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# Power Hydraulics - Switched Mode Control of Hydraulic Actuation

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*Abstract* - **This paper is concerned with the application of switching technology to hydraulic actuation. Over the last 50 years with advances in power electronics, faster and faster static switches have been developed and applied to the control of motors. Hydraulic technology evolved in the opposite direction: switching control was not considered, and more and more accurate proportional flow/pressure control devices (servo-valves etc) were developed. However despite the sophistication of such valves, from an energetic viewpoint proportional control is dissipative and inefficient. Indeed, by analogy it can be seen as the equivalent of resistive (rheostatic) motor control.**

**In robotic applications where high power density, ruggedness and reliability are key requirements hydraulic actuation can be a sensible choice. However, the low efficiency of proportional control can be a limitation and it is necessary to go beyond the paradigm of proportional flow/pressure control.**

**One response to this challenge is to revisit traditional on-off hydraulic technology and develop "power hydraulic" devices that behave in analogous manner to their power electronic counterparts. "Power hydraulics" is a challenging and little explored technology due to the markedly non-linear behaviour of hydraulic systems and the need of components with dynamic specifications that are not readily available off-the-shelf.**

**After an analysis of the real on-off characteristics of a valve, a prototype hydraulic switching converter, inspired by the electric DC-DC Buck converter, is presented and its performance in pressure control mode, relative to a classical proportional valve-controlled system, are assessed. An energy saving of 75% is achieved. Merits and limitations of the current design are identified.**

## I. Introduction

Energy efficiency is a critical issue in most engineering applications, and particularly in mobile ones where battery charging or refuelling may not be always readily available or may take place only at the end of a working cycle/day. In particular mobile robots development is constrained by this limitation and in their design a significant effort is invested in achieving a high level of energy-autonomy, using not only high efficiency actuators but also compliant elements storing energy [1].

It is germane that the efficiency of the actuation of a mobile machine dictates the onboard engine/tank size or the motor/battery size. This in turn impacts on the weight of the robot and ultimately on its autonomy.

Today's robots tend to be electrically-actuated. On the other hand in a significant number of robotic and automation applications where there is a need for high power-to-weight ratios, fast dynamics, high reliability and ruggedness, hydraulic actuation can be a sensible choice in lieu of electric actuation. It is worth noting that few decades ago hydraulic power was commonly used to actuate robots [2, 3] and recently there has been a renewed interest in robotic hydraulic actuation [4, 5]. However despite the technological improvements (e.g. better seals, non-flammable oils, fluid-borne noise reduction), the efficiency of fluid power still remains a key constraining feature. Conversely electric actuation has achieved a high level of efficiency with the advent of power electronics. Switching control has replaced dissipative motor control systems based on rheostatic devices.

If the technological development of electric actuation and hydraulic actuation are analysed in the light of efficiency improvements, interesting conclusions can be drawn and new avenues for improving efficiency envisaged.

The invention of the bipolar junction transistor (BJT) in 1947 and the subsequent developments in electronics (integrated circuit in 1958, CMOS technology in 1963 [6, 7]) paved the way to the development of power electronics. Over the years static switches (GTO, MOSFET, IGBT etc) have reached higher and higher switching speeds and power capability [8].

Hydraulic technology over the past 50 years has instead followed the opposite path. On-off valves (i.e. the equivalent of power electronic switches) were and are still used only for simple sequences and few efforts have been made to improve their performance. Research efforts were instead aimed at achieving more and more accurate proportional flow and pressure control. The main technological breakthrough in hydraulics was the development of the servo-valve [9]. Its performance is excellent: up to 200-300 Hz bandwidth, high linearity, low hysteresis, high reliability. It has a track record of successful applications in demanding applications such as aerospace or Formula 1 cars. Servo-valves rely their performance on an internal hydraulic pilot stage working closed-loop and on a torque motor actuating the spool and on micron-order machining tolerances. The price of such valves is consequently high. The second breakthrough in hydraulic technology was the proportional valve [10]. These meter the flow in and out in a proportional fashion, like servo-valves. Their core component is the proportional solenoid [11], a specially designed solenoid that gives an output force which is approximately proportional to the input current and independent of position to actuate the spool. The bandwidth is more limited, typically up to 100 Hz and performance slightly lower (and so the cost lower). These valves appeared to be a low-cost good-performance solution. Hybrid types of valves were subsequently developed, sometimes referred to as servo-proportional valves.

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However both servo and proportional valves suffer from a major drawback: proportional control of a fluid with valves is inherently dissipative, albeit it requires sophisticated components. Hence valve-controlled actuators, which form the majority of hydraulic drives, have a generally rapid response but their efficiency figure is low.

Other options to increase efficiency are: (i) hydrostatic actuation by variable displacement pumps, motors, or hydro-transformers [12, 13] which are heavy devices, hence not generally suitable for robotics or (ii) independent meter-in and meter-out control [14] which is a resistive-type control. However, there is a need to go beyond the paradigm of proportional flow/pressure control that it is leading to the design of new smart hydraulic actuation systems for robotics and other applications. Such systems should have good efficiency, high dynamics and light weight. On-off technology can be a response.

Only in very recent years the hydraulic community has realised the potential advantages of the on-off technology as in power electronics [15, 16, 17, 18]. This is also due to the technical challenges associated with the development of a "power hydraulic" technology. This requires fast switching valves to achieve sufficiently high switching frequencies and to minimise the pressure losses, a redesign of several components that are not available on the market with the right specifications and a refined understanding of both the behaviour of valves in on-off mode and of fast dynamic hydraulic processes.

This paper presents a work on the development of a hydraulic switching converter. Section II investigates the performance of a valve when used in on-off mode, in particular how leakage affects the real on-off characteristics. Section III describes a hydraulic switching converter inspired by the electric DC-DC Buck converter. Section IV presents the performance of the hydraulic Buck converter (HBC) and of a hydraulic proportional drive (HPD) in a pressure control system. Conclusions and comments on proposed further developments are presented in section V.

## II. Analysis of the Real On-Off Valve Characteristics

Switching valves are key elements in the design of hydraulic converters. In this section the analysis of the actual characteristics of the on-off response is presented. In on-off operations the spool moves around the central position and the pressure toggles between its maximum value (typically supply pressure) and its minimum value (typically tank pressure). In the theoretical case of an ideal leak-free valve the transition from the off-state to the on-state would have an ideal infinite gradient. Hence when "on" the resistance is nil (ideal hydraulic short circuit) and when "off" the hydraulic resistance is infinite (ideal open circuit). The real on-off characteristic depends on the valve geometry and ultimately is dictated by leakage flows. In hydraulic literature leakage flow is often overlooked or crudely approximated as laminar flow. However depending upon the length and the shape of the flow paths the regime can be laminar, transitional or turbulent depending on the actual value of the Reynolds number. Therefore a sufficiently accurate model of the flows past the valve is crucial for capturing the actual on-off behaviour of the "hydraulic switch".

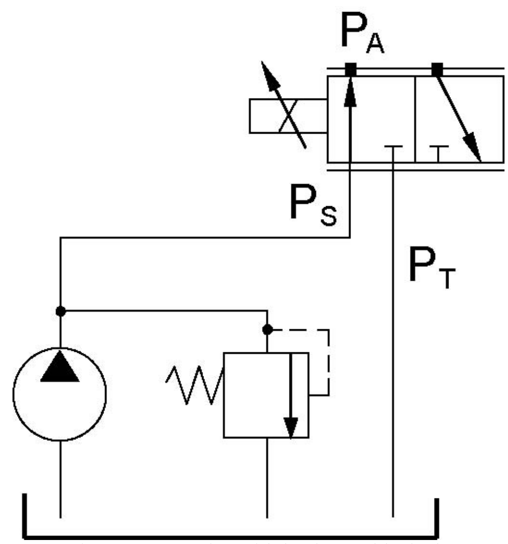

Fig. 1. 3-way valve with load ports blocked.

Typically standard on-off valves have poor dynamic performance and a significant hysteresis, hence they are not suitable for "power hydraulic" applications [18, 19]. Custom component should be developed or alternatively proportional valves (with sufficiently high dynamics) working in on-off mode could be used. For the purpose of analysing the effect of the leakage flows on the on-off characteristics, a 3-way underlapped proportional valve with both ports blocked (pressure control mode) is considered (Fig. 1).

The model here described combines the classic Bernouilli's equation with a model for flow through narrow edges depending on the edge size (i.e. the valve underlap $u$) and a leakage coefficient $k_{1s}$ [20]. With reference to Fig. 2 the governing equations are:

$$Q_1 = Q_2 + Q_3 \tag{1}$$

$$Q_1 = C_q \pi D(u+z)\sqrt{\frac{2(P_S - P_A)}{\rho}} \quad \text{if } z \geq 0 \tag{2a}$$

$$Q_1 = C_q \pi D\sqrt{\frac{2(P_S - P_A)}{\rho}}\frac{u^2}{(u - k_{1s}z)} \quad \text{if } z<0 \tag{2b}$$

$$Q_2 = \frac{V}{B}\frac{dP_A}{dt} \tag{3}$$

$$Q_3 = C_q \pi D\sqrt{\frac{2(P_A - P_T)}{\rho}}\frac{u^2}{(u + k_{1s}z)} \quad \text{if } z \geq 0 \tag{4a}$$

$$Q_3 = C_q \pi D(u-z)\sqrt{\frac{2(P_A - P_T)}{\rho}} \quad \text{if } z<0 \tag{4b}$$

with $-u \leq z \leq u$; $\rho$ is the oil density, $C_q$ the valve discharge coefficient, $D$ the bore diameter, $B$ the oil bulk modulus and $V$ the small volume upstream the valve.

The expression of pressure vs. demand input signal (sometimes referred to as pressure gain) can be analytically obtained considering that under static conditions $Q_1 = Q_3$. Electromechanical valve spool dynamics can be well approximated by a second order model. The measured value was 80 Hz which is fast enough for power hydraulic applications [18]. This switching frequency may seem slow compared to that of a classical PWM command to a motor (kHz order) but this is due to the difference in the electrical dynamics of a motor and of a hydraulic circuit (the switching frequency must be chosen sufficiently above the natural frequency of the system). The latter is dictated by the relatively limited valve dynamics of the switching valves and the hydraulic capacity effects of the fluid in the system.

Fig. 3 shows the experimental and simulated results. A sensitivity analysis varying the leakage coefficient $k_{1s}$ was performed. It is evident that for a set value of the underlap $u$ the slope of the curve depends on the amount of leakage. In particular the matching is better in the upper bound region of the characteristics rather than in lower bound region. The asymmetry in the behaviour either side of the central position (0 V) is caused by a small amount of hysteresis in the upper bound region, likely to be due to machining tolerances of the spool-bore assembly.

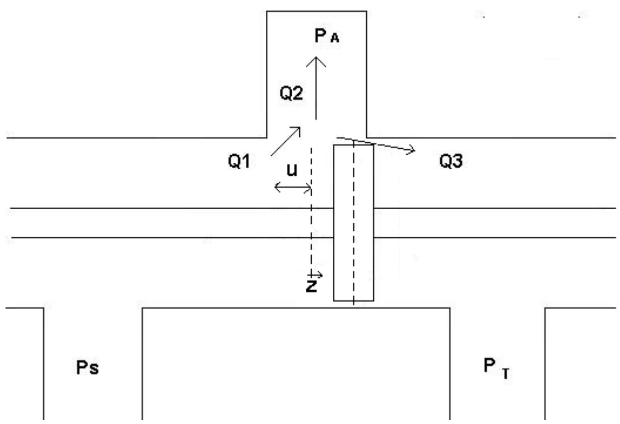


Fig. 2. 3-way valve flow paths.

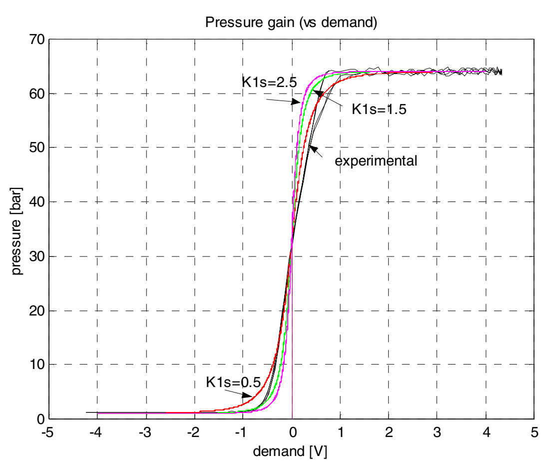


Fig. 3. Comparison of experimental (black) and predicted control valve on-off characteristics, varying the leakage coefficient $k_{1s}$ from 0.5 to 2.5.

## III. Hydraulic Switching Converter

After having analysed the on-off characteristics of a valve -the core element of any converter- a hydraulic switching converter is now presented. It is the hydraulic analogous of a classical power electronic converter: the DC-DC Buck converter [8]. The circuit of the equivalent electric converter, and of the hydraulic Buck converter alongside its idealised response are shown in Fig. 4. The key elements of the HBC are the switching valve $V_S$, a hydraulic diode or check valve $V_{CHKT}$, an inductance and a capacitance. The converter can work in two modes, termed "forward mode" and "reverse mode".

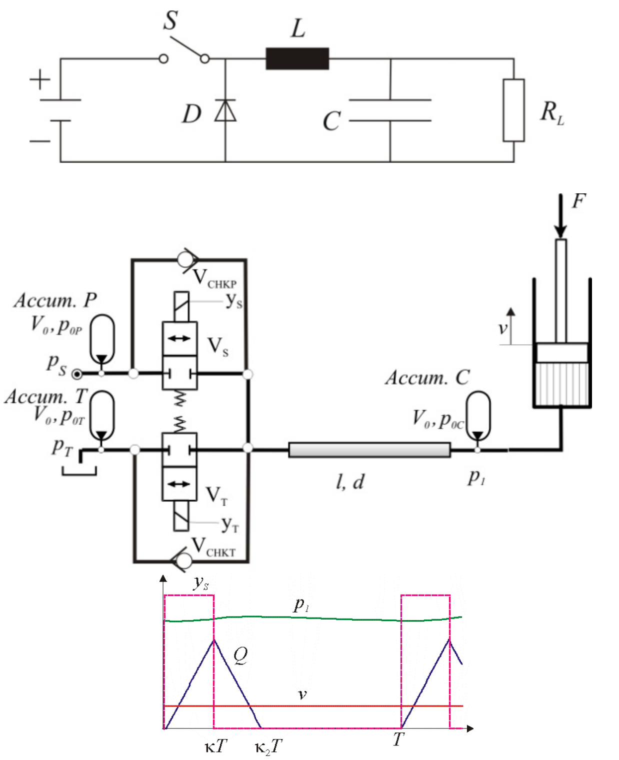


Fig. 4. Electric and hydraulic Buck converter and its basic operation characteristics in "forward mode"; $V_S$ and $V_T$: switching valves for high and low supply pressure; $V_{CHKS}$ and $V_{CHKT}$: check valves, $p_l$ load pressure, $Q$ flow rate in the pipe; $v$ cylinder speed, $y_S$ and $y_T$ the switching signals of $V_S$ and $V_T$ respectively.

In "forward mode" energy is fed to the load by operating the valve $V_S$ with a PWM command. The inertia of the fluid in the hydraulic inductance (a pipe of length $l$ and diameter $d$) forces flow $Q$ to continue after $V_S$ is switched off; at the same time hydraulic fluid is also sucked from the low pressure line (tank) through the corresponding check valve $V_{CHKT}$. In "reverse mode" $V_T$ is PWM operated, directing fluid to the low pressure line when $V_T$ is on. When $V_T$ is shut off the fluid linear momentum in the inductance forces some fluid to flow to the high pressure line over $V_{CHKP}$ , hence some energy is recuperated. Flow pulsations are filtered by the hydraulic capacitance that together with the inductance is a hydraulic LC low-pass filter. The capacitance can be realised with a gas filled accumulator of nominal volume $V_0$ and gas filling pressure $p_0$. The tuning of this filter is more difficult than that of an equivalent electric LC filter, due to the strong non-linear behaviour of the hydraulic components.

Fig. 5 depicts the prototype converter and Table I lists its main parameters. It has been built in a compact way considering that often in robotics small size is a critical requirement. The dimensions of the block (Fig. 5) are

175x112x85 mm. The first prototype in steel the HBC weighs 14 kg. This can be reduced to less than 4 kg if an aluminium alloy is used and the design is further optimised. Further component miniaturisation is possible compatibly with machining capabilities, but viscous forces would start playing a larger role and this might penalise the efficiency. A conventional HPD (considering that proportional valves need to be mounted on a manifold) has a comparable weight. Weight is the main reason to keep the system simple and to prefer the HBC to a full (H-) bridge concept as used in power electronics.

Fig. 6 shows experimental efficiency results on the HBC prototype. They exceed those of an equivalent conventional HPD (with a 4-way proportional valve, see Fig. 8) over the operating range of interest.

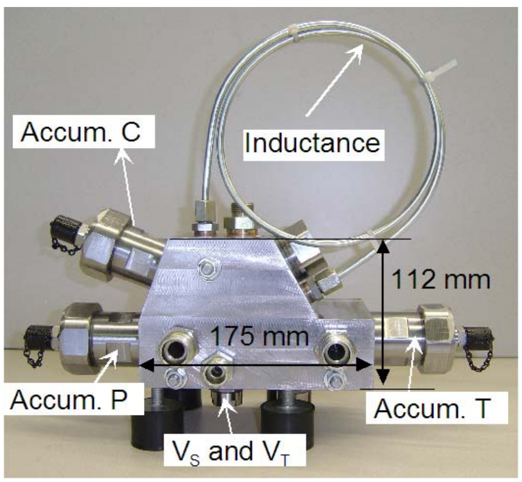


Fig. 5. Low power HBC prototype; all accumulators are piston-type.

TABLE I
HBC PROTOTYPE PARAMETERS

| Quantity | Value |
|---|---|
| Supply pressure | 160 bar |
| Nom. flow rate $V_S$, $V_T$ | 10 l/min at 5 bar |
| Pipe length | 1.15 m |
| Pipe radius | 2 mm |
| Oil density | 860 kg/m$^3$ |
| Accumulator volume | 0.075 l |
| Nom. flow rates of $V_{CHKS}$, $V_{CHKT}$ | 30 l/min at 5 bar |
| Tank pressure | 5 bar |
| Switching time of $V_S$, $V_T$ | 1 ms |
| Oil bulk modulus | 14000 bar |
| Oil kinematic viscosity | 46 mm$^2$/s |
| Accum. C,P,T volume | 0.04 l |
| Accum. C,P,T filling pressures | 50, 50, 2.5 bar |
| Block dimensions | 175x112x85 mm |

The electric DC-DC converter can operate either in current control mode or voltage control mode. Analogously the HBC can operate either in flow control mode or pressure control mode. In the former mode flow is present only for a part of the switching period $T$ and the average flow rate can be controlled by the duty cycle $\kappa$ [18]. Fig. 7 shows how the duty cycle $\kappa$ controls pressure or flow rate in the two modes of operation.

In [21] the application and performance of a HBC in flow control mode applied to a hydraulic robotic leg was studied numerically. It is reported that for a typical leg motion a 75% energy saving was achieved with respect to the HPD. In the subsequent section the performance in pressure control mode is investigated.

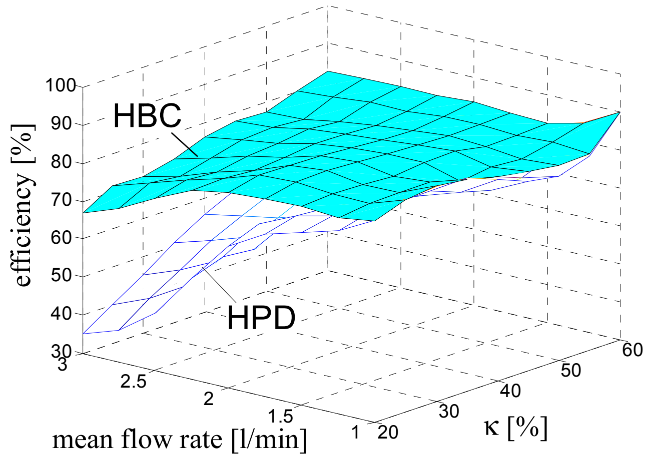


Fig. 6. Experimental efficiency results of the hydraulic Buck converter prototype compared to a HPD.

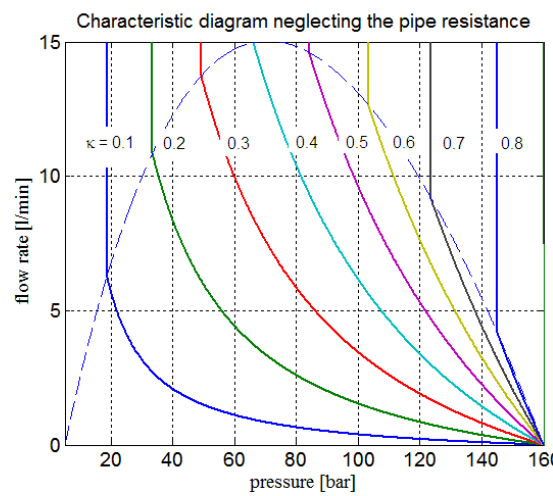


Fig. 7. Characteristic curves of a HBC showing the effect of duty cycle on pressure and flow rate. The dotted parabolic line divides the flow control mode region (below) from the pressure control mode region (above).

## IV. Efficiency Assessment of HBC in Pressure Control Mode

Pressure control with a HBC has not been investigated so far. Pressure control translates to force control in fluid power and in robotics, pressure control applications arise, e.g., in grasping control, in fluidic muscle control or, in industrial robotics, in grinding operations when the tool is guided with a set contact on the work-piece.

Pressure control could be obtained in quite a direct manner by operating both switching valves $V_S$ and $V_T$ alternatively. In this case, the HBC operates always in pressure control mode. If the system only works in this mode it could be built in an even more compact size as check valves would not be necessary. It should be noted that the "flow mode" (used for instance in position and velocity control loops) as described above is potentially better from an energetic viewpoint as energy recovery can be achieved, whereas in pressure control mode this is not possible.

A simulation has been carried out in pressure control mode using an appropriate model for the switching valves as outlined in section II. Wave propagation effects are included in the pipeline (inductance) model; a frequency-dependent friction model is used, based on a method of characteristics with a Kagawa friction model [22]. A polytropic state change is used for the accumulator pressure. As in most hydraulic circuit a cooler is present or the tank is big enough, temperature effects (that mostly affect viscosity) are negligible.

The benchmark for comparing the performance of a HBC and a HPD is a force-controlled piston producing a constant force while following a set sinusoidal profile (Fig. 8). In the HBC this translates to pressure control of $p_1$, while in the HPD both chamber pressures vary according to the flow metered over two edges of the proportional valve.

The focus of this study is not on the performance of the control algorithm but on the efficiency of the system. However, a control is required as the system inherently works in closed loop. Furthermore, it has to ensure a fair comparison of the efficiency of both drives. The converter data used in the simulation are listed in Table I; the double acting cylinder has a 16/10 mm piston/rod diameter, the exerted motion has amplitude $s_w$=0.025 m, $v_T/\lambda_W$ =2 s$^{-1}$. The desired force is $F_d$=500 N which corresponds to a pressure $p_1$=123 bar.

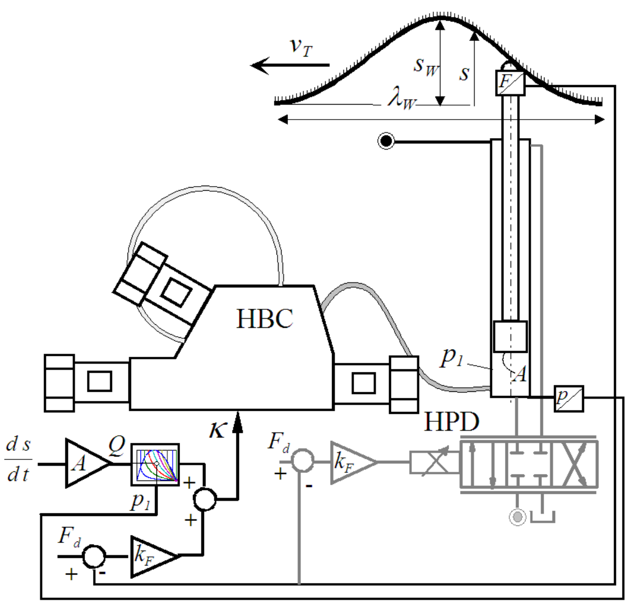


Fig. 8. HBC (dark) or HPD (grey) in force (pressure) control of a hydraulic cylinder performing a sinusoidal motion.

Control in both cases is proportional-type; HBC employs also a velocity feed-forward control. The required duty cycle $\kappa$ is computed from the velocity, the pressure $p_1$ and the characteristic curves of Fig. 7. The result is added to the output from the proportional controller. The gains of the controllers are $k_F=20/F_d$ for the HBC and $k_F=10/F_d$ for the HPD. The velocity profile is plotted in Fig. 9.

Although the controller is simple, the HBC succeeds in controlling the average force (Fig. 10). A ripple is superimposed to the mean value of the force due to switching. These fluctuations could be reduced by a larger accumulator, which, however, reduces the bandwidth for position or velocity control. Another factor affecting pressure ripple is the choice of the cylinder rod diameter as the required cylinder pressure is better balanced between pressure and tank line.

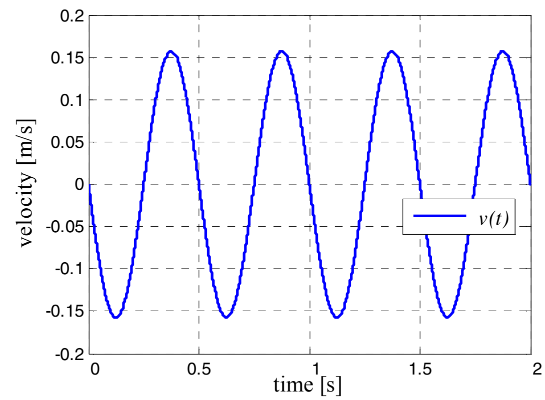


Fig. 9. Cylinder velocity enforced by an external process; force (pressure) is controlled.

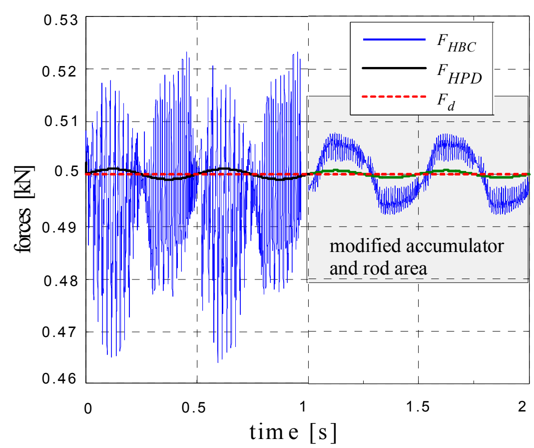


Fig. 10. Effects of filtering: average force with a smaller accumulator (0.075 l, left side) and with a larger accumulator (0.16 l) and a larger cylinder rod size (12.6 mm diameter, left side).

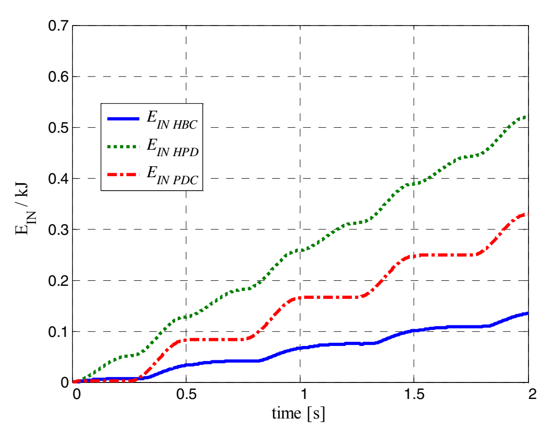


Fig. 11. Energy consumption over time of the HBC, the HPD, and the PDC.

The most important result of this simulation is the energy consumption ($E_{IN}$), that in the case of the HBC is in average less than 25% of that of the HPD, as plotted in Fig. 11, i.e. an energy saving of about 75% is achieved. If only the piston side pressure is proportionally controlled and the ring side is connected to the high pressure line analogously to the HBC schematic, the energy consumption is reduced and indicated by PDC in Fig. 11. But still, HBC consumes 59% less energy. This is an excellent result that shows the potentiality of this technology.

## V. Conclusions and Future Work

This paper has presented a novel high efficiency hydraulic technology based on the switched control of valves. A hydraulic switching converter inspired by the electric DC-DC Buck converter has been prototyped and its performance has been assessed in pressure control mode and compared to that of a traditional proportional-valve drive. It is shown that hydraulic switching control can achieve an energy saving of 75% compared to conventional resistive control using proportional valves.

Furthermore on-off valves offer several benefits for robotic actuation, particularly for outdoor applications as they are less sensitive to oil contamination, besides being cheaper than servo and proportional valves.

This research area is quite new in the hydraulic community and still several open questions need to be answered, as far as new components, system design and control are concerned to fully optimise the technology. This technology offer high potential for developing a new generation of hydraulic actuators having high efficiency. In particular the energy recuperation is of interest in mechanical motion control where a high recoverable power from mass acceleration is present.

Future work will involve the study of advanced position and force controllers for robotic joints and the application of this technology to legged robotic locomotion on a hydraulically-actuated quadruped platform.

## Acknowledgements

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## References

[1] B Vanderborght, B. Verrelst, R. Van Ham, M. Van Damme, D. Lefeber, B. M. Y. Duran and P. Beyl, "Exploiting Natural Dynamics to Reduce Energy Consumption by Controlling the Compliance of Soft Actuators," *Int. Journal of Robotics Research*, Vol. 25, N. 4, pp. 343-358, 2006.

[2] R. A. Liston and R. S. Mosher, "A Versatile Walking Truck", *Transportation Engineering Conference*, 1968.

[3] D.G.W. Walker, "Electric and hydraulic drives for heavy industrial robots," *IMechE Conf. on Electric versus Hydraulic Drives*, London, UK, October 1983.

[4] D. C. Bentivegna, C. G. Atkeson and J-Y. Kim, "Compliant Control of a hydraulic humanoid joint," *IEEE-RAS 7th International Conference on Humanoid Robots* (*Humanoids 07*), Pittsburgh, PA, USA, 2007.

[5] M. Raibert, K. Blankespoor G. Nelson, R. Playter and the BigDog Team, "BigDog, the Rough-Terrain Quadruped Robot," *Proc. 17th World Congress. The Int. Federation of Automatic Control*, Seoul, Korea, pp. 10822-10825, 2008.

[6] T. G. Wilson, "The Evolution of Power Electronics," *Proc. IEEE Int. Symposium on Industrial Electronics*, Xian, China, Vol. 1, pp. 1-9, 1992.

[7] C. Lécuyer, "*Making Silicon Valley: Innovation and the Growth of High Tech 1930-1970*", MIT Press Cambridge, MA, USA, 2006.

[8] N. Mohan, T. M. Undeland and W. P. Robbins, "*Power electronics: converters, applications and design*," Wiley, 1995.

[9] R. H. Maskrey and W. j. Thayer, "A Brief History of Electrohydraulic Servomechanisms," *Moog Technical Bulletin 141,* Moog Inc., NY 14052, 1978.

[10] N. D. Manring, "*Hydraulic control systems*," Wiley, 2005.

[11] Y. Hong and Y-C. Kwon, "Electromagnetic Analysis of a Flat-Type Proportional Solenoid by the Reluctance Method," *Int J. of Precision Engineering and Manufacturing,* Vol. 7, N. 2, pp. 46-50, April 2006.

[12] P. Rotthäuser, "Achten, Ein neuer alter Bekannter—der Hydrotransformator," *o+p Ölhydraulik Pneumatik*, Vol. 42 N. 6, 1998.

[13] H. Murrenhoff, "Systematic approach to the control of hydrostatic drives," *Proc. of the Inst. of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, Vol. 213, N. 5, pp. 333-347, 1999.

[14] B. Eriksson, J. Larsson, Jonas and J.O. Palmberg, "Study on Individual Pressure Control in Energy Efficient Cylinder Drives", *Proc. 4th FPNI-Ph.D. Symphosium, FPNI'06*, Sarasota, USA, June 2006.

[15] C. E. Jeronymo, H. Yamada and T. Muto, "Application of unified predictive control to on/off control of hydraulic system driven by fast-switching solenoid valves". *JSME International Journal Series C-Dynamics Control Robotics Design and Manufacturing* Vol. 39, pp. 515–521, 1996.

[16] H. Kaminaga, T. Yamamoto, J. Ono and Y. Nakamura "Backdrivable miniature hydrostatic transmission for actuation of anthropomorphic robot hands", *IEEE-RAS International Conference on Humanoid Robots*, pp. 36-41, 2007.

[17] M. Linjama, M. Huova, P. Bostöm, A. Laamanen, L. Siivonen, L. Morel, M. Walden and M. Vilenius, "Design and Implementation of Energy Saving Digital Hydraulic Control System," *The Tenth Scandinavian Int. Conference on Fluid Power* (*SICFP'07*), Tampere, Finland, May 2007.

[18] H. Kogler and R. Scheidl, "Two Basic Concepts of Hydraulic Switching Converters," *The First Workshop on Digital Fluid Power*, Tampere, Finland, 2008.

[19] A. Plöckinger, B. Winkler and R. Scheidl, "Development and Prototyping of a Compact, Fast 3/2 Way Switching Valve with Integrated Onboard Electronics," *Proc. 11th Scandinavian Int. Conf. on Fluid Power* (*SICFP'09*)*,* Linköping, Sweden, June 2009.

[20] B. Eryilmaz and B. H. Wilson, "Modeling the internal leakage of hydraulic servovalves," *Int. Mechanical Engineering Congress and Exhibition* (*ASME IMECE 2000*), Orlando, FL, USA, 2000.

[21] E. Guglielmino, C. Semini, Y. Yang, D. G. Caldwell, H. Kogler and R. Scheidl, "Energy efficient fluid power in autonomous robotics," *2009 ASME Dynamic Systems and Control Conference* (*ASME DSCC 09*), Hollywood, CA, USA, October 2009.

[22] B. Manhartsgruber, "On the Passivity of a Galerkin Finite Element Model for Transient Flow in Hydraulic Pipelines," *Journal of Systems and Control Engineering*, Vol. 220, N. 3, pp. 223-237, 2006.