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AN INTEGRATED COMPACT DIGITAL HYDRAULIC CONVERTER PROTOTYPE FOR HYDRAULIC TRANSMISSION

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ABSTRACT

Digital hydraulic converters are innovative devices that enable efficient regulation and control of hydraulic fluid flow and pressure. Unlike conventional methods that employ flow throttling and power dissipation, digital hydraulic converters use digital control signals to create highly efficient hydraulic fluid power systems. In this study, a new, compact, highly efficient, and high-bandwidth digital hydraulic converter prototype was developed and investigated. The new converter comprises a high-flowrate, low-resistance, and high-speed rotary valve, inertance and capacitive components, and real-time programmable logic controllers (PLCs) to form an integrated digital hydraulic device. Analytical models of the prototype were developed to investigate converter performance and energy efficiency, followed by experimental validations. Analytical and experimental results showed that the new hydraulic converter has very good pressure dynamics, performance, and energy efficiency. This work contributes to the design and development of high-performance digital hydraulic components for sustainable hydraulic machinery.

KEYWORDS: digital hydraulic converters, digital control, dynamics, efficiency, sustainable hydraulic machinery

1. INTRODUCTION

Digital hydraulics is an innovative technology using digitally controlled (0/1) components such as on/off valves to control flow and pressure, which can achieve high energy efficiency, good controllability and are insensitive to contamination [1-4]. Digital hydraulic converters consist of high-speed switching valves (switching), inertance tubes (inertia), and accumulators (capacitance) [5-15]. The flow booster can deliver significantly higher flow than the supplied flow by switching between the high-pressure (HP) supply and low-pressure (LP) at a high speed.

When the LP is connected, the momentum of the fluid in the inertance tube can overcome the adverse pressure gradient and draw the flow from the LP supply [4]. The delivery flow reduces when connecting to the LP supply, but the reduction will be small as long as the switching time between HP and LP is short, and the average delivery flow will be significantly higher than the HP supply flow rate. The operation can be achieved by controlling the switching ratio (pulse width of the valve control signal) to change the movement or force directions of the load [12-14].

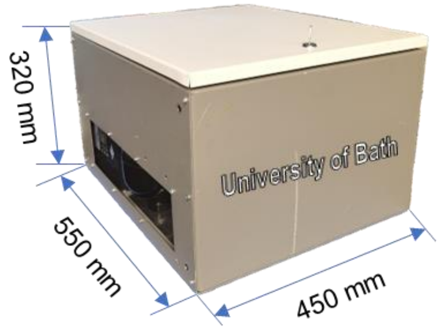
Brown et al. conceptualised digital hydraulic converters in the 1980s [15]. The static test results matched well at a switching ratio of 90% and 100% but considerably deviated at below 90% due to severe cavitation at the tank side with a high switching frequency of 500 Hz. Scheidl et al. developed a hydraulic bulk converter prototype using two on/off valves as the switching element in 2008 [16]. The prototype was tested with HP and LP pressures of 100 and 30 bar, and up to 16% increase in efficiency was achieved at a switching ratio of 55% and switching frequency of 70 Hz. The overlap and underlap of the on/off valves can cause cavitation and affect the efficiency and the control of two on/off valves is difficult, therefore, they replaced the on/off valve in the return line with a check valve [17]. The new prototype was used to drive a differential cylinder and showed a high efficiency of 70% at steady state compared with 50% using proportional valve control. The team extended the prototype with bi-directional ability by using an on/off valve and check valve at both HP and LP supply lines [17]. With a delivery pressure range of 60-120 bar, the extended prototype achieved a maximum of 30% increase in energy efficiency with a switching frequency of 50 Hz. The prototype was then compactly designed by integrating accumulators, valves, and coiled inertance tubes into a manifold. The compact prototype was designed with an HP and LP supply pressure of 160 bar and 5 bar and a nominal flow rate of 3 L/min. Compared with proportional valve control, the prototype exhibited a 34% energy saving on charging and discharging an accumulator. It was then applied to a robotic leg [18] and showed up to 31% energy saving at a demand flow rate of 1 L/min, and it could be more efficient for loads requiring higher flow rates.

Digital hydraulic converters require an integrated and compact design with low resistance at high flow rates to achieve high efficiency for application on hydraulic machinery. In this paper, we developed a new, compact, highly efficient, and high-bandwidth digital hydraulic converter prototype, including a high-flow rate, low-resistance, high-speed rotary valves, inertance and capacitive components, and real-time programmable logic controllers. The prototype can either be independently controlled by the PLC controller offline or can be controlled using Simulink real-time platform through EtherCAT. The prototype performance and energy efficiency were investigated by analytical models and experimental validations. The results showed that the developed prototype achieved a high flow rate and low resistance (64 L/min at 3.7 bar), a very fast switching time of less than 1 ms, good pressure dynamics, and energy efficiencies (82-86%) at flow rates up to 21 L/min. This work contributes to the design and development of high-performance digital hydraulic components for sustainable hydraulic machinery.

2. PROTOTYPE DESIGN

2.1. Overall design

A digital hydraulic converter prototype was integrated into a box (550×450×320 mm) to achieve a compact design, including a high-performance valve, inertance components, accumulators, real-time programmable logic controller (PLC), and power converter, as shown in **Figure 1**. The target maximum working pressure and delivery flow rate is 400 bar and 200 L/min. The prototype can be either independently controlled by the PLC with the pre-programmed control algorithm offline or can be real-time controlled and tested with Simulink through Ether-CAT, which provides flexibility for developing and optimising control logic and algorithms. Using the power converter, the prototype can be directly plugged into any hydraulic machine with a 12/24V DC power supply without the need to adapt the machine power supply.



Target specifications	Value (unit)
Operating pressure	50-400 bar
Flow rate	0-200 L/min
Supported control	PLC/EtherCAT/Simulink
Power supply	DC 12 or 24V

Figure 1. Integrated converter prototype design

2.2. Rotary valve design

A 4/2-way high-performance valve was developed to work at switching frequencies of 50-250Hz with a switching time of 1 ms, using the rotary working principle of the valve [6, 9] as shown in **Figure 2(a)**. The valve switches from one status that the HP supply is connected to Port A and LP is connected to Port B to the other status that the LP supply is connected to Port A and HP is connected to Port B. The rotor speed determines the switching frequency of the valve while the control shaft determines the switching ratio. The valve orifice areas during switching can be calculated based on the valve geometry parameters [6]. **Figure 2(b)** shows the flow paths from HP supply to Port A, where orifice areas such as A_{shaft}, A_s, A_m, A_p, and A_{stator} limit the valve flow capacity and cause the orifice area difference of the two ways in the valve. Therefore, the new valve was redesigned and optimised to achieve an increased and balanced orifice area with a maximum value of 70 mm^2 (see **Figure 3**), which is 3.5 times that of the previous valve [9].

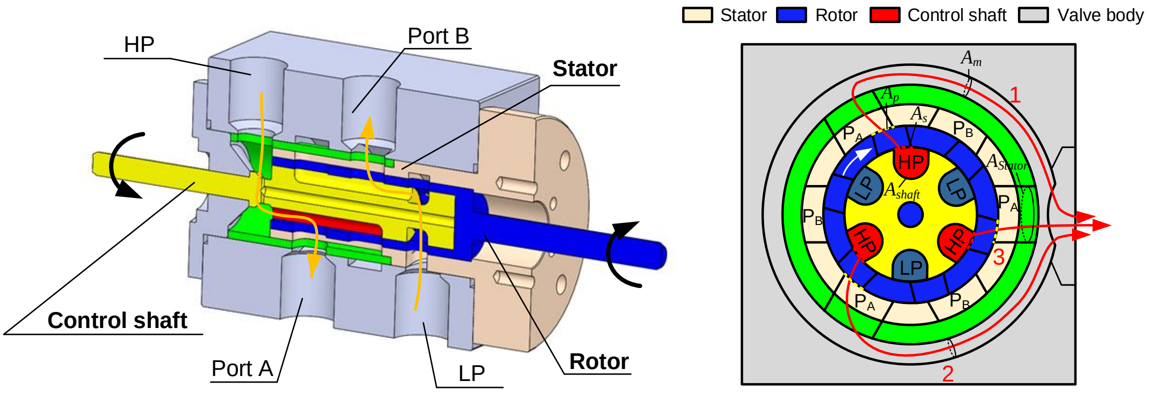


Figure 2. High-speed rotary valve design [6,9] (a) working principle (b) flow paths from HP to Port A

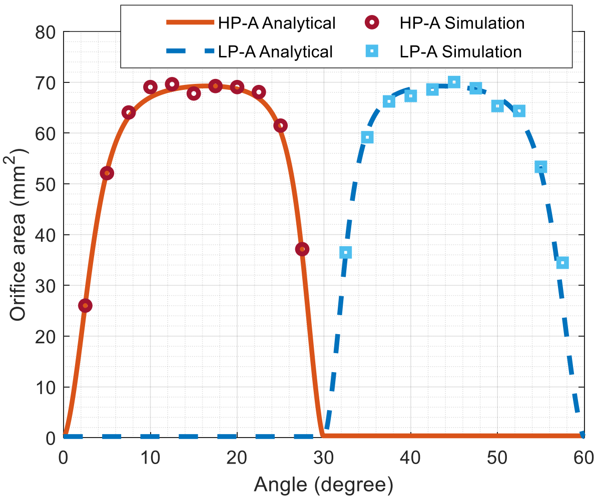
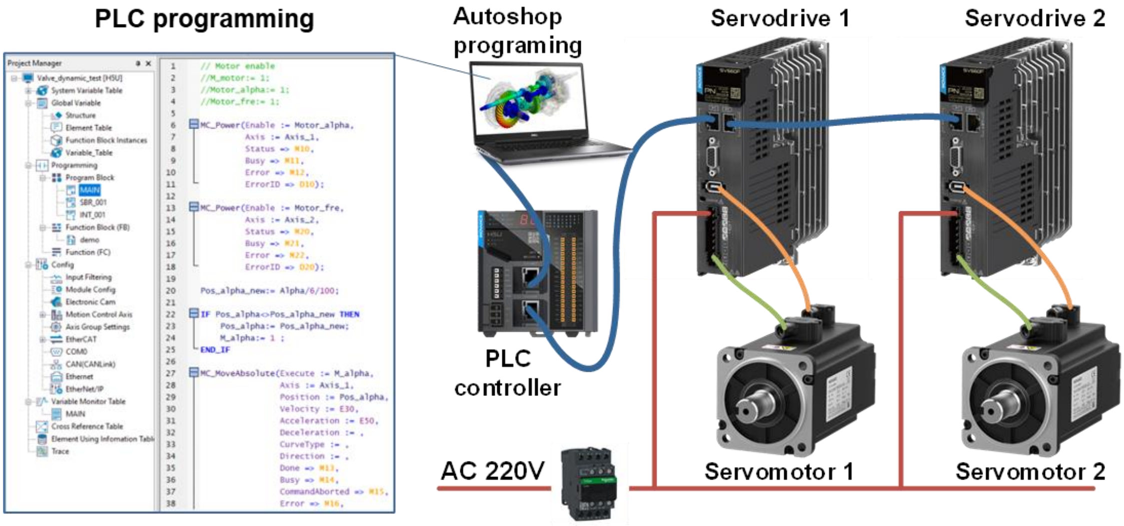


Figure 3. Analytical and simulated valve orifice area with a rotating angle

3. PROTOTYPE INVESTIGATION

3.1. Programmable logic control

An industrial standard PLC controller was used to implement independent offline control of the digital hydraulic converter prototype, which can be easily integrated with other industry applications. As seen in **Figure 4**, the control logic and algorithm can be designed and programmed in the host computer such as a laptop, and then downloaded to the PLC to control the servomotors of the prototype. The prototype can be expanded with I/O boards to acquire and send data to the application system, which enables integrations with other devices and advanced control design. The prototype also supports online tuning of the parameters of the controller, which is user-friendly for troubleshooting and maintenance.



```
// Motor enable
//M_motor:= 1;
//Motor_alpha:= 1;
//Motor_fre:= 1;

MC_Power(Enable := Motor_alpha,
         Axis := Axis_1,
         Status => M10,
         Busy => M11,
         Error => M12,
         ErrorID => D10);

MC_Power(Enable := Motor_fre,
         Axis := Axis_2,
         Status => M20,
         Busy => M21,
         Error => M22,
         ErrorID => D20);

Pos_alpha_new:= Alpha/6/100;

IF Pos_alpha<>Pos_alpha_new THEN
    Pos_alpha:= Pos_alpha_new;
    M_alpha:= 1 ;
END_IF

MC_MoveAbsolute(Execute := M_alpha,
                Axis := Axis_1,
                Position := Pos_alpha,
                Velocity := E30,
                Acceleration := E50,
                Deceleration := ,
                CurveType := ,
                Direction := ,
                Done => M13,
                Busy => M14,
                CommandAborted => M15,
                Error => M16,
```

Figure 4. Programmable Logic Control and hardware schematics

3.2. EtherCAT enabled real-time control system

The prototype can be real-time controlled using Simulink Real-Time for hardware-in-the-loop testing for its EtherCAT compatibility, which is desired for research and development in universities and companies. Advanced controller design was implemented in Matlab/Simulink on a host computer and downloaded to the target computer, which works as the EtherCAT Master to control the slaves on the EtherCAT network such as servo drives to drive servo motors, as shown in **Figure 5**. Data acquisition systems such as NI cards can be incorporated with the EtherCAT network in Matlab/Simulink to provide high flexibility for real-time control design and optimisation of complex systems.

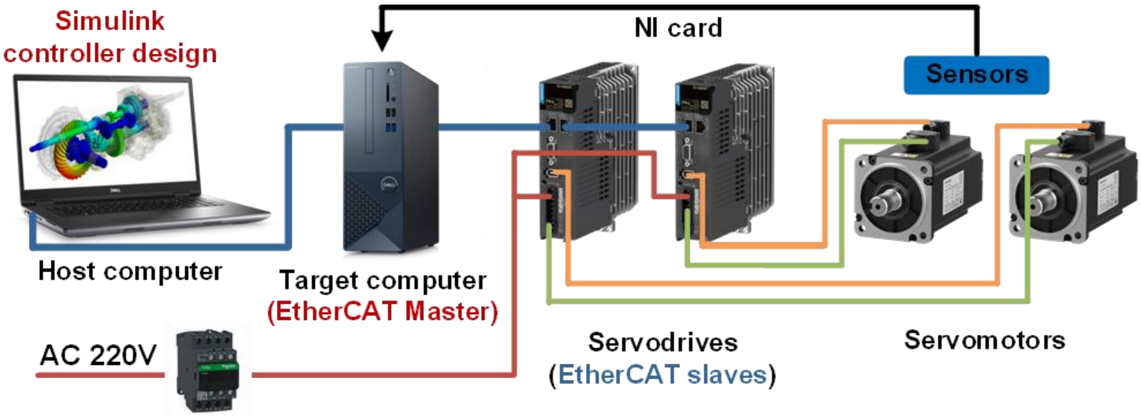


Figure 5. EtherCAT enabled real-time control system

3.3. Experimental validation

The prototype was experimentally tested in a flow booster configuration without the inertance components to validate the performance and characteristics of the new high-performance valve. A hydraulic power pack including two gear pumps with a maximum supply pressure of 100 bar and 50 bar are used as HP and LP supplies. Accumulators and shock suppressors (Inline Pulse-Tone™ Shock Suppressors, Parker Hannifin) are used to eliminate the pressure pulsations at HP and LP supplies. The charging pressures of the HP and LP accumulators are 45 bar and 15 bar, and the charging pressures of the shock suppressors are 22.5 bar and 7.5 bar respectively. Three miniature piezoresistive dynamic pressure transducers (TE connectivities XP5 series) are used to measure the pressure of the HP port, the LP port, and Port A of the valve, with ranges of 0-350 bar, 0-70 bar and 0-200 bar, correspondingly. A gear flow meter (0.5 – 70 L/min, ZHM series from KEM) was used to measure the dynamic HP supply flow rates. The delivery flow rate at Port A was measured by using a turbine flow meter (HYDAC, 6 – 60 L/min).

Figure 6 shows the analytical, CFD, and experimental results of the flow rate versus pressure drop of the new valve. The analytical results were obtained from the orifice equation (1) with a valve orifice area of about $A_\text{v} = 70\ \text{mm}^2$ at fully open. This was validated by the CFD simulations conducted in Ansys/Fluent using the flow channel of the valve including the fittings and the results matched well with the analytical values.

$$\Delta p = \frac{q^2}{C_d{}^2 A_v{}^2}\frac{\rho}{2} \tag{1}$$

The orifice areas from HP to Port A (Experimental HP) and LP to Port A (Experimental LP) were tested, and the results agreed well with analytical and CFD results despite the slight deviation that could be caused by the small fluctuations of the pressure transducers. The valve can achieve *64 L/min* with a pressure drop of only *3.7 bar*, which is significantly improved compared with that (64 L/min at 23 bar) of the previous prototype [6, 9]. Therefore, the new valve is promising to achieve much higher energy efficiency at high flow rates.

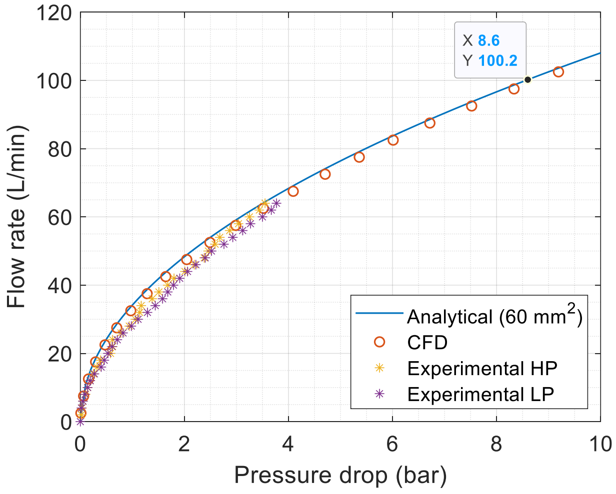
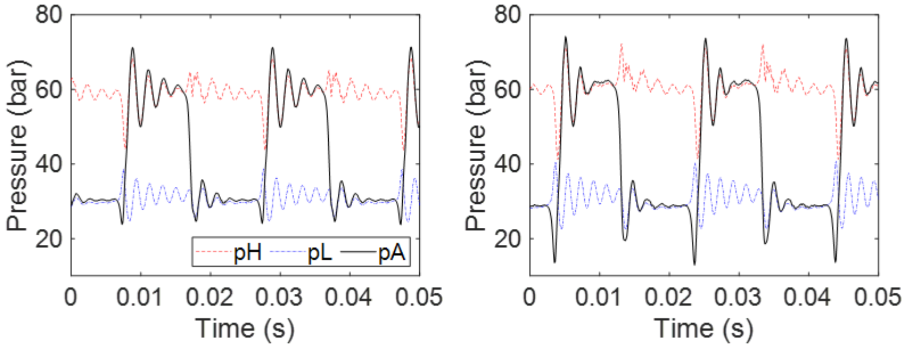


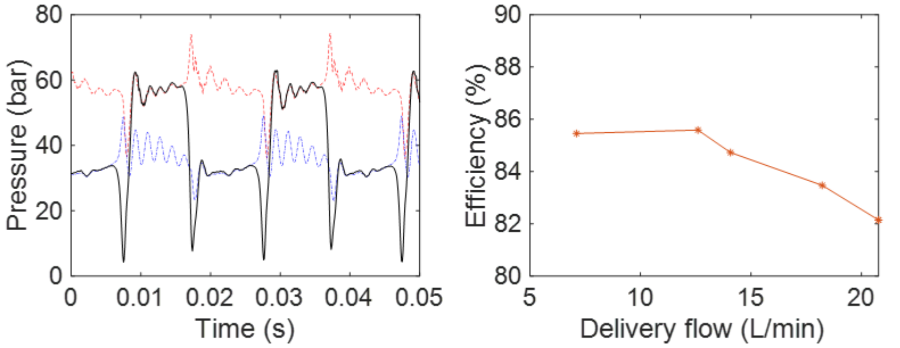
Figure 6. Flow rate versus pressure drop of the new high-performance valve

The dynamic tests of the new valve were conducted with a switching ratio of 50% and a switching frequency of 50 Hz at flow rates of 7-21 L/min. The HP and LP supply pressures were 60 and 30 bar. **Figure 7** shows the pressure dynamics at Port A of the valve with deliver flow rates of 7, 14, and 21 L/min. The pressure switches from 60 bar to 30 bar with a clear square shape and a quick switching time of less than *1 ms*. The oscillations occurred at HP and LP supply and reduced at higher flow rates of 14 and 21 L/min. The pressure dynamics were stable with less oscillation compared with that in the previous valve [6] and the additive-manufactured high-speed switching valve [19, 20]. **Figure 7 (d)** shows the prototype achieved high efficiencies of 82-86% for flow rates of 7-21 L/min. The energy efficiency is expected to be higher with the fluid inertia provided by the inertance components, which will be investigated in the future.



(a) 7 L/min

(b) 14 L/min



(c) 21 L/min

(d) Efficiency

Figure 7. Switching characteristics of the high-speed rotary valve at different delivery flow rates

4. DISCUSSION AND CONCLUSION

Digital hydraulic converters have been proven to be highly efficient and promising to improve the efficiencies of hydraulic systems and machines. In this paper, we developed a new, compact, highly efficient, and high-bandwidth digital hydraulic converter prototype, which incorporates programmable logic control and EtherCAT-enabled real-time control and exhibits good dynamics, excellent performance, and energy efficiencies.

The prototype is designed with promising features to be a solution for improving the energy efficiencies of hydraulic machinery. Integrated into a compact size of 550×450×320 mm with a maximum design pressure and flow rate of 400 bar and 200 L/min, the prototype can satisfy the requirements for typical hydraulics machinery. The prototype can be directly plugged into machines with a DC power supply and eliminate the need for power supply adaption.

The prototype supports various ways of control, providing high flexibility for onsite offline control of machinery for industrial applications and real-time control for research and development purposes at universities and companies. It can be independently and offline controlled using the PLC with pre-programmed control logic and algorithm and can be expanded with I/O boards to integrate with other devices to realise more advanced control. The online tuning of parameters of the controller, system, and other devices is user-friendly for troubleshooting and maintenance. Enabled by the EtherCAT compatibility, the controller design can be implemented in Simulink and real-time tested with hardware-in-the-loop. Data acquisition systems can be incorporated with the EtherCAT network in Simulink for control design and optimisation of complex systems.

The prototype can achieve very good performance and energy efficiency enabled by the new high-performance valve. The valve was designed and optimised to work at switching frequencies of 50-250 Hz with a switching time of 1 ms and achieved a balanced orifice design and low resistance. The analytical results show that with HP and LP supply pressures of 350 and 50 bar, the prototype can achieve high energy efficiencies of 80-94% for flow rates up to 150 L/min. The experimental results showed that the prototype achieved a high flow rate and low resistance (64 L/min at 3.7 bar), a very fast switching time of less than 1 ms, good pressure dynamics, and excellent energy efficiencies (82-86%) at flow rates up to 21 L/min.

This work introduced the development of an integrated compact digital hydraulic converter prototype with high control flexibility, which can achieve very good dynamics, performance, and energy efficiencies at high flow rates and pressures. The developed prototype is a promising solution to improve energy efficiencies of hydraulic systems and machinery, which contributes to their sustainable development.

REFERENCES

[1] Scheidl, R., Linjama, M. & Schmidt, S., 2012. Is the future of fluid power digital? Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, 226(6), pp. 721-723.

[2] Yang, H.Y. & Pan, M., 2015. Engineering research in fluid power: A review. J ZHEJIANG UNIV-SC A, 16(6), pp. 427-442.

[3] Pan, M. & Plummer, A., 2018. Digital switched hydraulics. Frontiers of Mechanical Engineering, 13(2), pp. 225-231.

[4] Yuan, C., Pan, M. & Plummer, A., 2020. A review of switched inertance hydraulic converter technology. Journal of Dynamic Systems, Measurement, and Control, 142(5), p. 050801.

[5] Yuan, C., Plummer, A. & Pan, M., 2023. Efficient control of a switched inertance hydraulic converter with a time-varying load1. Journal of Dynamic Systems, Measurement, and Control, 145(8).

[6] Yuan, C., Plummer, A. & Pan, M., 2022. Switching characteristics of a high-speed rotary valve for switched inertance hydraulic converters. Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, 236(7), pp. 1421-1441.

[7] Yuan, C., Plummer, A. & Pan, M., 2021. Efficient control of a switched inertance hydraulic converter with a time-varying load. In: Proceedings of the ASME/BATH 2021 Symposium on Fluid Power and Motion Control, October 19-21 2021, Virtual, Online. p. V001T01A034.

[8] Yuan, C., Mao Lung, V.L., Plummer, A. & Pan, M., 2020. Theoretical and experimental studies of a digital flow booster operating at high pressures and flow rates. Processes, 8(2), p. 211.

[9] Pan, M., Johnston, N., Robertson, J., Plummer, A., Hillis, A. & Yang, H.Y., 2015. Experimental investigation of a switched inertance hydraulic system with a high-speed rotary valve. Journal of Dynamic Systems, Measurement, and Control, 137(12), p. 121003.

[10] Pan, M., Johnston, N., Plummer, A., Kudzma, S. & Hillis, A., 2014. Theoretical and experimental studies of a switched inertance hydraulic system including switching transition dynamics, non-linearity and leakage. Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, 228(10), pp. 802-815.

[11] Pan, M., Johnston, D.N., Plummer, A., Kudzma, S. & Hillis, A., 2014. Theoretical and experimental studies of a switched inertance hydraulic system. Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, 228(1), pp. 12-25.

[12] Johnston, D.N., 2009. A switched inertance device for efficient control of pressure and flow. In: Proceedings of the ASME 2009 Dynamic Systems and Control Conference, October 12-14 2009, Hollywood, California, USA. American Society of Mechanical Engineers, pp. 589-596.

[13] Negri, V.J., Wang, P.F., Plummer, A. & Johnston, D.N., 2014. Behavioural prediction of hydraulic step-up switching converters. International Journal of Fluid Power, 15(1), pp. 1-9.

[14] Johnston, N., Pan, M., Plummer, A., Hillis, A. & Yang, H., 2015. Theoretical studies of a switched inertance hydraulic system in a four-port valve configuration. In: The Seventh Workshop on Digital Fluid Power, February 26–27 2015, Linz, Austria.

[15] Brown, F.T., 1987. Switched reactance hydraulics: A new way to control fluid power. In: National Conference on Fluid Power, 1987. pp. 25-33.

[16] Scheidl, R., Manhartsgruber, B., Kogler, H., Winkler, B. & Mairhofer, M., 2008. The hydraulic buck converter-concept and experimental results. In: Proceedings of the Sixth International Conference on Fluid Power, Dresden, Germany, March 31-April 2 2008, Dresden, Germany.

[17] Kogler, H. & Scheidl, R., 2008. Two basic concepts of hydraulic switching converters. In: The First Workshop on Digital Fluid Power, October 3rd 2008, Tampere, Finland. pp. 7-30.

[18] Peng, S., Kogler, H., Guglielmino, E., Scheidl, R., Branson, D.T. & Caldwell, D.G., 2013. The use of a hydraulic dc-dc converter in the actuation of a robotic leg. In: 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), November 3-7 2013, Tokyo, Japan. pp. 5859-5864.

[19] Matias, L., Chu, H., Pan, M., Plummer, A., Stephen, S. & Collins, A., 2022. Design and control of an additively manufactured valve for switched inertance hydraulic converters. In: Proceedings of Digital Fluid Power 2022, September 19-20 2022, Edinburgh, Scotland.

[20] Matias, L., Pan, M. & Plummer, A., 2023. Design and experimental investigation of an additively manufactured high-speed switching valve. In: Proceedings of the ASME/BATH 2023 Symposium on Fluid Power and Motion Control, October 16-18 2023, Sarasota, FL, USA. V001T01A038.