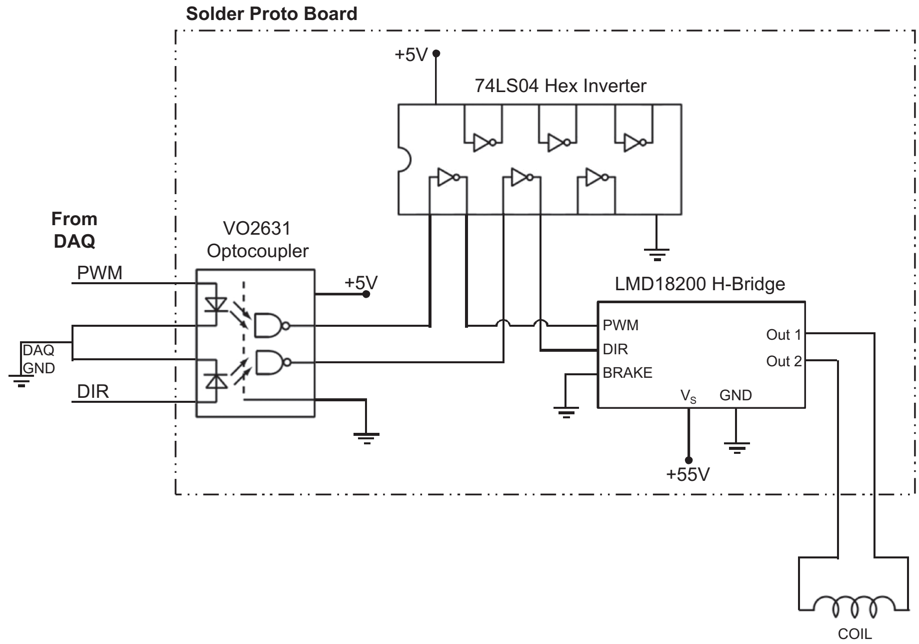

Figure 6. Valve power electronic circuit (Holland 2012).

Table 2. Truth table for H-bridge circuit.

State	Direction	PWM
Peak	Low	High
Hold	Low	Modulated
Reverse current	High	High
Off	Low	Low

to be recognized at the load. The hold state modulates the input signal at the PWM pin to reduce the apparent voltage realized at the load. A low input signal to the DIR pin directs the power signal in the forward DIR, while a high input signal to the DIR would achieve a reverse current. An off state was achieved by having a low input PWM signal.

The same circuit was used to perform the single valve tests and when testing the four-quadrant digital pump/motor.

Single valve hydraulic circuit

The hydraulic circuit used in evaluating the valves' response to the electric circuit's commands is shown in Figure 7. A 2000 Hz pressure transducer was placed on each side of the valve to be evaluated, allowing for measurement of the pressures at ports 1 and 2. A fixed displacement pump capable of providing around 31 l/min at 124 bar was used as the flow source. Operating pressure was set by a pressure relief valve and flow across the tested valve was controlled by a needle valve. A flow meter was used to measure the output flow from the valve.

Flow from port 1 to port 2 was considered forward flow while flow from port 2 to port 1 was considered reverse flow as labeled in Figure 8.

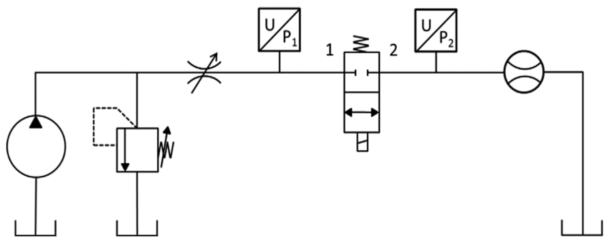

Figure 7. Valve response test circuit.

During both opening and closing tests, the differential pressure across the tested valve was measured and used to determine response times. The pressure values chosen to estimate delay and transition time were 10% and 90% of the difference between the initial and final values of the differential pressures, labeled t_{10} and t_{trans} in Figure 9. These points were taken at the first instance the pressure reached these values. Overshoot-settling did not affect these values and were disregarded as the proposed method gave the most consistent results and allowed for numerical comparison between signal inputs and valve types. The valve opening delay time was estimated by the elapsed time from the signal trigger to t_{10}. The transition time was estimated by the time difference of the t_{trans} and t_{10} points. The delay and transition times for closing were determined in a similar manner to that of opening though t_{10} and t_{trans} referred to rising times as opposed to drop times.

Single valve experiment setup

The components tested were two normally closed cartridge valves; a Sun Hydraulics DTDA-XCN valve with a 770–212 12 V coil and a modified Sun Hydraulics

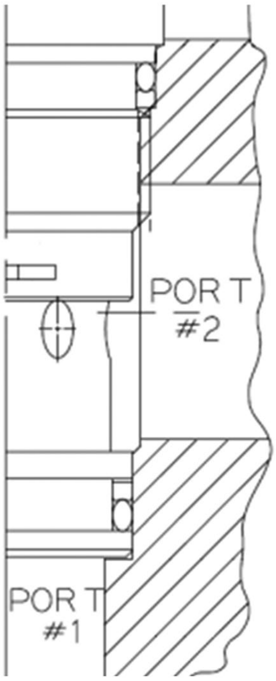

Figure 8. Port and valve axisymmetric cross-section.

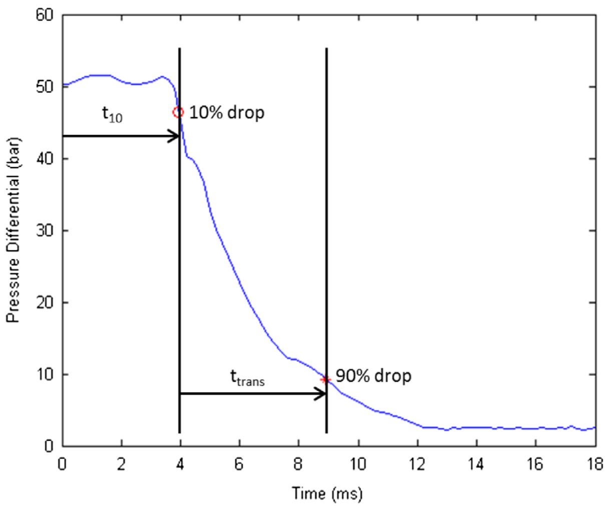

Figure 9. Calculating turn-on (opening) response using t_{10} and t_{trans}.

DTDA-XCN valve with a 760–212 12 V coil which uses a solenoid tube and coil from Sun Hydraulics DAAA valves. The ratings of the coils used in both valves are shown in Table 3. These valves were selected because they could be implemented and tested on the digital pump/motor as well. The experiments were conducted at a differential pressure of 52 bar, 28 l/min flow, 55 V peaking voltage and 12 V holding voltage achieved through applying a PWM on the 55 V peak voltage.

National Instruments (NI) hardware was used for testing the valves. A PXI-1031 chassis with a Field Programmable Gate Array (FPGA) card were used. The peak-and-hold turn-on and reverse current turn-off strategies were programmed in the FPGA, which was also used to read the output from the pressure transducers. The sensor calibrations were done in Matlab/Simulink. NI Veristand was used to interface the FPGA and Matlab/Simulink and provide the user with a control interface. The Veristand panel allowed the user to independently specify the peak and reverse voltage duration for both turn-on and turn-off response.

Table 3. Coil ratings.

	Coil	
Rating	770–212	760–212
Supply voltage (V)	12	12
Power consumption (cold) (W)	22	12
Maximum coil temperature (°C)	105	105
Connector	ISO/DIN 43650A, form A	ISO/DIN 43650A, form A

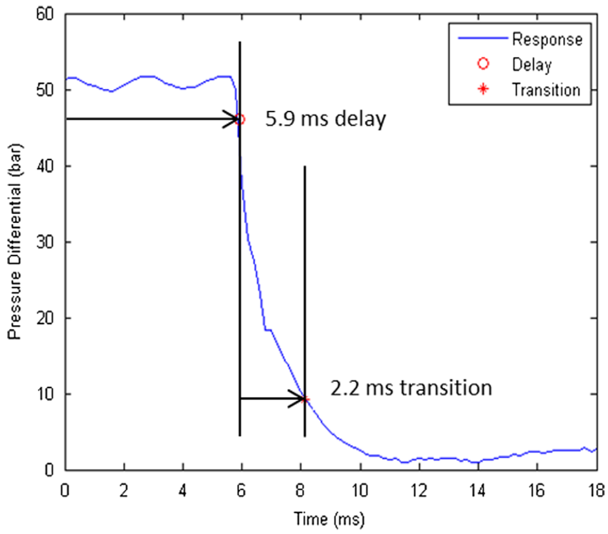

Figure 10. Modified DTDA-XCN turn-on response at 10 ms voltage peak.

Single valve results

After the tests were run with this setup, results were tabulated. Figures 10 and 11 show an example turn-on and turn-off response for the modified Sun Hydraulics DTDA-XCN valve. The signal was sent at time zero, a delay in valve opening and closing was recorded to be 5.9 and 19.9 ms respectively. The transition time for opening was calculate to be 2.2 ms with a 10 ms voltage peak duration, while the transition time of closing was calculated to be 4.8 ms when using a 5 ms voltage peak.

Both valves were tested in forward and reverse flow. Both the opening peak voltages and closing reverse current durations were varied from zero to ten milliseconds in increments of one millisecond. The experiment was repeated three times under the same conditions.

The time it takes for the pressure difference to change, decreasing or increasing, by 10% from the time the control signal is sent is labeled as t_{10} and represents the delay time of the valve. The value t_{trans} tells the amount of time the valve spends moving between the 10 and 90% change

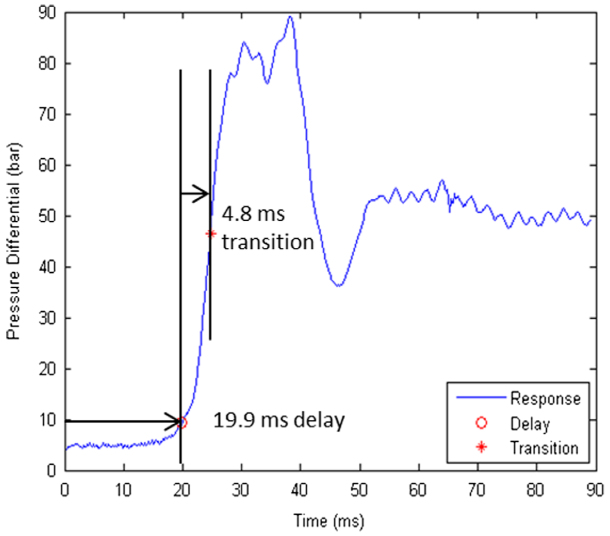

Figure 11. Modified DTDA-XCN turn-off response at 5 ms reverse current.

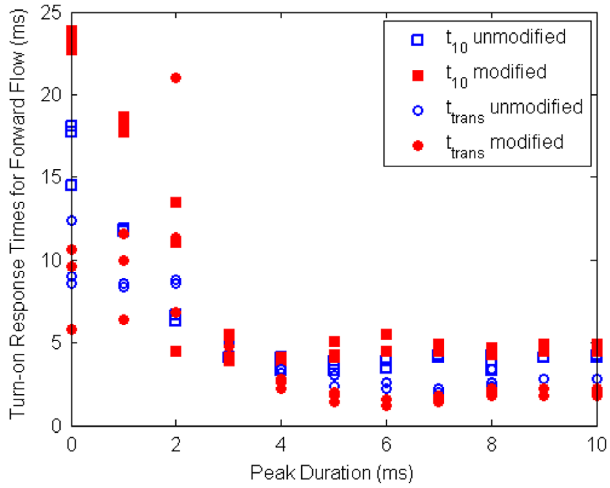

Figure 12. Comparison between the modified and unmodified valves delay and transition turn-on response for forward flow.

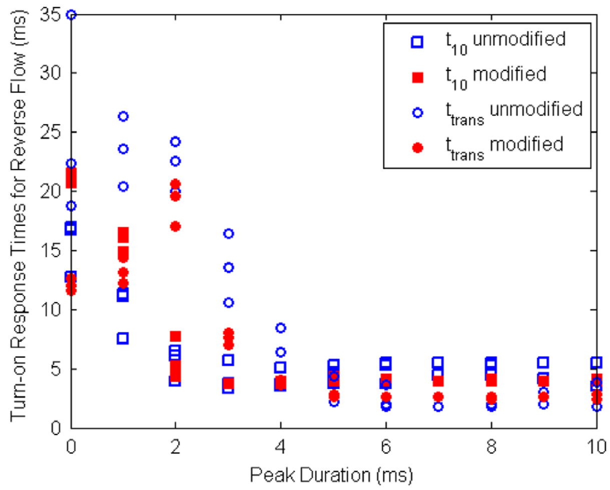

Figure 13. Comparison between the modified and unmodified valves delay and transition turn-on response for reverse flow.

in differential pressure points which is called the transition time of the valve. For both valves, the fastest opening response time in the forward flow DIR was achieved at a peak duration equal or larger than five milliseconds, while the fastest opening response time in the reverse flow DIR was achieved at a peak duration equal or larger than seven milliseconds. The averages for the calculated response times are presented below.

Six sets of the modified and unmodified valves were tested to compare the delay and response times under the effect of the peak-and-hold and reverse current strategy at different peak durations. The peak duration was varied from 0 to 10 ms with an increment of 2 ms. One result from each of the tested sets was selected for Figures 12 and 13, showing the turn-on response for the DTDA-XCN and the modified DTDA-XCN valves for forward and reverse flow DIRs, respectively.

For opening the valves with flow in the forward DIR, the delay and transition times for both the modified and unmodified valves improved considerably using the peak-and-hold strategy. Improvement in the delay time was observed until the duration of the peak was greater than or equal to the delay time itself as any peak time beyond this affects the transition time instead. The optimal transition time occurred when the peak duration was equal to the sum of the delay and transition times; this is because the transition time starts after the end of the delay phase. However, the transition time reaches its optimum value when the peak duration is equal to the sum of both the delay and the transition time, where the excess peak would be acting for holding and not for improving the transition since the transition phase would have already ended.

The turn-off response for the DTDA-XCN and the modified DTDA-XCN valves for the reverse flow DIR is shown in Figures 14 and 15, respectively. The modified valve had a smaller coil, so it couldn't always fully open against pressure when a low peak duration was sent, resulting in the missing data points in Figure 15 when the peak duration was less than six milliseconds.

The optimal reverse current duration for the modified and unmodified DTDA-XCN was at 5 ms. However, as the peak duration increased beyond these optimal points, the delay time increased due to the excess duration of the reverse current restablishing the magnetic field. This slowed down the valve when closing as anticipated from Equation (1). Because the force to close the valve is based on the stiffness of the spring and not the solenoid force, the transition time for all of the valves was not improved by electrical signal strategies.

A direct comparison of the two valves total turn-on and turn-off time ($t_{10} + t_{trans}$) can be found in Tables 4 and 5, respectively. Both valves have similar turn-on response times; however, the modified valve had significantly better turn-off response times with 19.83 and 11.63 ms compared to 27.17 and 20.43 ms for the forward and reverse flow, respectively. So in summary, the peak-and-hold and reverse current strategy significantly

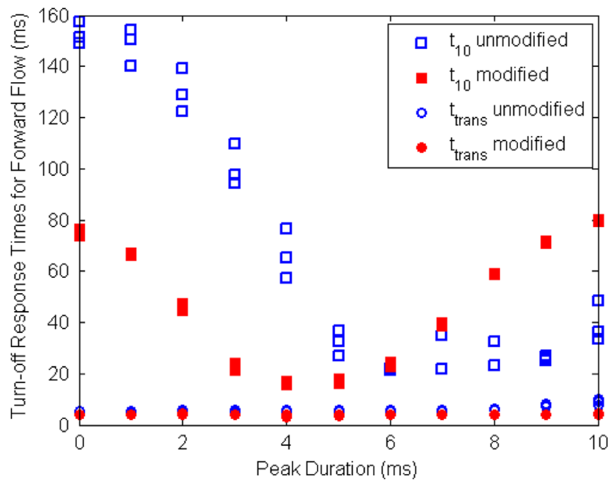

Figure 14. Comparison between the modified and unmodified valves delay and transition turn-off response times for forward flow.

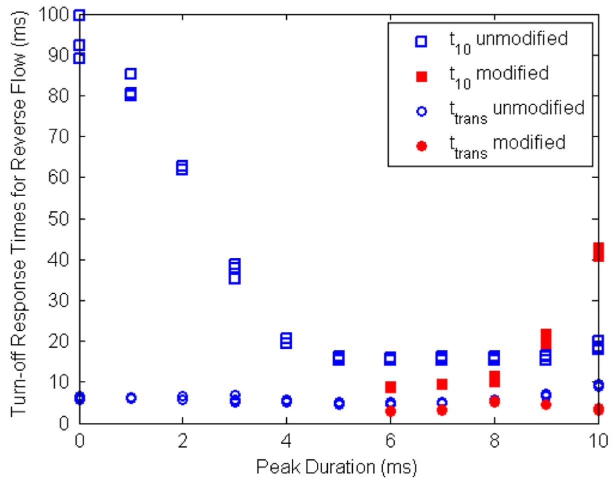

Figure 15. Comparison between the modified and unmodified valve delays and transition turn-off response times for reverse flow.

Table 4. Comparison of average total turn-on time of modified and original valves DTDA-XCN valves.

	Turn-on response time (ms)			
	Forward		Reverse	
Peak duration (ms)	Unmodified	Modified	Unmodified	Modified
0	26.77	31.97	40.83	33.30
1	20.37	27.57	33.43	29.10
2	15.17	22.77	27.77	24.83
3	9.03	9.23	17.77	11.23
4	7.10	6.50	10.37	7.57
5	6.43	6.23	7.70	6.77
6	6.10	6.30	7.30	6.57
7	6.30	6.23	7.23	6.50
8	6.63	6.50	7.23	6.50
9	6.90	6.70	7.37	6.50
10	6.97	6.77	7.30	6.63

improved the delay and transition times of two different electrically controlled cartridge on/off valves, and the modified version of the valve had significantly

Table 5. Comparison of average total turn-off time of modified and original DTDA-XCN valves.

	Turn-off response time (ms)			
	Forward		Reverse	
Reverse current duration (ms)	Unmodified	Modified	Unmodified	Modified
0	158.17	79.10	99.90	–
1	153.30	70.77	88.10	–
2	135.77	50.17	68.23	–
3	106.03	26.43	43.10	–
4	71.77	19.83	25.17	–
5	37.50	20.83	20.70	–
6	27.17	27.37	20.43	11.63
7	32.03	42.90	20.63	12.83
8	32.30	62.97	21.10	16.17
9	33.63	75.37	22.90	24.77
10	48.23	83.77	28.17	45.30

faster turn-off response times compared to the original DTDA-XCN valve.

Digital pump/motor hydraulic circuit

Following the results from the single valve testing, additional testing was completed by implementing the valves in a digital pump/motor to determine the effects of faster valve actuation on the efficiency of the pump/motor. A digital pump/motor test stand utilizing a regenerative circuit, shown in Figure 16, was used for the efficiency testing. Pressure transducers and flow meters are present in the high and low pressure lines. Torque is measured on the shaft connecting the two pump/motors. Port A referred to the low pressure port, while port B referred to the high pressure port. The charge pressure was provided by a separate hydraulic unit to the low pressure side; this unit filters and cools the fluid as well as provide the reservoir for the test setup. A pump/motor unit is connected to the digitial pump/motor through a common shaft, and an electric motor was used to add more power to the shaft to accommodate for the losses. The pressure in the system is controlled by changing the settings on the electrically controlled proportional relief valve located on the high pressure side of the circuit.

The valves are placed in the high and low pressure ports for each of the three chambers of the digital pump/motor, six valves total. In-cylinder pressures are taken by 2000 Hz pressure transducers similar to those used in the single valve testing. A diagram of a single chamber of the three chamber unit can be seen in Figure 17.

Based on the angular location of the shaft, the appropriate valves are opened and closed to allow for pumping or motoring, varying flow, and different operating strategies. There are four different operating strategies in all. Figure 18 shows the different valve states for different operating strategies. Bold and highlighted states indicate that the valve state (open or closed) changes during this part of the piston cycle.

The first operating strategy is Partial Flow Diverting. In this case, the piston takes in the full chamber displacement during the intake stroke and diverts flow in excess

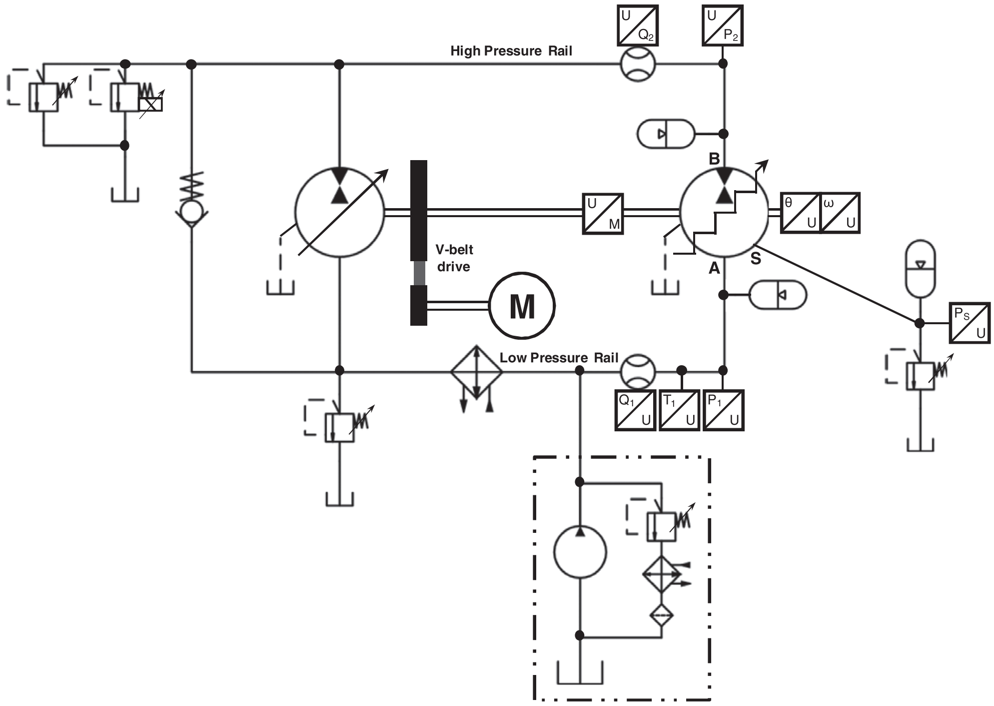

Figure 16. Regenerative test circuit (Holland 2012).

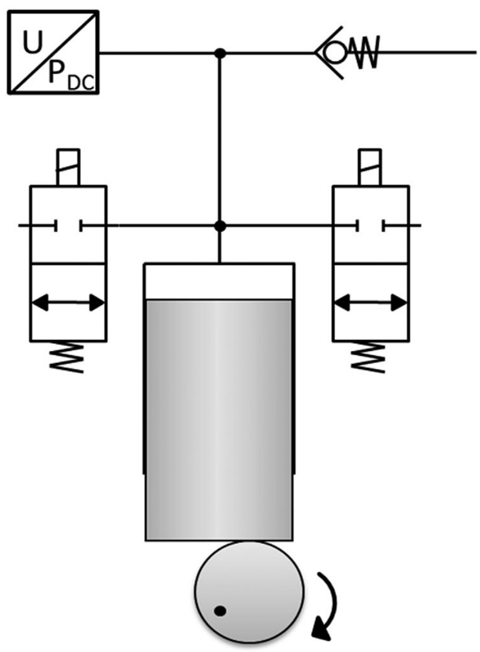

Figure 17. Individual displacement chamber schematic.

of the desired amount to the low pressure port during a portion of the expulsion stroke.

The second strategy is Partial Flow Limiting in which the amount of flow taken into the chamber is limited to the desired flow amount. This results in "voiding" the chamber through the part of the cycle when both valves are closed. This is called chamber voiding and is different from cavitation in that this is controlled and the rate of change in pressure with respect to time is not high enough to produce the detrimental effects of cavitation.

The final strategies are Sequential Flow Limiting and Sequential Flow Diverting (FD seq). The only difference between these two is the manner in which the Sequential flow strategy is implemented. Varying flow rates are achieved by operating chambers in either full displacement pumping or zero displacement idling with the ratio of pumping to idling equaling the desired displacement.

Digital pump/motor simulation model

A three-piston digital pump/motor was modeled and simulated using Matlab Simscape (Merrill *et al.* 2013). The system was modeled with all components and included compressibility effects, fluid leakage, viscous friction in between the piston and the cylinder, valve throttling losses as well as valve electrical consumption. This model was modified and used to predict the change in the overall efficiency of the system when using both Sun Hydraulics cartridge valves. The result is shown in Figure 19, where the simulation was conducted at 500 rpm and a 103 bar differential pressure, in both flow diverting (FD) and FD seq operating strategies for both valves. As seen in the figure, the overall efficiency of the digital pump/motor was greatly improved with the new valves; the model predicts around 8% efficiency improvement in the FD seq mode and around 15% improvement in the partial flow diverting mode.

Digital pump/motor experimental setup

In order to validate these results, the valves were installed on a three-piston digital pump/motor test stand. Similar software and hardware was used to control the six valves in the digital pump/motor as was used with the single valve testing. Additional software was utilized to implement the operating strategies mentioned previously. The same valves that were tested individually were installed in the digital pump/motor.

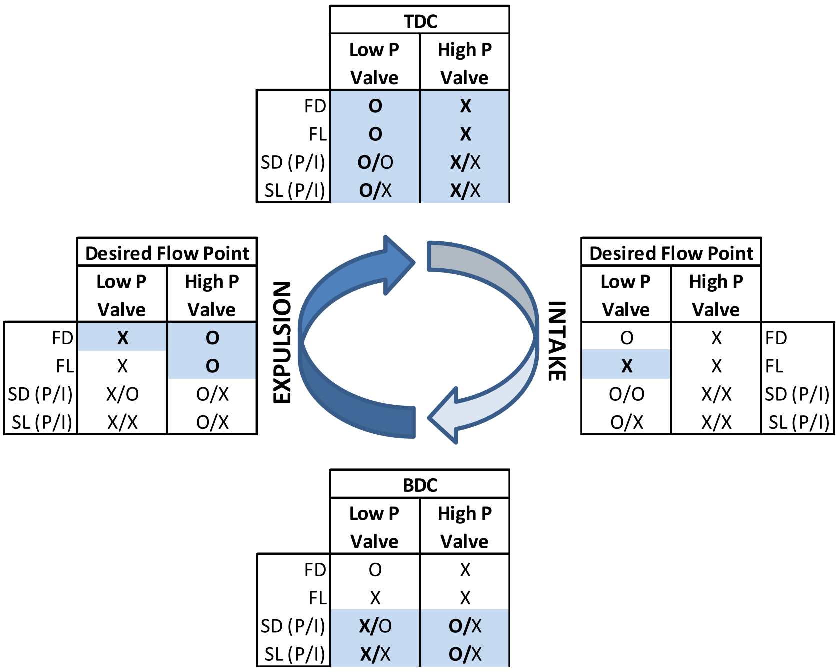

Figure 18. Valve changes for the four operating strategies (FD = Flow Diverting, FL = Flow Limiting, SP = Sequential Pumping, SI (D/L) = Sequential Idling Diverting/Limiting), O = Open, X = Closed.

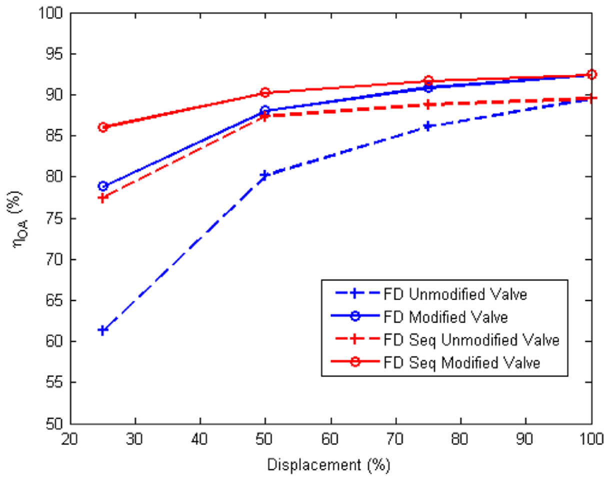

Figure 19. Digital pump/motor simulated efficiency comparison when using the unmodified and modified valves for flow diverting and sequential flow diverting (FD seq) strategies.

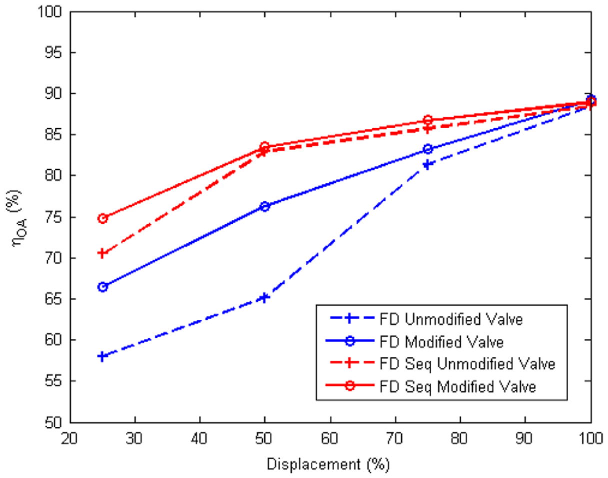

Figure 20. Digital pump/motor measured efficiency comparison when using the unmodified and modified valves for flow diverting and FD seq strategies.

The results of the single valve testing of the modified valves were used to determine optimal delay times for the pump/motor configuration, and were thus incorporated as an advance time in the control code. The valves were signaled to open or close earlier based on the predetermined delay times of each valve.

Digital pump/motor results

All experimental results were obtained while operating at 500 rpm and 103 bar differential pressure. The FD and FD seq strategies were used while operating the digital pump/motor, the results of which can be found in Figure 20. It can be clearly seen that the overall efficiency for both strategies increases when the modified valve is used. The FD sequential strategy's efficiencies were similar for both valves down to 50% displacement, though a 5% improvement in efficiency is realized at 25% displacement. The FD strategy shows significant improvement as implementation of the new valve resulted in an overall efficiency increase of up to 12%. Experimental results validated the predicted efficiencies obtained from the simulation model. It revealed that an increase in efficiency was obtained for the new valve in both partial and FD seq operating modes. Non-linearity in delay and transition times creates a slight discrepancy in efficiency at lower displacements, however. This variation occurs in all six valves resulting in lower efficiencies than that of the simulation. It should be noted that electrical losses have not been considered in the efficiency plots.

Conclusion

This work experimentally examined the effect of peak-and-hold and reverse current strategies on the turn-on and turn-off response of two commercially available solenoid actuated cartridge valves. Experimental results show a decrease of more than 80% in turn-on response time and more than 64% decrease in turn-off response in both valves, for both flow DIRs when using peak (55 V) and hold (12 V) and reverse current strategies compared to steady 12 V input. The delay time was reduced in both opening and closing phases for both flow DIRs. The transition time for opening was improved under peak-and-hold voltage strategies, but stayed relatively constant during closing (reverse current, turn-off strategy) because closing force is dependent on the stiffness of the spring.

To demonstrate the larger system benefits of using valves with improved dynamics (same flow area), a three-piston digital pump/motor was modeled and simulated using Matlab Simscape. This model showed an improvement in efficiency of up to 15% using the FD mode and up to 8% using the FD seq mode. This strategy was then implemented on a three-piston digital pump/motor test stand where valve accuracy is crucial. It was shown that an improvement in efficiency could be achieved by using faster valves, where an increase of up to 12% was achieved in the partial flow diverting mode and up to 5% in the FD seq mode.

Additional electrical energy consumption is needed to implement these strategies; this energy would be dissipated in the coil and armature leading to heat generation. This heat generation can be minimized by precise timing of the peak-and-hold and reverse current strategies determined by testing of valve performance for different signal durations. Though additional energy is needed, no physical or mechanical alterations to the valves are required to achieve these results. Many applications would benefit from this strategy, especially those in which additional electrical energy consumption and heat generation wouldn't be a problem. This strategy could be used in many digital hydraulic systems where valve timing and accuracy is needed similar to digital pump/motors.

Acknowledgments

The authors would like to thank Sun Hydraulics for their help customizing and donating a new set of valves.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Center for Compact and Efficient Fluid Power, a National Science Foundation Engineering Research Center funded under cooperative [agreement number EEC-0540834], and by the National Fluid Power Foundation.

Notes on contributors

Farid Breidi received his BE degree from the American University of Beirut in 2010, the MSE from the University of Wisconsin-Madison in 2012, and is working towards PhD in the area of digital hydraulics at Purdue University. His research interests include fluid power systems, modeling and simulation, and component design.

Tyler Helmus received his BSE degree from Calvin College in 2012 and is currently working towards his doctorate at Purdue University with a focus on digital hydraulics. His research interests include mechatronics, fluid power systems, simulation, and design.

John Lumkes received the BSE degree from Calvin College in 1990, the MSE from the University of Michigan-Ann Arbor in 1992, and the PhD from the University of Wisconsin-Madison in 1997. From 1997 to 2004 he was an assistant and associate professor at Milwaukee School of Engineering. In 2004, he joined Purdue University where he is an associate professor and is active in digital hydraulics, modeling and controls, mechatronics, and design.

ORCID

Farid Breidi http://orcid.org/0000-0003-4959-3292

References

Batdorff, M.A., 2010. *Transient analysis of electromagnets with emphasis on solid components, Eddy currents, and driving circuitry*. Dissertation (PhD). Purdue University.

Bishop, E.D., 2010. Digital hydraulic transformer – efficiency of natural design. *7th international fluid power conference*, Aachen, Germany.

Ehsan, M., Rampen, W.H.S., and Salter, S.H., 1996. Computer simulation of the performance of digital-displacement pump-motors. *Fluid power systems and technology: collected papers*, 3, 19–24 (Proceedings of the 1996 international mechanical engineering congress & exposition).

Heikkila, M., *et al.*, 2010. Experimental evaluation of piston-type digital pump-motor-transformer with two independent outlets. *Proceedings of the Bath/ASME symposium on fluid power and motion control*, Bath, UK.

Holland, M.A., 2012. *Design of digital pump/motors and experimental validation of operating strategies*. Thesis (PhD). Purdue University.

Long, G.R., 2009. *Comparison study of position control with 2-way and 3-way high speed on/off electrohydraulic valves*. Thesis (Master). Purdue University.

Long, G. and Lumkes, J. Jr., 2010. Comparative study of position control with 2-way and 3-way on/off electrohydraulic valves. *International journal of fluid power*, 11 (1), 21–32. doi:10.1080/14399776.2010.10780995.

Love, L., 2009. Fluid power research: a fundamental concern for U.S. energy policy [PowerPoint slides]. *Presented at the national fluid power association industry and economic outlook conference*, 17 August, Wheeling, IL.

Love, L., 2014. Energy impact of fluid power [PowerPoint slides]. *Presented at the 2014 IFPE technical conference*, 5 March, Las Vegas, NV.

Lumkes, J. and Andruch, J., 2011. Hydraulic circuit for reconfigurable and efficient fluid power systems. *Proceedings of the 12th Scandinavian international conference on fluid power, SICFP,* Tampere, Finland (1096), 16.

Lumkes, J., Jr., Batdorff, M.A. and Mahrenholz, J.R., 2009. Model development and experimental analysis of a virtually variable displacement pump system. *International journal of fluid power*, 10:3, 17–27. doi: 10.1080/14399776.2009.10780985

Merrill, K.J., 2012. *Modeling and analysis of active valve control of a digital pump-motor*. Thesis (PhD). Purdue University.

Merrill, K.J., Breidi, F. and Lumkes, J., 2013. Simulation based design and optimization of digital pump/motors. *Proceedings of the ASME/BATH 2013 symposium on fluid power and motion control,* Sarasota, Florida.

Merrill, K., Holland, M., Batdorff, M. and Lumkes, J. Jr., 2010. Comparative study of digital hydraulics and digital electronics. *International journal of fluid power*, 11 (3), 45–51. doi:10.1080/14399776.2010.10781014.

Mikkola, J., *et al.*, 2007. Improving characteristics of on/off solenoid valves. *The tenth Scandinavian international conference on fluid power,* Tampere, Finland.

Nieling, M., Fronczak, F. and Beachley, N., 2005. Design of a virtually variable displacement pump/motor. *Proceedings of the 50th national conference on fluid power (NCFP)*, Las Vegas, NV, USA.

Scheidl, R., *et al.*, 2008. Hydraulic buck converter – concept and experimental results. *6th international fluid power conference*, Vol. II, 501, Dresden.

Shenouda, A. and Book, W., 2008. Optimal mode switching for a hydraulic actuator controlled with four-valve independent metering configuration. *International journal of fluid power*, 9 (1), 35–43. doi:10.1080/14399776.2008.10781295.

Skelton, D., *et al.*, 2013. High performance actuation systems enabled by energy coupling mechanisms. *SAE 2013 commercial vehicle engineering congress*, 1 October, Rosemont, IL, USA.

Skelton, D., Xiog, S. and Lumkes, J., 2014. Design of high performance actuation system for high speed valves. *9th international fluid power conference*, Aachen, Germany.

Tu, H.C., *et al.*, 2012. Design, modeling, and validation of a high-speed rotary pulse-width-modulation on/off hydraulic valve. *ASME journal of dynamic systems, measurement, and control*, 134 (6), 061002.

Van de Ven, J.D. and Katz, A., 2011. Phase-shift high-speed valve for switch-mode control. *ASME journal of dynamic systems, measurement, and control*, 133 (1), 011003.

Williamson, C. and Ivantysynova, M., 2007. The effect of pump efficiency on displacement-controlled actuator systems. *Proceedings of the 10th Scandinavian international conference on fluid power*, Tampere, Finland.

Xiong, S., and Lumkes, J., 2014. Coupled physics modelling for bi-directional check valve system. *International journal of fluid power*, 15 (2), 55–67, doi: 10.1080/14399776.2014.897500