The Hydraulic Buck Converter

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1. Introduction

Hydraulic drives suffer from a bad efficiency if proportional control is applied. The Hydraulic Buck Converter (HBC) is a concept transferred from power electronics to hydraulics to improve the efficiency of hydraulic drives, like depicted in Fig. (1). The HBC is a traditional step down converter, i.e. the load pressure is always lower than the supply pressure. The hydraulic switching valves are operating in pulse-width-mode at a certain switching frequency f_S. The control input is the duty ratio κ between the on- and off-time of the active switching valve.

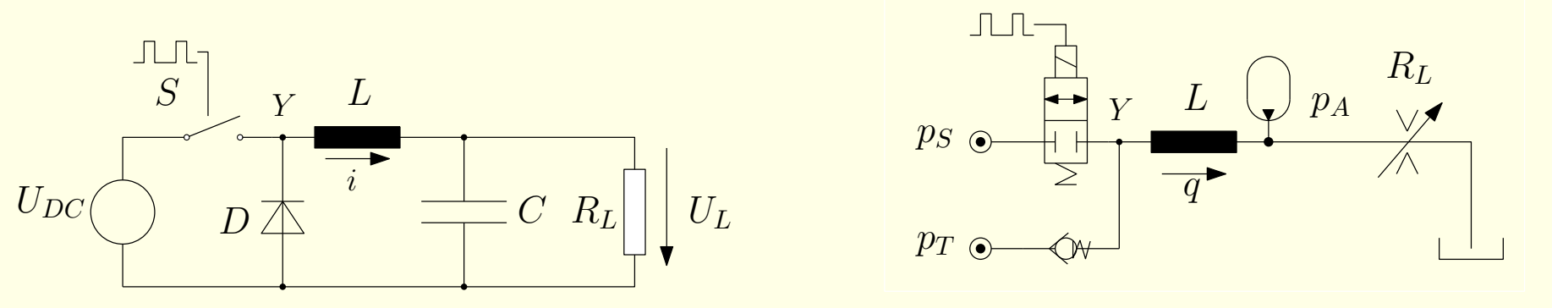

Figure 1: *Left: electric buck converter, right: hydraulic buck converter*

The inertia of the fluid in the hydraulic inductance is accelerated by opening the switching valve. After the quick closing of the valve the spill-over of kinetic energy in the hydraulic inductance initiates a suction from the tank side, which is responsible for the efficiency improvement. At the output of the HBC an accumulator has to be placed to smoothen the pressure fluctuations due to the switching process. Detailed information can be found, for instance, in [3].

2. Theoretic Characteristics

For the theoretic analysis the valves are assumed to be infinitely large that no pressure drop occurs, and, the switching time of the valves is assumed to be zero. Further the capacity at the output of the converter is infinitely large, such that no pressure pulsations at the output of the converter occur.

2.1 Modes of Operation

Like in the electrical engineering, there exist two different modes of operation, a discontinuous and a continuous mode, like depicted in Fig. (2). In hydraulics these modes are renamed in flow control mode and pressure control mode, due to their characteristic behaviour.

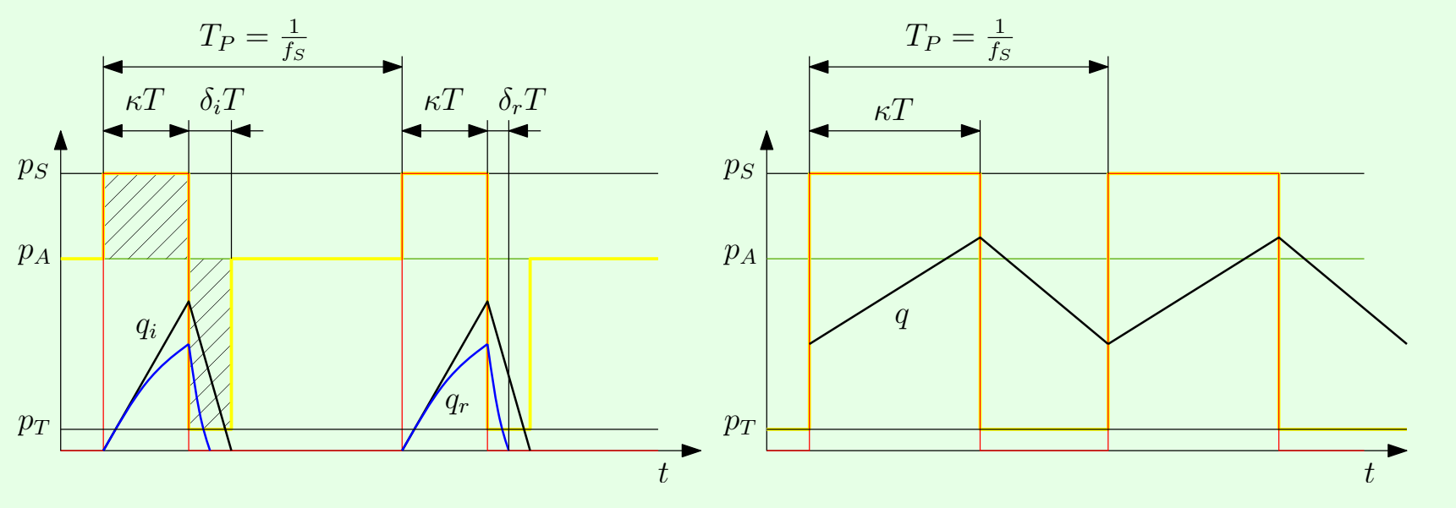

Figure 2: *Left: flow control mode, right: pressure control mode*

During the on-time κT of the active switching valve the flow rate q through the inductance accelerates. After closing the valve, the inertia of the fluid causes a suction flow from the tank for the free-wheeling time δT. In flow control mode the relation $\kappa + \delta < 1$ is valid, thus, the flow rate through the inductance vanishes before the next switching cycle starts. This leads to a mean flow rate

$$\bar{q}_{fc}(\kappa)\big|_{R\to 0} = \frac{1}{2}\frac{(p_S^2 + p_A p_T - p_S p_A - p_S p_T)}{(p_A - p_T) L f_S}\kappa^2, \qquad (1)$$

where the static resistance of the pipe inductance is neglected. If $\kappa^{\#} + \delta = 1$ is fulfilled the behaviour changes to pressure control mode. At duty ratios beyond $\kappa^{\#}$ a mean pressure in the node point Y according to

$$\bar{p}_Y = p_T + (p_S - p_T)\,\kappa \qquad (2)$$

is enforced.

2.2 Characteristics

The resulting characteristics in forward flow direction are depicted in Fig. (3) on the left. The solid and the dashed lines represent the characteristics accounting and neglecting the static resistance of the pipe inductance, respectively. The parabolic line indicates the transition from flow control mode to pressure control mode.

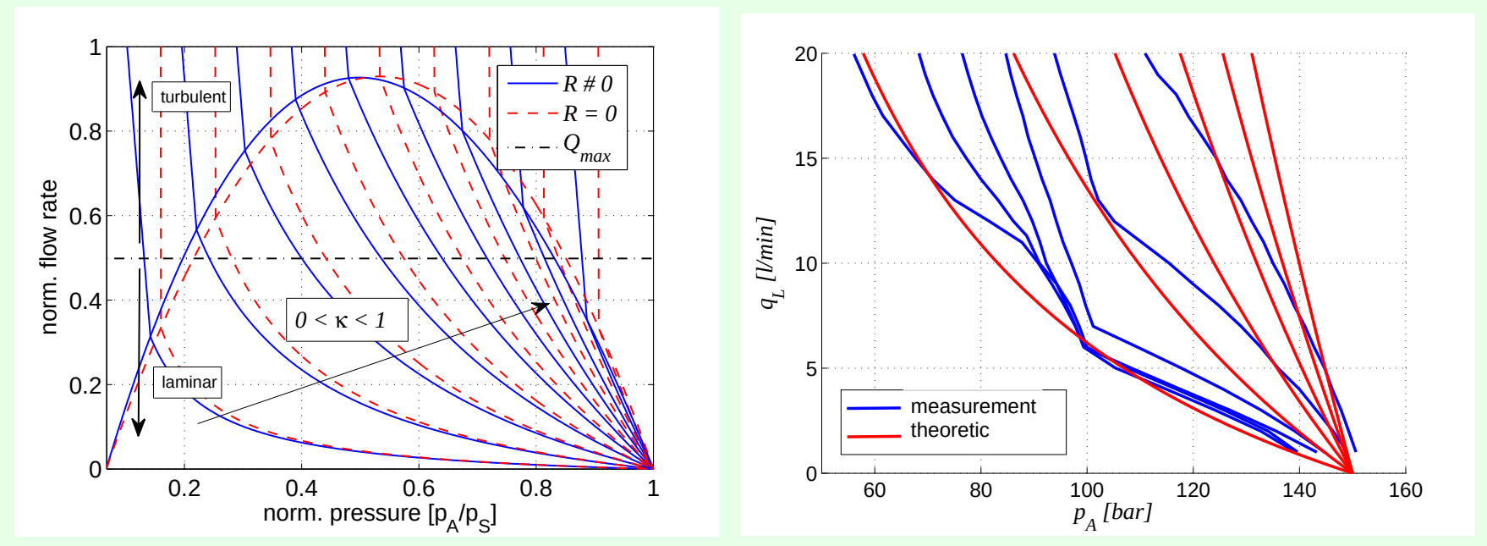

Figure 3: *left: theoretic characteristics of the simple HBC, right: measurements vs. theoretic characteristics*

Beyond the horizontal dashed dotted line the flow through the inductance is supposed to change from laminar to turbulent due to a high flow velocity. Thus, an operation of the converter in this area is not proposed.

2.3 Efficiency

In Fig. (4) the theoretic efficiency characteristics are illustrated. On the left side, the efficiency in forward flow direction is depicted. If an additional mirrored valve stage is applied to the simple HBC, like in Fig. (10), the converter also operates in the back flow direction, if the tank sided active switching valve is pulsed. Hence, both flow directions are maintained. In the back flow direction the converter is able to recuperate energy to the supply system. The corresponding efficiency characteristics can be examined on the right side of Fig. (4). In both diagrams the black mesh indicates the efficiency of a proportional hydraulic drive.

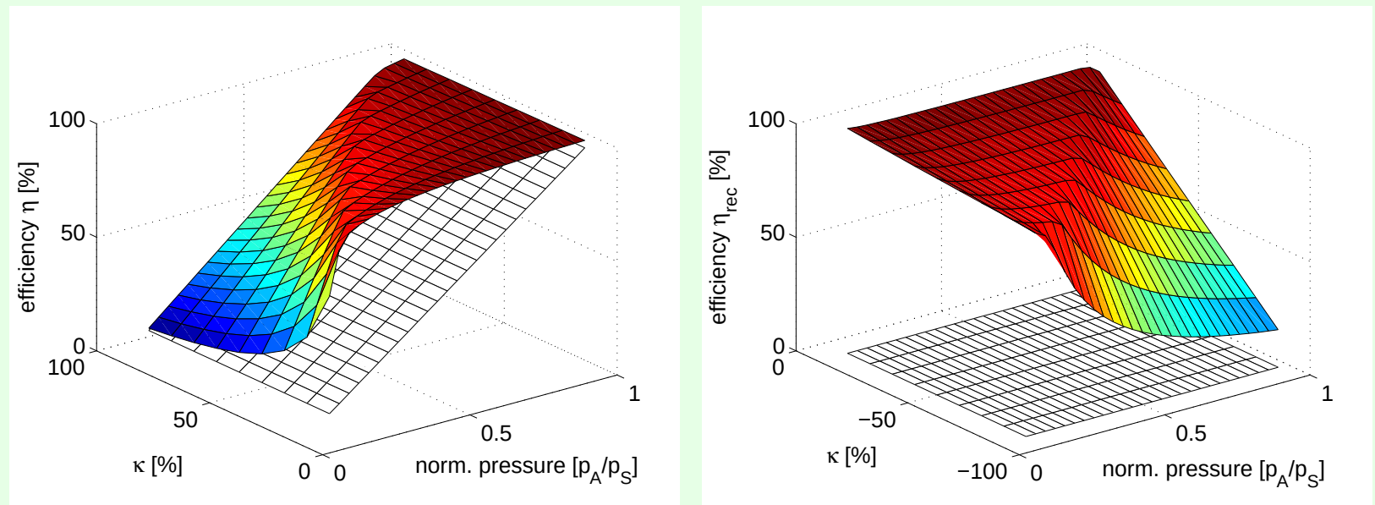

Figure 4: *Theoretic efficiency in both flow directions*

3. Basic Experiments

The basic experiments consider the measurements of the HBC characteristics. Further the influence of different geometries of the inductance are investigated.

3.1 Test Stand

The test configuration of the prototype *HBC020* for the basic experiments is depicted in Fig. (5). The load is specified either by a flow control valve for characteristic measurements or by a differential cylinder for drive experiments. The test stand was set up in the frame of a students project according to [2].

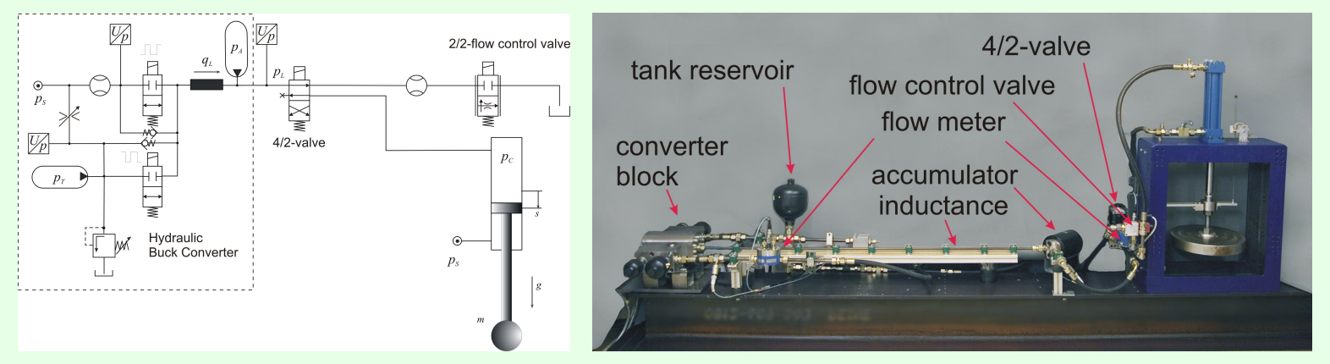

Figure 5: *Schematic and test rig of the* HBC020

The measured converter characteristics of the *HBC020* are illustrated in the right diagram of Fig. (3).

3.2 Different Geometries of the Pipe Inductance

Since a straight pipe inductance occupies a large amount of space, different coil inductances according to Fig. (6) were investigated to reduce the overall size of the HBC.

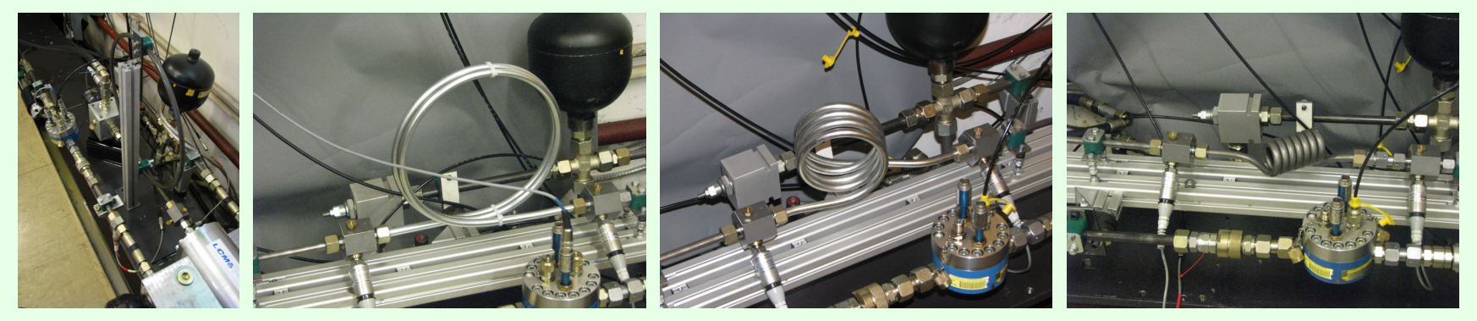

Figure 6: *Different coil geometries*

The specifications of the individual coils are listed in Tab. (1).

Configuration	Windings	Coil Diameter	Colour
1	0	∞	green
2	1	$\approx 60\ cm$	blue
3	2	$\approx 25\ cm$	cyan
4	4	$\approx 8\ cm$	magenta
5	7	$\approx 3\ cm$	red

Table 1: *Colour assignments of different coils*

The different colour assignments correspond to the results depicted in Fig. (7). The left diagram illustrates the absolute efficiency values and in the right diagram the efficiency improvement compared to a conventional proportional drive can be examined. Of course, the straight pipe delivers the maximum improvement followed by the inductance with one winding. But it is remarkable, that the remaining coils have nearly the same performance. These investigations were carried out in the frame of a student project according to [5].

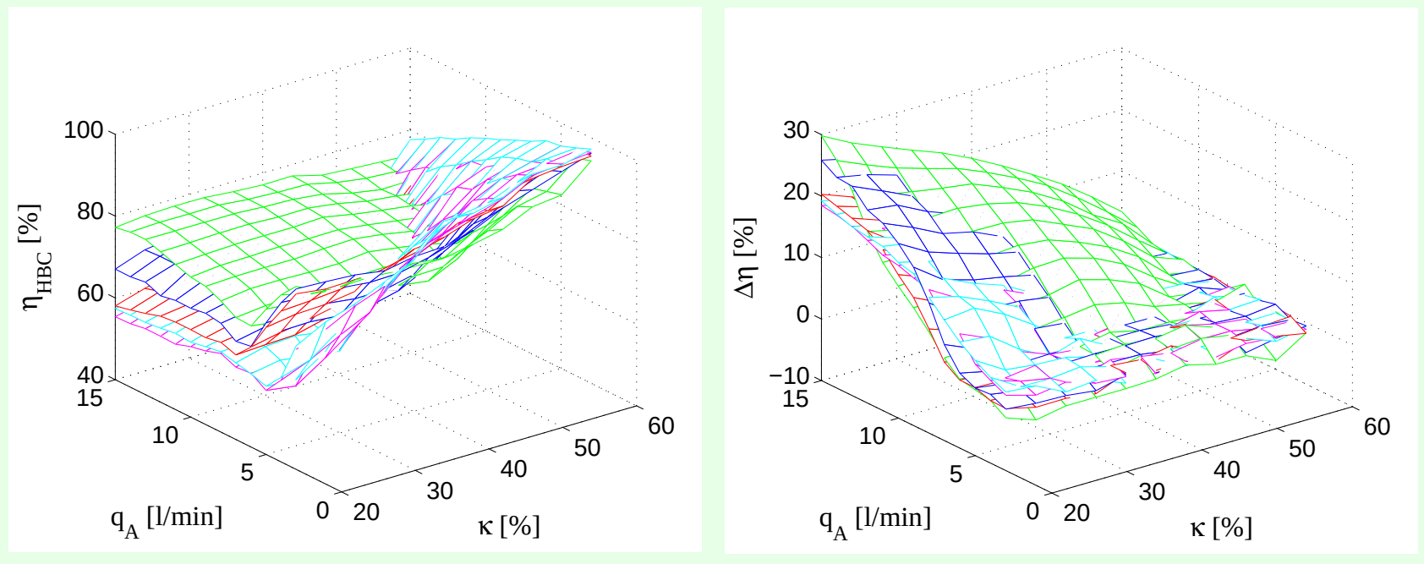

Figure 7: *Resulting efficiencies with different coils*

3.3 Compact Design

The most compact configuration of the *HBC02*-series is depicted in Fig. (8), where the inductance is realised as a threaded spindle, which is situated inside the converter block. The efficiency performance is nearly equal to configuration 5 from Tab. (1). The power range of this HBC is about $10\,kW$.

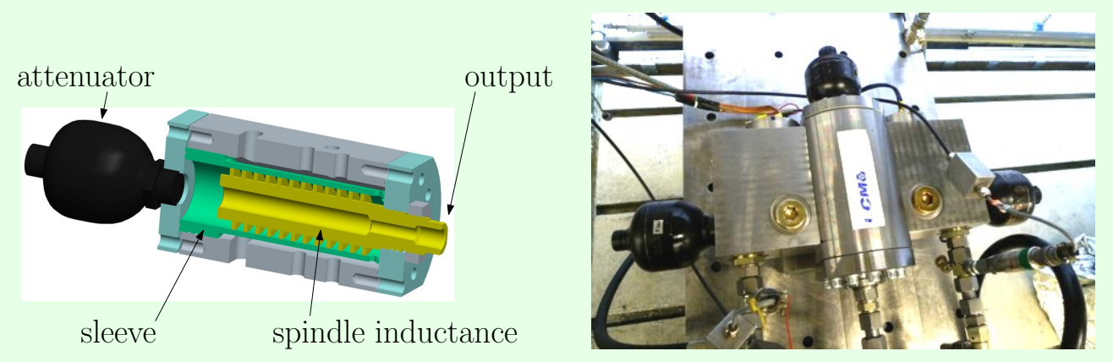

Figure 8: *Prototype* HBC021 *with a threaded spindle inside the valve block*

Another compact realisation is the *HBC030*, which is illustrated in Fig. (9). This converter was designed for low power applications of about $1.5\,kW$ and offers the ability to arrange several HBCs in a sort of cluster in the sense of a compact hydraulic control unit.

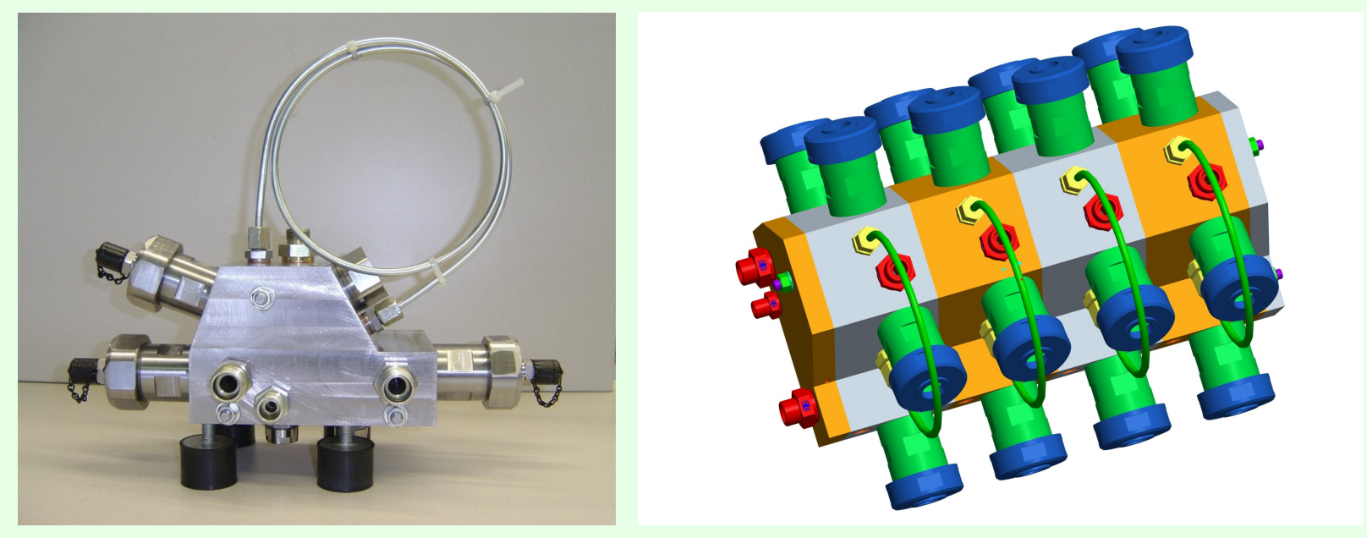

Figure 9: *Prototype* HBC030 *according to [1]*

4. Advanced Modelling

Examining the right diagram of Fig. (3) the dissatisfying agreement between the measurements and the theoretical characteristics makes an advanced dynamic modelling of the HBC necessary. Therefore, a configuration according to Fig. (10) was investigated.

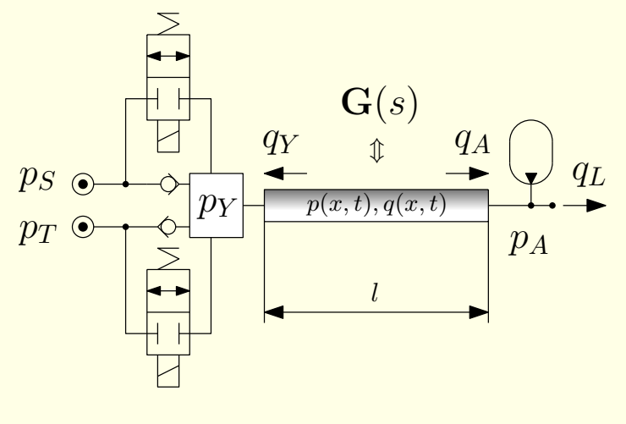

Figure 10: *Considered system*

Therefore, the size and the dynamics of the different valves, the non-linearity of the gas spring in the accumulator and linear wave propagation in the pipe inductance according to

$$\begin{bmatrix} \hat{p}_A(s) \\ \hat{Q}_A(s) \end{bmatrix} = \begin{bmatrix} \cosh(\gamma(s)l) & -Z(s)\sinh(\gamma(s)l) \\ -\frac{1}{Z(s)}\sinh(\gamma(s)l) & \cosh(\gamma(s)l) \end{bmatrix} \begin{bmatrix} \hat{p}_Y(s) \\ \hat{Q}_Y(s) \end{bmatrix} \qquad (3)$$

with

$$Z(s) = \frac{\sqrt{E'\rho}}{r^2\pi}\sqrt{-\frac{J_0\left(j\sqrt{\frac{s}{\nu}}r\right)}{J_2\left(j\sqrt{\frac{s}{\nu}}r\right)}} \text{ and } \gamma(s) = \frac{s}{\sqrt{\frac{E'}{\rho}}}\sqrt{-\frac{J_0\left(j\sqrt{\frac{s}{\nu}}r\right)}{J_2\left(j\sqrt{\frac{s}{\nu}}r\right)}} \qquad (4)$$

were considered. The satisfying simulation results with this advanced model are depicted in the left diagram of Fig. (11).

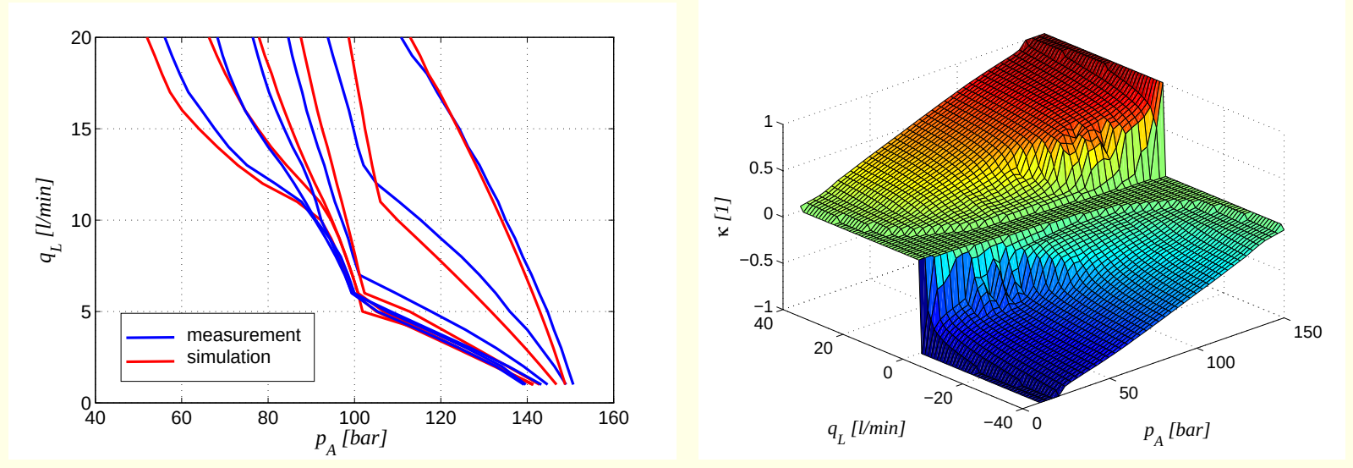

Figure 11: *left: comparison of theoretic and measured characteristics, right: simulated characteristics for control issues*

5. Control Experiments

Since the accumulator at the output of the converter makes the overall system very soft, an advanced control strategy has to be adopted, to avoid unwanted oscillations at the load.

5.1 Flatness Based Control

For the linear drive experiments (see Fig. (13)) a flatness based control (FBC) was applied, which is based on an inversion of the system dynamics. Further a stabilisation of the tracking error can be assured. The results of measurements with the different controller concepts from Fig. (12) are depicted in Fig. (14). A similar application of the flatness based controller concept is given in [4].

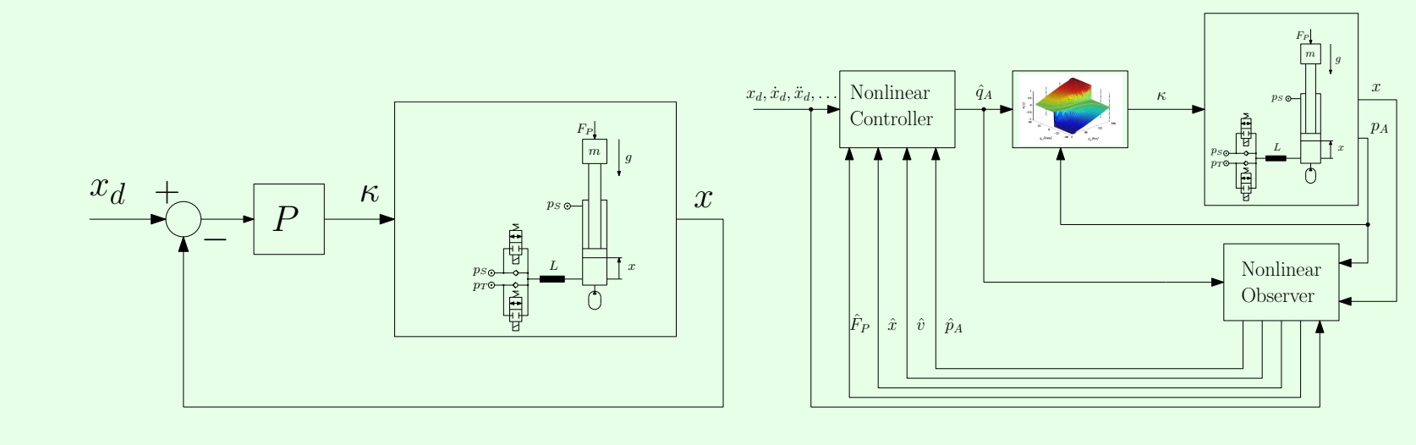

Figure 12: *left: P-Controller, right: control scheme of the FBC*

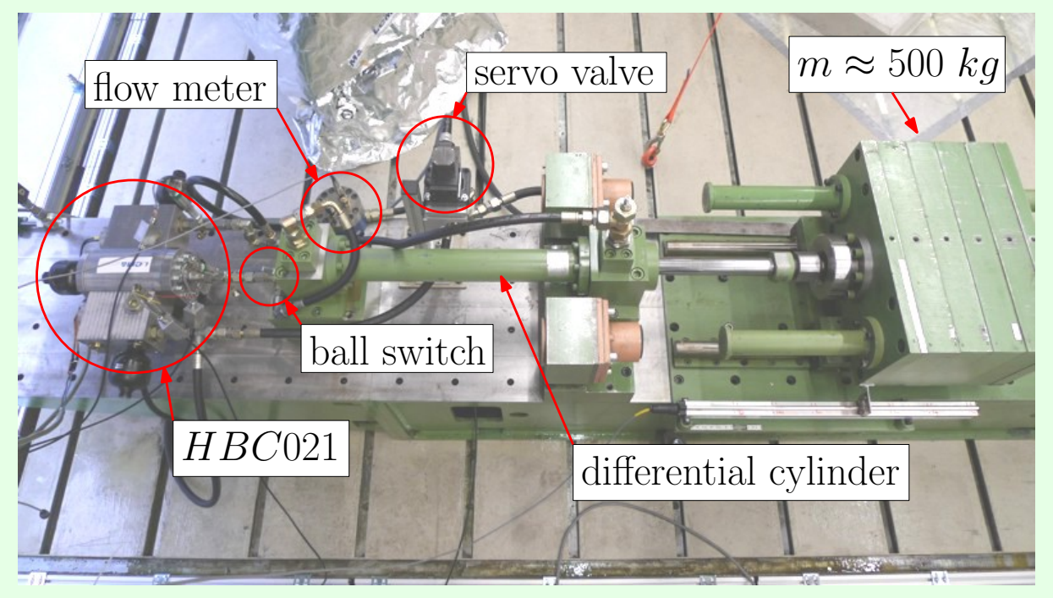

Figure 13: *Linear Axis controlled by an HBC*

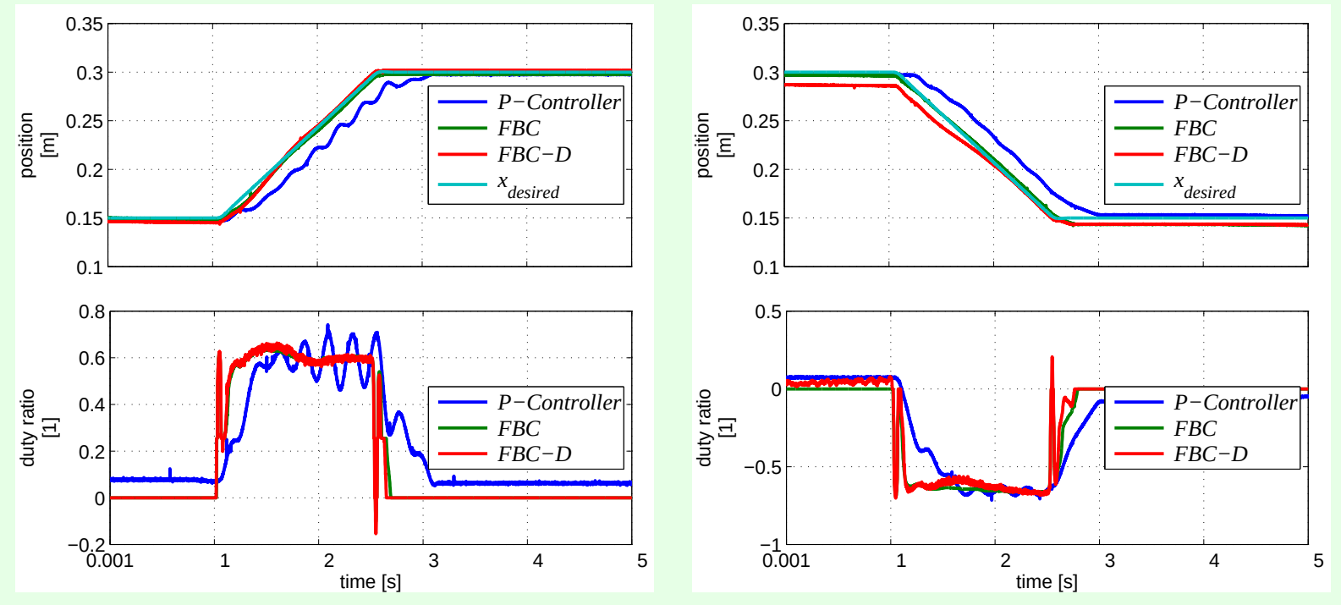

Figure 14: *Measured control performance*

5.2 Energy Consumption

The efficiency improvement of a linear drive controlled by an HBC compared to a conventional hydraulic proportional drive (HPD) can be examined in the right diagram of Fig. (15), where the energy consumption of both drives is opposed. In each case, the HBC and the HPD were controlled by a P-controller, like depicted in the left diagrams of Fig. (12) and Fig. (15), respectively.

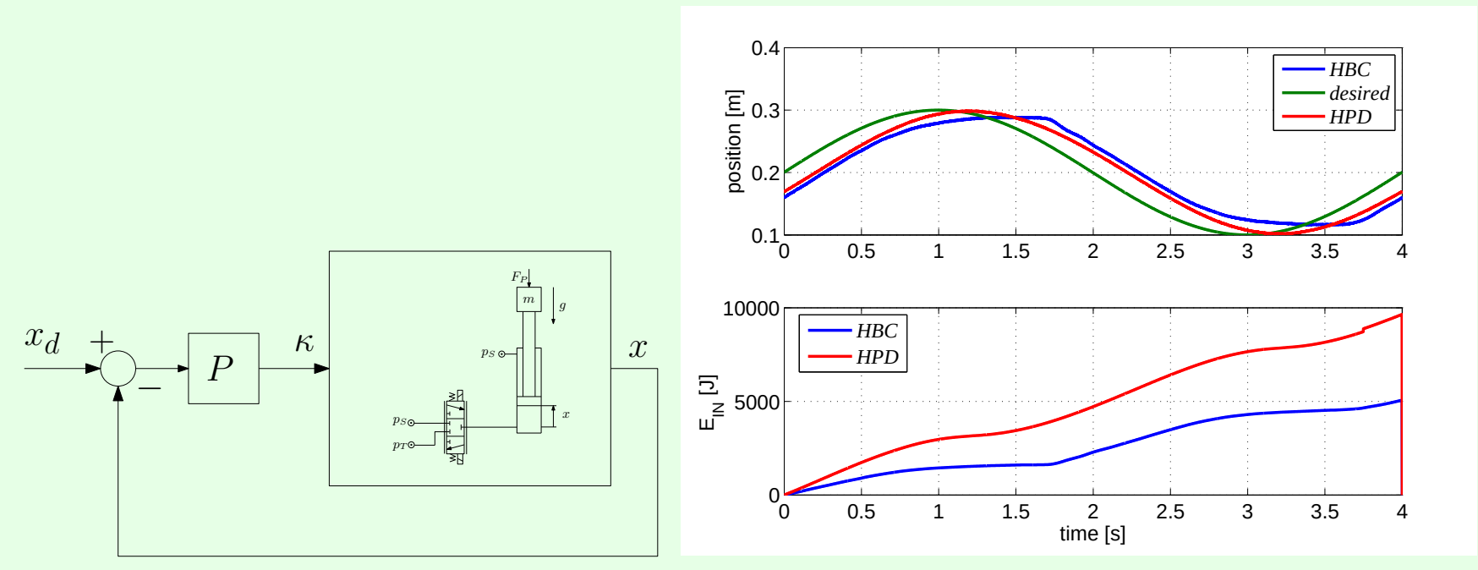

Figure 15: *left: HPD with P-Controller, right: Comparison of the energy consumption*

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