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The Use of a Hydraulic DC-DC Converter in the Actuation of a Robotic Leg

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Abstract— **This paper presents the application of a hydraulic DC-DC converter, namely a step down Buck Converter to the actuation of a robot leg that is part of the quadruped robot HyQ. The use of a Hydraulic Buck Converter (HBC) offers significant advantages in terms of improved efficiency of hydraulic actuation systems analogously to an electric switching DC-DC converter as opposed to a rheostatic-type system. In this paper, a HBC consisting of two digital valves and two check valves is introduced to improve the efficiency performance of a singl leg of a hydraulic quadruped robot (HyQ). This type of hydraulic buck converter is able to support the locomotion in two directions. The HBC operates at a switching frequency of 100 Hz in pulse-width-modulation. The better energy performance compared to proportional control is achieved by the use of fast check valves. The performance of the system with a 3-way-4-position proportional valve is compared with the HBC drive. A test rig is set up to investigate the performance of HBC with two different controllers and a Hydraulic Proportional Drive (HPD) system, based on proportional valves which control flow, by throttling it, in a dissipative manner. The performance of position tracking and energy consumption is evaluated. The experimental results indicate that HBC systems can achieve similar position tracking with relatively less consumed energy.**

I. Introduction

Most robots are electrically-actuated. Electric motors are widely used because of their low cost, and large availability of sizes and specifications. Despite electric motors offer a large number of advantages, in some application fluidic actuation using hydraulic oil offers benefits because of the high power-to-weight ratio and its fast dynamic response; hydraulic actuation is particularly interesting for outdoor applications where reliability and ruggedness are required. Hydraulic actuation was thoroughly studied as a means to actuate legged robots. Early studies in this areas date back to the 1980's with the work of Raibert [1]. Over the years researchers investigated different aspects of legged locomotion. In 1998 Sang-Ho built the monopod robot KenKen [2]. Boston Dynamics first presented a quadruped robot, BigDog, which is able to go through outdoors, and recover balance after being laterally kicked, as well as other types of dynamic tasks [3-5]. KITECH and POSTECH are quadruped robots developed for the South Korean defense industry [6]. In 2007 Istituto Italiano di Tecnologia developed a hydraulic quadruped Robot (*Hy*Q) [7].

A major drawback of servo hydraulic systems based on metering valves is their low efficiency that results in heat generation within the oil that needs to be dissipated. This also results in large flow rates requiring larger sized pumps. To improve efficiency Song and Bin proposed a two-level coordinated control scheme to achieve energy-saving performance with digital valves [8]. Their digital hydraulic system required one third of the energy consumed by the corresponding servo hydraulic systems, which was still based on using proportional valves (that control flow by throttling it, hence with a rheostatic type method). The main reason of the efficiency improvement is that a special digital hydraulic configuration which was able to regenerate flow was applied. Lumkes applied a high speed on/off valve to modulate flow from a fixed displacement pump, directing the flow either to the tank or high pressure supply line of the hydraulic system [9], and showed an improvement in system efficiency of 14% over a range of switching frequencies and duty cycles.

The hydraulic buck converter is another digital hydraulic solution for energy-saving performance. This system is the equivalent hydraulic counterpart of the well-known step down DC-DC converter. In an electrical system the power consumption is obtained by the product of voltage and current. Likewise in a hydraulic system the power consumption is the product of pressure and flow. The switching nature of converters helps reducing the power consumption. Preliminary simulation results showed a considerable efficiency improvement with the application of hydraulic buck converter to a specified type of hydraulic cylinders [10, 11].

In this paper, a hydraulic buck converter (HBC) consisting of two digital on-off valves and two check valves is applied. Position tracking and efficiency performance are evaluated in a robotic leg, part of the hydraulic robot HyQ [7]. The paper is structured as follows: in section II, the HyQ robot robotic platform and the characteristics of its leg are presented. Section III and IV present the model of the system and of hydraulic buck converter. Section V describes the experimental work and result, and section VI the conclusion of the work.

II. HyQ Robot

HyQ stands for Hydraulic Quadruped and is a robot designed to perform highly dynamic tasks such as running and

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jumping. The dimensions of HyQ are 1.0m*0.5m*0.98m (L*W*H), and its weight is 65kg. It has 12 DOFs and the joint range is 120°. Fig. 1 shows the profile of the robot while sitting and standing. Each leg has one electric actuator (roll motion) and two hydraulic actuators composed of hydraulic cylinders and proportional valves. In this paper, the right hind leg (Fig. 1 and 2) is used in this work to investigate the performance of the HBC system. The hydraulic actuators used to activate the upper and lower parts of the leg and are the same, thus only the lower leg is analyzed to evaluate the performance of the two actuation systems (proportional valve and HBC).

Figure 1. HyQ Robot Sitting and Standing

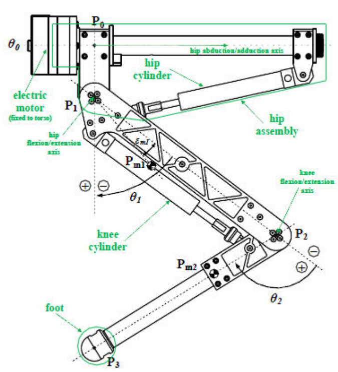
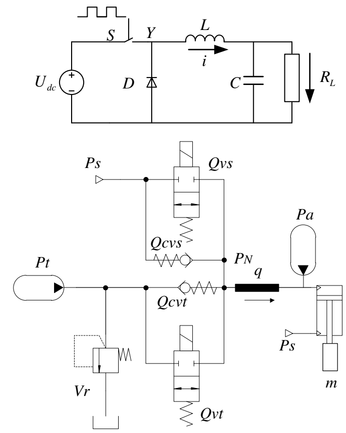


Figure 2. HyQ Leg (Right Hind Leg)

III. HYDRAULIC BUCK CONVERTER

The HBC is the hydraulic analogous of a classical power electronic converter, the DC-DC step down or Buck converter. The circuit of the equivalent electric converter, and of the hydraulic Buck converter together its idealised response are shown in Fig. 3 and Fig. 4.

The hydraulic components, the accumulator P_a, the hose L, the check valve play the roles of electric ones i.e. capacitance C, the inductance L, and the diode D, respectively (so the LC filter is obtained by a hose and an accumulator). The hydraulic cylinder and its load is equivalent to the load resistance and the digital valves act as switches. The actuator can drive the load in two directions. The accumulator *Pt* can store the maximum oil volume that is needed in the suction phase. Tank pressure is held by the pressure relief valve *Vr*.



(A) Electronic buck converter (B) Hydraulic buck converter

Figure 3. Electric and Hydraulic Buck Converter (left and right)

The feature of this configuration is the possibility to recuperate energy to the pressure supply when the rod is retracting. Thus the spill-over of the flow rate from the accumulator *Pa* rises the pressure at *PN* above the supply pressure and the oil can be fed back to the system line *Ps* through the check valve *Qcvs.*

A. Working Principle

An electric buck converter operates in two modes, continuous mode and discontinuous mode. Similar to the electric buck converter, there are also two different modes of operation for the Hydraulic Buck Converter: flow control and pressure control. The main characteristic of the flow control mode is that the actual flow rate through the pipe decays to zero at each cycle. The corresponding pressures and flow rates are depicted in Fig. 4 where κ is duty ratio, δ is free-wheeling ratio needed for the vanishing of the flow rate via the check valve after the digital valve at the same side closes, f_s is the frequency of PWM, T is time period. During the on time (determined by duty ratio κ) of the switching valve, the flow rate through the pipe increases; during off time (determined by 1-κ) of the valve, the pressure at the node point C_{HI} falls to tank pressure due to the impulse of the oil in the pipe. For the duration of the free-wheeling ratio – afterwards, the node pressure equals the load pressure until the next switching cycle starts.

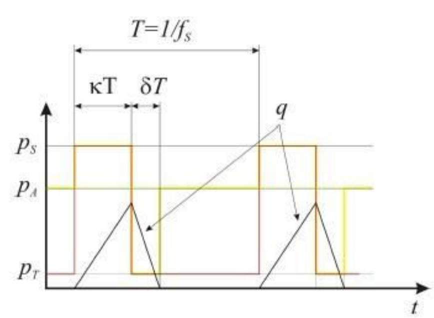


Figure 4. Flow control mode

Normally, the switching frequencies in electronics are in kHz range, while the typical switching frequencies in hydraulics can be in the range of fifty up to a few hundred Hz. There are physical reasons which prevent higher frequencies in hydraulics, like the limited dynamics of switching valves and hydraulic capacity effects of the fluid in the system. The control input of the valves is the duty cycle $\kappa \in [0,1]$, which controls the required flow rate. The average flow rate in flow control mode under ideal circumstances is

$$\bar{q} = \frac{1}{2}\frac{(p_S{}^2 - p_S p_A - p_S p_T + p_T p_A)}{(p_A - p_T) f_S L}\kappa^2 \tag{1}$$

When $\kappa + \delta = 1$, the system switches to pressure control mode.

B. Limited Effects and Nonidealities

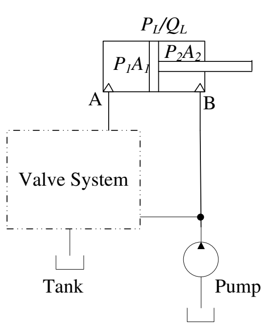
The performance of an HBC are limited by two main effects: switching digital valve static and dynamic characteristics and distributed effects in the hoses.

In a PWM controlled system it is essential that the response time of the valves is shorter than the switching frequency to implement an adequate pulse width. One of the fastest commercial on/off valve is Sterling7020, whose response time is 10ms [12]. The available commercial on/off valves are not fast enough to effectively follow the switching frequency of required PWM signals. Research on fast new valve prototypes is currently carried in several institutions [13, 14]. The development of faster and larger digital valves makes digital hydraulic technology even more promising in future research.

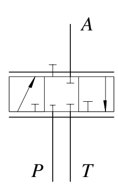
Furthermore due to the fluid compressibility and inertia pressure waves can be excited in the hoses. In digital hydraulic systems a broad band excitation caused by the switching of the valves occurs. The natural frequencies of the transmission lines hence set an upper limit to the switching frequency.

IV. Hydraulic Actuation

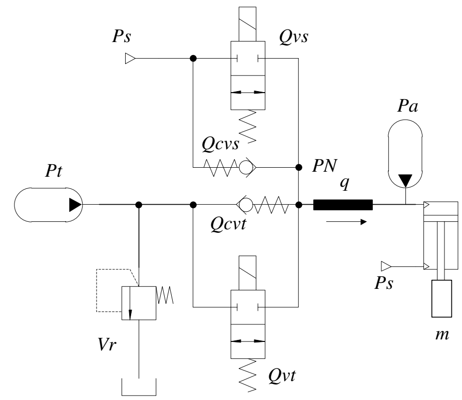
A simplified schematic of the hydraulic system used in this work is shown in Fig. 5. At B side, a pump is used to provide a pressure source, with the flow finally goes back to the tank. With proper configurations, the valve system keeps A side at specified pressure to support the desired locomotion. B side of the cylinder is always connected to the constant pressure source. Both A and B side share the same pump.



(a) Hydraulic system



(b) A proportional valve



(C) Hydraulic buck converter

Figure 5. Schematic of Hydraulic System, a proportional valve and a hydraulic buck converter

In the dashed box ‘Valve System’, the valves in a specified configuration are used to provide the demanded flow rate to the A side of the cylinder. In this work, two types of valve systems are assessed: a proportional valve (Wandfluh valve, shown in Fig. 5 (b)), and the HBC (shown in Fig. 3) that is composed of two digital valves and two check valves.

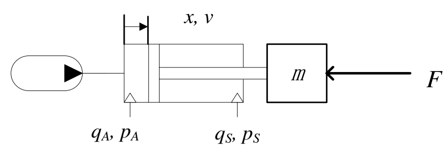


Figure 6. Actuation system

The hydraulic actuation system is simplified as shown in Fig. 6. The power source (p_S, q_S) is connected to the B side and demanded flow rate (p_A, q_A) is input to the other side to drive a set locomotion. The dynamic system can be expressed as:

$$\begin{bmatrix} \dot{x} \\ \dot{v} \\ \dot{p}_A \end{bmatrix} = \begin{bmatrix} v \\ \frac{1}{m}(p_A A_1 - p_S A_2 - d_v v - F) \\ \frac{p_A k}{V_A \left(\frac{p0_G}{p_A}\right)^{\frac{1}{k}}}(-A_1 v + q_A) \end{bmatrix} \tag{2}$$

Where x and v are the position and velocity of the cylinder; p_A is the pressure at A side; p_S is the pump pressure; A_1 and A_2 are the piston and rod side areas; F is the force exerted on the rod; d_v is the viscous friction coefficient; k is the polytropic exponent of the accumulator; p_{oG} is its gas pre-charge. Linearizing (2) yields the following transfer function.

$$G(s) = \frac{x(s)}{q_A(s)} = \frac{1}{A_1}\frac{1}{s\left(s^2 \frac{V_A m (p0_G A_1)^{\frac{1}{k}}}{A_1 k (pSA_2 + F)^{\frac{k+1}{k}}} + s\frac{d_v V_A (p0_G A_1)^{\frac{1}{k}}}{A_1 k (pSA_2 + F)^{\frac{k+1}{k}}} + 1\right)} \tag{3}$$

V. Experimental Work

A set of experiments was carried out to measure the position tracking and efficiency of the systems with HBC and HPD. Three types of locomotion were chosen to analyze the results. For each types of locomotion, three cases were compared: the HBC system with proportional control, the HBC system with feed forward plus proportional control, and HPD system with a proportional controller. It should be highlighted that the target of this study is not the design of the controller, but the efficiency of the system. However, a control is required as the system is closed loop and it is also necessary to ensure a fair comparison of the efficiency of both systems.

A. Test Rig

The test rig is designed to work with both HBC and HPD It includes a pressure source, a 3-position-4-way proportional valve (for the upper leg), a hydraulic buck converter and a 3-position-4-way proportional valve for the lower leg. A relief valve sets the tank pressure. The test rig and the HBC are shown in Fig. 7 and 8. The switching time for valves VS and VT is 2 ms. The volume for accumulator C is 0.04L The pipe length is 1.15m.

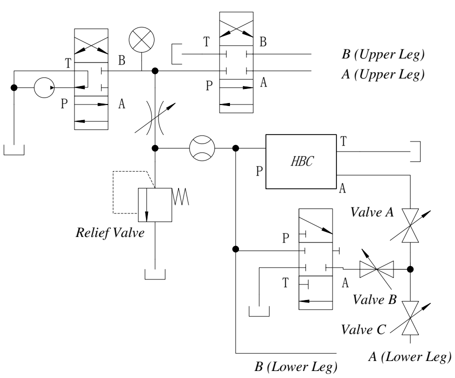


Figure 7. Schematic of the Test System

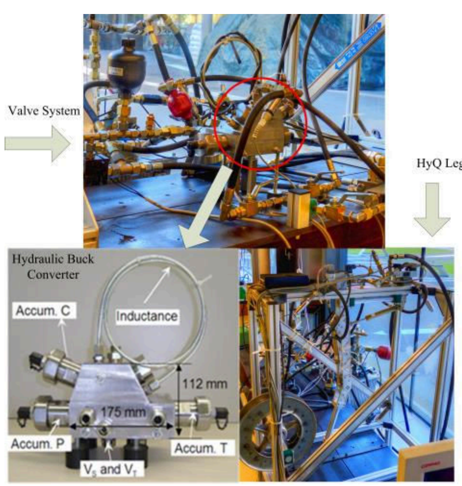


Figure 8. Test Rig and HyQ Leg

To compare the performance of the two systems, both HBC and HPD are connected to the A side of the actuator, and a constant pressure source is connected to B side of the actuator (Fig. 8). Three ball valves (valves A, B and C) are used to manually switch the experiment between HBC and HPD.

TABLE I. Parameters of the Locomotion

Locomotion Type	Parameter for Sine Wave Trajectory		
	Amplitude	***Frequency***	***Offset***
Locomotion 1	30 degrees	0.5 Hz	60 degrees
Locomotion 2	30 degrees	0.25 Hz	60 degrees
Locomotion 3	40 degrees	0.5 Hz	60 degrees

Three types of locomotion (Table I) are tested to evaluate the performance of the actuation systems. The 0 angular position is defined when the rod of the cylinder is at the bottom of the rodless chamber, and angular displacement increases as the cylinder extends. The initial position of all the locomotion is 60°, which is the middle point of the moving range.

B. Controllers

The controllers are modeled in Simulink and implemented in dSpace. Joint angular positions, pump and tank pressures, and flow rates to the digital and proportional valve are collected by a data acquisition board in dSpace.

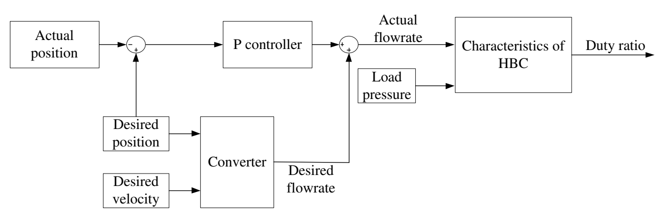


Figure 9. Controller for HBC

Fig. 9 shows the controller involving both P control and feed forward control for the HBC (and similarly for HPD, as a particular case without the feedforward term). Desired flow rate and pressure at A side of the cylinder is sent to a lookup table with the HBC characteristics and the required duty cycle is calculated and output as the command to the valves. A feedback is used to compensate the flow rate error. The performance of a proportional valve is investigated in a HPD system to compare with that of the two HBC systems. The controller for HPD is a particular case. The angular position is fed back to the controller and a P gain is used to output the command for the valves.

C. Characteristics of HBC

In the controller of HBC system, a lookup table (shown in Fig. 10) is used to decide the desired command of the valves. The characteristics is a form of duty cycle as a function of pressure at the output of the HBC manifold and the desired flow rate through HBC. A limited amount of stable working points are measured in the experiments. For each working point, the velocity of the cylinder and the duty cycle of the input signals to the valves are fixed and the corresponding pressures are measured as the characteristics of HBC. A continuous 3D surface is created by interpolation. Additionally, a dead band around zero flow rate line is added.

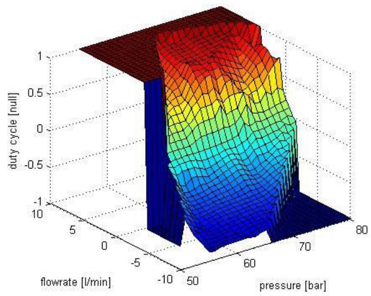


Figure 10. Characteristics of HBC

D. *Experimental Results*

Experimental results for three types of locomotion are presented in Fig. 11, and 12. The system can recuperate energy when the rod is retracting, thus the locomotion along one direction (retracting of the cylinder) is selected to evaluate position tracking and energy consumption.

In Fig. 11, the results of the first plot show the error of angular position for the three systems. The errors of HPD system range between -6.5 ° to 0.8 °; the errors of the HBC system with a P controller go from -10° to 1.7 °; and the errors of the HBC system are in the -9.8 ° to 1.7° range. The second plot shows the flow rates of the three systems. At the beginning, the flow rate consumed by two HBC systems is larger than that consumed by HPD system. From 0.78s the HPD system starts to show more flow rate than the two HBC systems. The HBC with feed forward controller needs a little bit less flow rate than the HBC system with proportional control. The third plot shows the accumulated consumed energy: the HPD consumes more energy than HBC with the P controller. When it comes to the energy consumed by the HBC with P controller, it starts at a higher point compared to the other two systems. However, at the end of the plot, it achieves a lowest point. That means, the HBC with P controller consumes the least energy among the three systems.

Fig. 12 shows the results for locomotion 2. In the error plot, the error of HPD is in the range of -4.2° to 1.2 °; the error of HBC with a P controller is from -5.8 ° to 2.8 °; and for HBC with both P and feed forward controller, the error is from -7.7 ° to 2 °. For HPD it becomes stable soon and shows even distributed errors. However, in the two HBCs, peak errors appear in the early period of the retracting, and get smaller gradually.

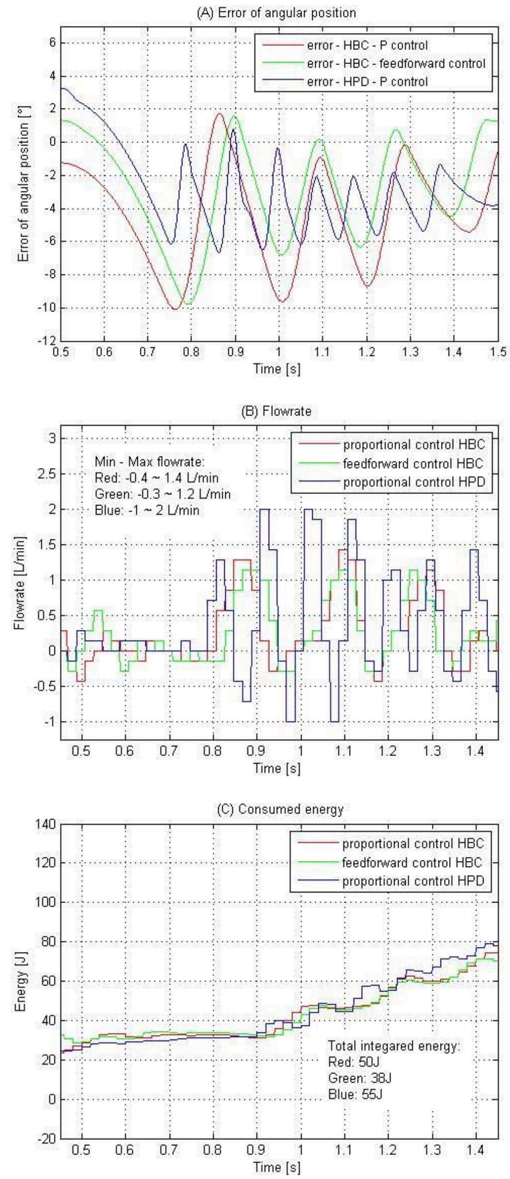


Figure 11. The performance for locomotion 1

In the flow rate plot, similar comparison is found among the three systems. The HPD requires the largest flow, and the HBC with feed forward system needs the least flow rate.

The energy plot shows a significant higher energy consumption for the HPD. The HBC with feed forward controller shows the least energy consumption. The energy consumed by the HBC with proportional controller is a little higher than that of the HBC with feed forward controller.

Locomotion 3 shows similar result with locomotion 1 and 2. Figures are not shown due to the limited pages.

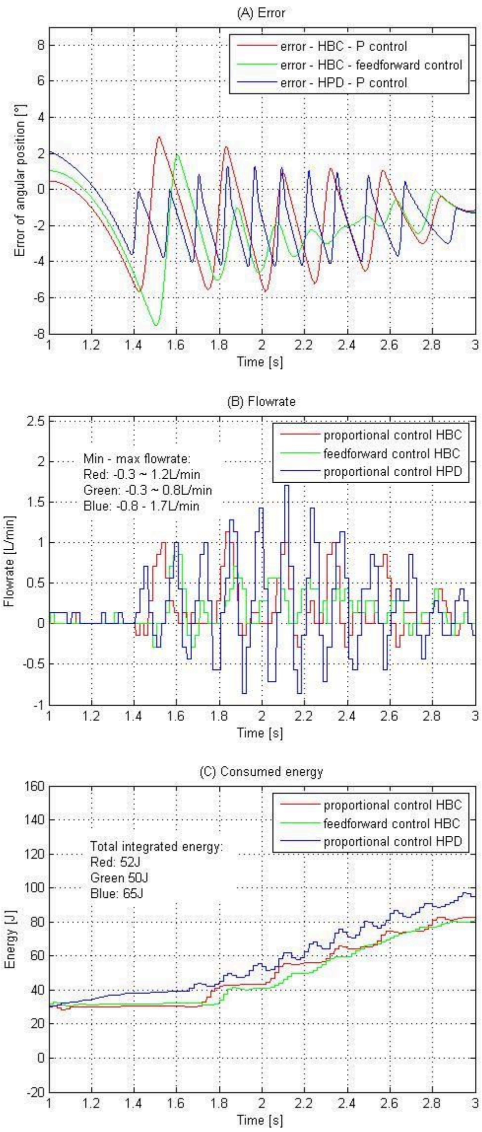


Figure 12. The performance for locomotion 2

VI. CONCLUSIONS

In this work, the performance of an HBC is compared with an HPD. Two types of controllers are applied to HBC systems, a P controller and a P plus feed forward controller. The results indicate that the HBCs are able to achieve similar position tracking as HPD. The HBC with feed forward controller has a slightly better position response compared to the same hydraulic system with only a proportional controller. The sharp waves in the HPD position error are due to large overlap of the proportional valve. There are also some sharp waves in the errors for HBCs, but caused by different reasons. The accumulator at the output of the hydraulic buck converter for pressure attenuation makes the system soft. Together with the stick-slip effect, the position response shows some steps.

The HBC consume generally less energy than HPD. However when the velocity of the cylinder is relatively low, the HBC shows similar energy usage with HPD. When the velocity increases, the HBC show less energy usage than the HPD. Since the supply pressure is a constant, the required flow rate shows the changing of the consumed power.It can be also noted that the HBCs consume less power than the HPD when it is around the middle part when the velocity is at the peak point. This can be explained by the working principle of the hydraulic buck converter. The inertia of the fluid in the pipe is accelerated by switching the supply sided valve. The rated flow rate of the digital valves is 10l/min at 5bar, which is much higher than the required flow rate of 1l/min. Moreover, the opening of the check valve is much slower than that of the digital valves. Thus, the kinetic energy of the oil is too low to open the check valve. When the velocity of the cylinder is large enough, the hydraulic buck converter can recuperate energy. This indicates that the HBC is oversized for this available load, but might be more efficient for a load needing larger flowrates. To sum up, the HBCs present a similar position response with a HPD. When the velocity of the locomotion is large enough, the HBCs can recuperate the energy for the supply pressure and achieve energy-saving performance. With a feed forward controller, the position tracking and energy consumption can be slightly improved.

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