Hydraulic Switching Control of Resonant Drives

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Abstract

In this paper the concept of a hydraulic buck converter driving a load at resonance is discussed. The performance is compared with conventional proportional control and proportional control of a resonant drive. As an example the oscillation drive for a mould of a continuous steel slab caster is taken to benchmark the concept. Such moulds have typically a weight of 20 tons and are oscillated at frequencies up to 5 Hz and a stroke of 7 mm. It is shown that a good performance and substantial energy savings compared to conventional hydraulic resistance control can be achieved with this concept.

1. Introduction

The idea to exploit resonance for an energy efficient generation of mechanical motion or force is fairly old. In a general sense it means that system design and motion planning are such that essential parts of intended motions are generated by an interplay of inertia and elastic forces. Already 1828 Julius Albert [1], for instance, used this principle in his fatigue testing machines of chains. In the mechatronic context, Babitsky [2] brought up the idea of using a free swing motion for an efficient high-speed robotic actuation. A further important mechatronic application of the resonance drive principle was proposed for magnetic as well as for hydraulic actuators for variable valve timing of combustion engines (e.g., [3, 4, 5]). In [6, 7] resonant hydraulic actuation was investigated for mechanical engineering drive applications and [8] presents resonant MEMS actuators exploiting electrostatic force generation for signal filtering applications. The diploma thesis [6] also dealt with the continuous adjustment of the resonance frequency by exploiting the nonlinear stiffness properties of gas filled hydraulic accumulators.

The main advantages of resonant actuation are twofold:

1. To generate the motion with smaller drives; this saves investment costs and may be the key to the realization of very high bandwidth motion, since in general smaller drives have higher bandwidth capabilities than larger ones. This is true for electrical as well as for hydraulic drives.
2. To save energy consumption; this is particularly expressed for hydraulic servo- or proportional drives.

Hydraulic switching control is the control of hydraulic drives by an appropriate timing of the switching of on-off valves [9, 10]. Several principles have been proposed so far, many of which can provide a significantly higher efficiency than hydraulic resistance control (HRC) by proportional or servo valves. So far, the best investigated energy efficient hydraulic switching drive is the hydraulic buck converter (HBC) which is fully analogous to the electric buck (DC-DC) converter, comprising fast valves, diodes, an inductance, and a capacitance. A prototypal realization of a HBC is published, e.g., in [11]. Since today the feasible switching frequencies in hydraulics are in the order of magnitude of 100Hz the required hydraulic capacitance of the HBC for a reasonable attenuation of pressure pulsation is relatively large. This capacitance and the load inertia define an oscillator, the natural frequency of which can be tuned by the HBC capacitance. If the motion to be generated is close to the free vibration of this oscillator the hydraulic power in- and out-flow through the HBC is strongly reduced which improves efficiency and allows equipping the system with smaller components, in particular smaller supply units and valves. That saves cost and space but puts higher demand on the control development of such drives.

In this paper the concept of a HBC driving a load close to or at resonance is discussed. The performance is compared with conventional HRC and HRC in combination with a resonant actuation (HRCr). As an example an oscillation drive for a continuous slab casting mould is taken to benchmark the concept.

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2. RESONANT HYDRAULIC DRIVES

Resonant hydraulic drives discussed in this paper exploit the mechanical inertia of the load and a hydraulic spring element. The latter can be realised either by fluid or by gas compressibility. In this paper gas filled accumulators are considered, because of their unrivalled compactness.

A schematic of a resonant hydraulic drive is shown in Figure 1. Its ring side is supplied with system pressure p_S. Motion control is done by a hydraulic control unit (HCU) that adjusts the flow rate Q_c properly. The HCU may be a proportional valve or a hydraulic switching converter. A power saving effect occurs if a substantial portion of the required flow Q_1 is provided by the accumulator flow Q_{Acc}.

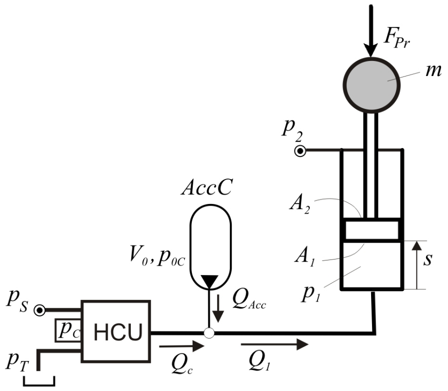

Figure 1: Schematic of a resonant hydraulic drive exploiting a hydraulic accumulator as compliance element

Resonant drives make sense if the motion can be planned in advance, if it can be reasonably approximated by the interplay of load inertia and the spring, and if conservative forces dominate. In this paper only sinusoidal motions are studied.

The resonance angular frequency ω follows form the momentum equation of the load, the linearized equation of the hydraulic accumulator, and the relation between piston speed and flow rate Q_1 (see Eq. (1)).

$$m\ddot{s} = p_1 A_1 - p_S A_2 - F_{pr} - m\,g\,; \quad Q_{Acc} = -\frac{1}{n} V_{G,ref} \frac{\dot{p}_1}{p_{1,ref}}; \quad Q_1 = \dot{s} A_1 = Q_{Acc} + Q_c$$
$$\omega = \sqrt{\frac{n\,A_1^2\,p_{1,ref}}{m V_{G,ref}}}; \quad p_{1,ref}\,V_{G,ref}^n = p_{0C} V_0^n; \quad p_{1,ref}\,A_1 = p_2 A_2 + F_{pr,ref} + m\,g \tag{1}$$

ω can be adjusted off-line by the accumulator size V_0 and its filling pressure p_{0C}, but could be also done on-line if the pressure p_2 is controlled, since the reference pressure $p_{1,ref}$ depends on p_2 according to the equilibrium condition (last equation of (1)). $F_{pr,ref}$ is the mean value of F_{pr}. Such on-line control - as studied, e.g. , in [6] - constitutes a logical extension of the resonance principle if oscillation frequencies vary. The mould oscillation frequency in continuous casting, for instance, ranges typically from 1 to 5 Hz and is adjusted to the casting speed. But the resonance frequency adjustment requires extra components and the feasible frequency range ratio is not more than ca. 3:1, due to limitations of the allowable accumulator pressure ranges.

Of course, only the inertia forces, the dead load $m\,g$, and the constant part of the process force $F_{pr,ref}$ can be compensated by the accumulator. Dissipative forces require a corresponding power flow from the supply system. Losses P_{loss} of this power flow according to Eq. (2) occur if the hydraulic power source's pressure p_C is higher than the actual pressure p_1.

$$P_{loss} = Q_c\left(p_c - p_1\right) \tag{2}$$

If the drive is run below or above resonance, Q_c has to account also for part of the inertia forces.

3. Switching Control of a Resonant Hydraulic Drive

In this case the HCU of Figure 1 is realized as a HBC. Its schematic is shown by the box 'HBC' of Figure 2. It comprises two fast switching valves (V_S and V_T) and two fast check valves (V_{CHKP}, V_{CHKT}), a hydraulic inductance realized by a pipe of length *l* and diameter *d*, and an accumulator AccC. In 'forward mode' only V_S is switched periodically in a pulse-width modulation (PWM) mode and fluid is fed to the cylinder. The frequency (*1/T*) is mostly constant and the control of flow rate or pressure is done by the duty cycle κ: If V_S is switched on, the flow rate in the inductance is increasing and still goes on a while after V_S is switched off. In this phase oil is sucked from the tank line via V_{CHKT}. In 'recuperation mode' V_T operates in PWM mode, directing flow to the tank line when it is on. After each valve closure the momentum of the oil flow in the inductance pipe forces also some oil to the pressure line via V_{CHKP}.

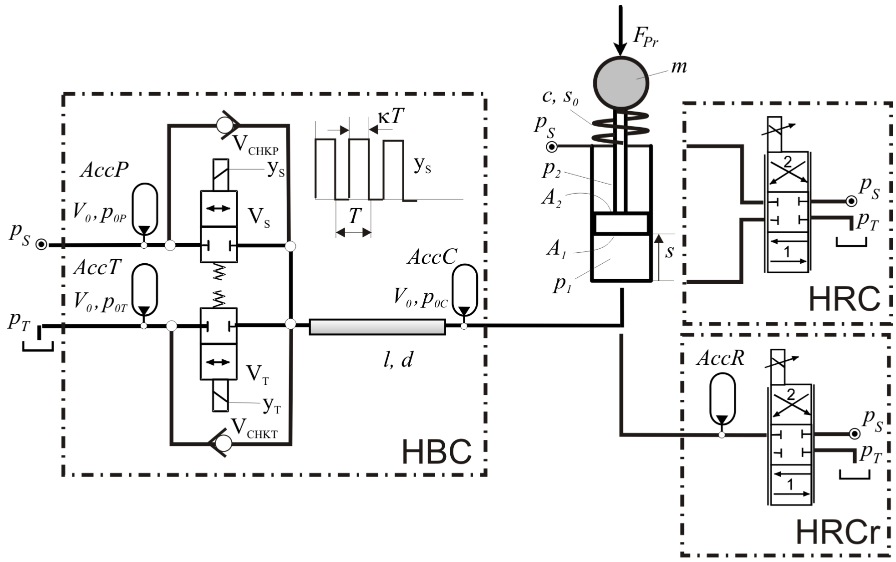

Figure 2: Three ways of controlling an oscillatory motion hydraulically: conventional hydraulic resistance control with a proportional valve (HRC), resonant drive with either a proportional valve (HRCr) or a hydraulic buck converter (HBC)

Since in 'forward mode' fluid is taken not only from the pressure line but also from the tank line and part of the flow goes to the pressure line in 'recuperation mode' the HBC requires less energy than a HRC. The HBC switches between two pressure sources (p_S and p_T), thus the average pressure p_C – indicated in Figure 1 - is closer to the actual cylinder pressure p_1 than p_S. Even though a HBC without resonance can realize a much more efficient motion control of an oscillatory drive than a HRC operation at resonance provides additional energy saving and a smaller sizing, i.e. smaller components and also a smaller hydraulic supply unit.

3.1 Comparative Numerical Study

A comparative simulation is presented to check the energy saving potential and the performance of three different hydraulic drive systems (see Figure 2): i) a conventional proportional drive (HRC), ii) a hydraulic resonant drive controlled by a proportional valve (HRCr), and iii) a resonant drive controlled by a buck converter (HBC).

Mould oscillation of continuous slab casters is taken as benchmark problem. Today, two HRC drives are employed to oscillate the mould vertically. It weighs typically 20 t and oscillates at frequencies up to 5 Hz with a stroke up to 7 mm. 70% of the weight of the mould is spring compensated to reduce power consumption. This is accounted in the simulation model by a constant process force. In this study only one of the two mould actuators is treated. Thus, the mass of the mould and the process force are reduced to the half of the respective values of the complete mould. The process force stems from the friction between mould and the solidified steel shell in the mould. It is modelled as a force proportional to the mould speed, since molten casting powder between strand and mould provokes mainly liquid type friction behaviour.

For the conventional mould oscillation drive by a HRC a double acting differential cylinder is used, which is also considered in the simulations. For the resonant drives (HRCr & HBC) the rod side chamber of the differential cylinder is connected to constant supply pressure permanently. The ratio of the cylinder cross sections is adapted, such that the mean pressure in the piston side chamber is approximately half of the supply pressure.

A model in Matlab/Simulink shown in Figure 3 was setup for the three drive systems. Elements of the hydraulic model library *hydrolib3* [12] have been used. The data are listed in Table 1.

Table 1: Simulation parameters of the mould oscillators

Parameter	Value	Parameter	Value
Supply pressure	200 bar	Accumulator Volume	0.32 l
Tank pressure	10 bar	Gas prepressure	50 bar
Piston diameter	125 mm	Polytropic exponent	1.3
Rod diameter HRC	90 mm	Pipe length (HBC inductance)	1.5 m
Rod diameter HRCr & HBC	96.4 mm	Pipe radius	7.5 mm
Half the mass of the mould	10000 kg	Switching frequency	100 Hz
Process force (weight relieving)	7000 kg 9.81 m/s²	Nominal flow rate of switching valves	70l/min@5bar
Viscous friction (process force)	25000 Ns/m	Nominal flow rate of proportional valve	100l/min@5bar

The basic control scheme of the resonant drives is identical for all three drive systems and is shown Figure 4. A feed-forward block representing a simplified inverse model of each drive generates the main part of the input signal. This feed-forward computes the necessary flow rate for the desired mould motion, which reads

$$Q_d = A_1\dot{s}_d + V_0\left(\frac{p_0}{p_d}\right)^{\frac{1}{n}} \frac{d\left(A_1 p_d - mg - d\,\dot{s}_d + F_{pr} - p_S A_2\right) + m^2\dddot{s}_d}{n\,A_1 p_d m}$$
$$\text{with } p_d = \frac{1}{A_1}\left(p_S A_2 + mg + d\,\dot{s}_d - F_{pr} + m\ddot{s}_d\right) \tag{3}$$

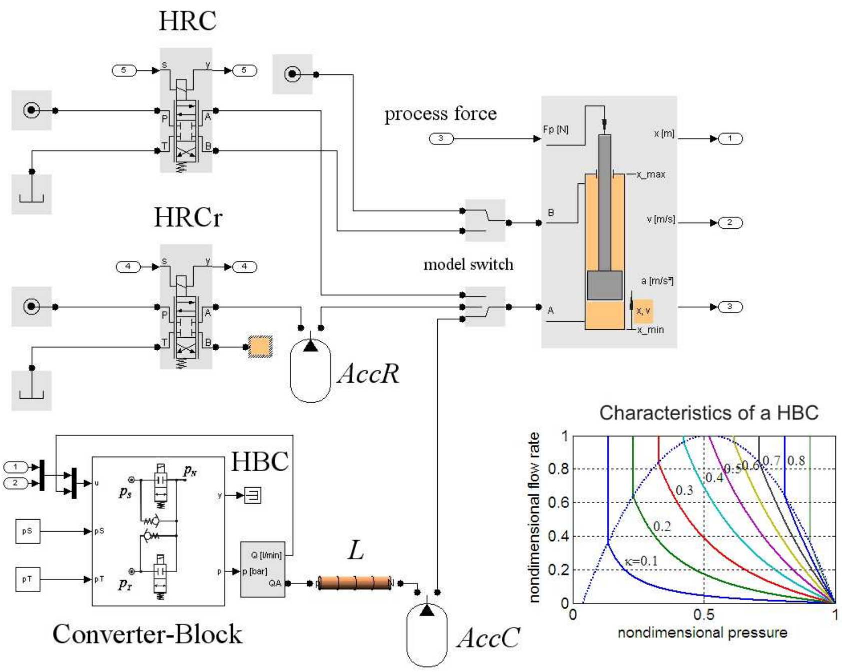

Figure 3: Schematic of Matlab/Simulink models of three different drives according to Figure 2 and nondimensional characteristics of a HBC; (control blocks are not shown)

The desired flow rate Q_d of Eq. (2) has to be converted into a set value for the respective control element. For the HRC and HRCr, respectively, this is the proportional valve input signal according to its pressure/flow characteristics. For the HBC the pulse-width κ of the PWM signal commanded to the switching valve is derived from characteristics of the HBC. They are shown graphically in Figure 3 in nondimensional form.

The high stiffness of the HRC allows its control without feed-forward with a satisfying performance. For all three drives a PD-controller compensates the model errors and keeps the systems on track. The gains were adjusted empirically for each operating frequency and for each system and are listed in Table 2.

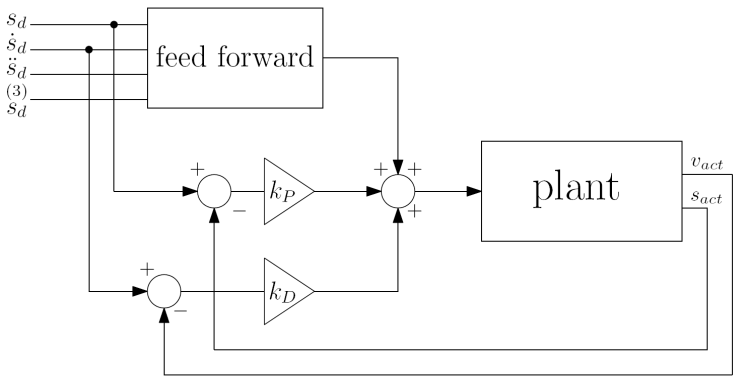

Figure 4: General controller structure of all three drives; HRC uses no feed-forward

Table 2: Controller parameters of the different configurations and oscillation frequencies

configuration	**2 Hz**		**3 Hz**		**5 Hz**	
	k_P	k_D	k_P	k_D	k_P	k_D
HRC	50	20	50	20	50	20
HRCr	30	10	30	10	30	10
HBC	10	4	15	5	40	7

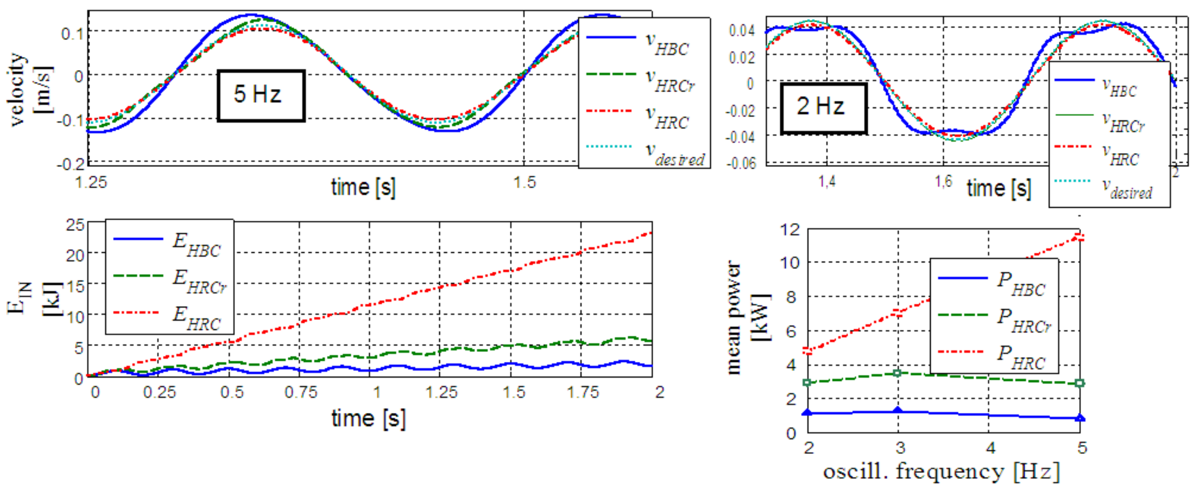

Figure 5: Results of the simulation study of three different mould oscillation drives: left diagrams: velocity and energy (E_{IN}) consumption curves at resonance (5 Hz); upper right diagram: velocity curves for a 2 Hz operation which is below resonance; lower right diagram: mean power consumption for different oscillation frequencies (resonance frequency of HBC and HRCr: 5 Hz)

Performance and mean power consumption were computed for three operating frequencies (3, 2, 5 Hz) and are shown in Figure 5. The natural frequency of the oscillator was 5 Hz in all cases. Nonetheless, the HRCr needs less power even for smaller frequencies. The HBC shows by far lowest energy consumption but is following the desired motion with less accuracy. This is partly the result of the internal HBC inductance pipe wave propagation dynamics which is not considered in the HBC characteristics shown in Figure 3.

6. Summary and Outlook

In this paper the hydraulic switching control of a resonant oscillation drive was evaluated by a comparative simulation study. Comparison was done with a conventional hydraulic proportional drive and a proportionally controlled resonant drive. Mould oscillation of a slab caster was taken as an example. The results show

1. a remarkable energy saving by the resonance principle
2. an additional energy saving if a resonance drive is controlled by a hydraulic buck converter.

Even though the resonant tuning was done only for the highest operating frequency the resonant operation needs lower energy also for lower frequencies.

Control is more challenging for the resonant operation and was realized by a combination of a feed-forward and PD feed-back control.

The improved control of the HBC by taking its internal dynamics of wave propagation in its inductance pipe into account will be subject of future research work.

In an ongoing co-operation with the Italian Institute of Technology the authors will investigate the concept of resonant actuation by a buck converter for the actuation of a leg of a quadruped robot in the near future.

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