RECENT ADVANCES IN DIGITAL HYDRAULIC COMPONENTS AND APPLICATIONS

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ABSTRACT

The digital hydraulic technology has approached the market in the last years and its market share is constantly growing. This is a consequence of a sound scientific and applied research in the last years combined with a constantly growing product range of digital hydraulic components. More and more vendors are offering digital hydraulic valves and components to the market. This allows the realization new applications and encourages others to come up with new products like valves and actuators. This paper gives an overview on the recent advancements in digital hydraulic components and applications with a focus on marketable solutions.

KEYWORDS: Fast switching valves, digital valves, state of the art.

1 INTRODUCTION

The digital hydraulic technology has found its recognized place in science in a big number of countries all over the world, and the attentiveness is still growing. Besides the traditional Institutes in Tampere, Finland (TUT/IHA) and Linz, Austria (JKU/IMH/LCM), digital hydraulic research topics has also been addressed in other European hydraulic research Institutions like Bath University (PTMC) [1], RWTH Aachen (IFAS) [2] and Aalborg University (AAU/ET) [3] etc.. But digital hydraulics attracts also attention in China [4], India, Brazil [5], and Iran [6], just to name a few. Besides the traditional research areas also new branches like chemical and pharmaceutical science [7] or cooling technology [5] takes a closer look on this technology.

Whereas digital hydraulics is a fixed element in academia since decades it penetrates also the market of hydraulic drive technology in a growing pace. This paper will give an overview of new applications and components in digital hydraulics with a focus on market-ready solutions. The range of market relevant applications is meanwhile considerable and can, from the author`s viewpoint and experience, be categorized basically in 4 fields:

1. **Simple pressure and position control at low dynamics**: Such applications can be found for instance in presses where a position or a force has to be kept almost constant for a longer time period. The achievable accuracy in position (<1µm) and pressure (<10 mbar) in combination with extremely low energy consumption is unattainable with other hydraulic drive principles. Due to the use of seat type valves operated in the so called ballistic mode the mentioned power consumption is extremely low. Often a small pressurized accumulator is a sufficient power-supply for several minutes of operation. Such applications are market ready and can be engineered typically in a very short time to market.

2. **High dynamic position and pressure control without a focus on energy efficiency**: Such applications can be found in many industry branches. For instance the gap control in rolling mills, distance control in mobile hydraulics, positioning in tool machines etc. They are typically characterized by fast actuator movements and high flow rates, respectively, what can lead to problems with noise, pressure pulsations and position oscillations. Thus, the system architecture needs a sound understanding of hydraulic phenomenon`s and often complex design process. Several solutions based on PCM (Pulse Code Modulation; multi-bit-per-metering-edge approach) or PWM (Pulse Width Modulation; single-bit-per-metering-edge approach) already exist. Also new control methods, like the High Dynamic Digital Control (HDDC) can be promising solutions.
   Though, the energy efficiency is often not in the focus in such applications, the energy consumption compared to proportional or servo solutions is by far lower, what is a consequence of the low leakage of the typically used seat type valves.

3. **Energy efficient position and pressure control exploiting converter principles**: Here applications where energy efficiency, often combined with the possibility of energy recuperation, are in focus. Examples are all types of dead load handling drives like for cranes, fork lift trucks etc. Here some converter principles like the Buck/Chuck-converter or the resonance converter are presented by research institutes. Due to some problems with noise, valve durability and complexity, such solutions have not approached the market up to now, but some approaches are promising to do so in future.

4. **Special purpose applications**: Besides the above mentioned types of applications there are a lot of special purpose tasks in hydraulics which can be done quite advantageous with digital hydraulics. Examples are sensorless digital hydraulic stepper drives, clamping in tool machines, emergency applications or punching machine drives.

As an indispensable prerequisite for new promising digital hydraulic applications a continuous development of digital hydraulic components is needed.

In the focal point of interest stands the digital hydraulic valve. The requirements on such a fast switching valve are extremely demanding. A high durability (>10^9 cycles) combined with low electric power consumption at high frequencies (>100Hz), low costs, good integrability are just some of the challenging boundaries in valve development. Though, in the last years more and more vendors are contributing with digital hydraulic valves.

Besides reliable digital valves also other digital hydraulic components like multi-chamber cylinders, low cost power electronics or digital accumulators and passive filters are needed in future.

In the following chapters more or less new solutions in digital hydraulics categorized by applications and components will be highlighted.

2 APPLICATIONS

The range of solutions reaches from simple market ready applications comprising low dynamics to high sophisticated solutions like digital displacement units in wind power.

2.1 Simple pressure and position control at low dynamics

In case of low dynamics pressure and position control it can generally be said that such applications are off the shelf available and need low engineering effort to be adapted to a certain drive solution. Such applications work typically as follows:

- Valves are operated in the so called ballistic mode where the valves are not opened completely.
- This leads to tiny oil volume “shots” into the system, what causes only small pressure pulsations at a very low noise level.
- Due to the good repeatability of the switching valves the oil volume “shots” are very exact.
- The small stroke of the poppet leads to very low seat wear and thus a high durability of such systems.

Below some realized application examples are given:

2.1.1 Pressure and position control in presses as add on to a displacement controlled electrohydraulic drive.

Displacement controlled drives are well known for their high energy efficiency in case of typical operating modes (moving actuator with reasonable flow rates). As soon as such a drive comes to very low speeds or stand still at high loads the pump and the electric motor, respectively, operate in a poor efficiency region. This is typical for press drives when the press has to hold a certain pressure or position at high loads for several minutes up to hours. Here a simple digital hydraulic add-on can lead to much higher efficiencies.

Such an add-on has recently been applied on a sinter-press of a vendor of automotive components by LCM. Due to confidential reasons we are not allowed to show the real application but Fig. 1 shows the simplified hydraulic circuit of the implemented solution.

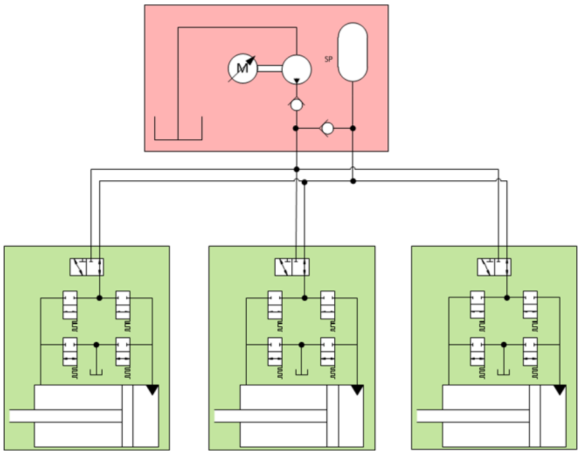


Fig. 1: Simple example for a digital hydraulic add-on.

2.1.2 Micro-positioning system for ANGER Machining

The micro-positioning system for ANGER Machining has been presented already in some earlier publications [8] but it is under permanent advancement. Since the system, which was implemented in milling machines for Daimler for the production of the 9-speed automatic gear (9G-Tronic) works completely flawless since 3 years, a new machine series was ordered and delivered in 2017 for another big player in automotive industry. The new system is now equipped with a digital hydraulic positioning system for all 3 axes but only for two workpieces (spindles) in order to machine more complex workpieces.

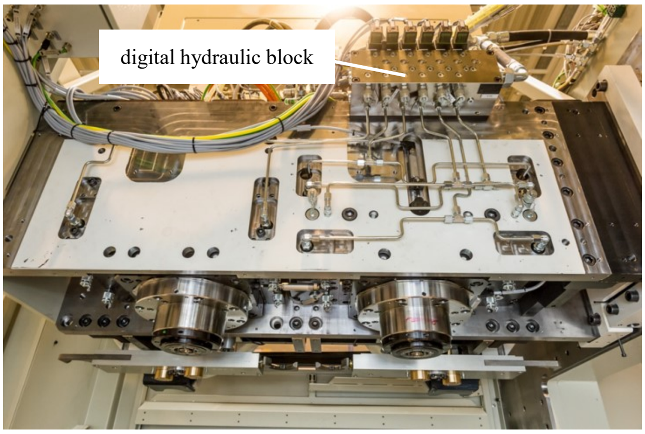


Fig. 2: Micro-positioning system for 2 Spindles in 3 axes

Due to cost reasons the system is now equipped with low cost parker valves GS02 and a B&R electronic hardware. In order to collect information on the durability of these valves, a condition monitoring system is implemented.

2.1.3 Calibration devices

One of the real big advantages of digital hydraulics is its achievable accuracy in pressure and position combined with extremely low power consumption compared to servo-hydraulic drive systems.

This was the reason to develop a system for calibrating torque measurement flanges for a big automotive supplier. With a very similar system to the ANGER micro-positioning

system it was possible to realize an accuracy within a band of +-0,02% (!!!) of the flanges measurement range.
Meanwhile the system is market-ready and will be sold to customers in early 2018. Due to confidential reasons and a pending patent it is not possible to give more details on this product. A publication of the product is planned in 2018.

2.2 High dynamic position and pressure control without a (main) focus on energy efficiency

The examples above are all characterized by low dynamics. Thus small pressure peaks due to small volume portions per switching cycle peaks are excited. What in turn leads to low noise emissions and low valve wear. Such a certain number of advantageous digital hydraulic solutions can be realized, but the majority of hydraulic drives work in a different mode of operation. Typically, high flow rates at high pressures occur several times in a normal cycle.
Whenever big power peaks are transferred over a fast switching valve it comes to significant pressure peaks in the system. Sometimes, with a clever system design, such peaks can be kept within some limits in order to realize systems without annoying noise levels.

There are different measures to keep such pulsations within a certain limit:

- Clever system design, where all Eigen-frequencies are in a sufficient distance to switching frequencies.
- Implementation of passive damping devices like hydraulic dampers, absorbers or RC-filters [9].
- Sophisticated operation modes like "Pulse Width Modulated control with Variable Carrier Frequencies" (PWMVCF) [10].

Though, efficient measures to overcome the mentioned pulsation problems are available such drives cannot be offered "off the shelf". It is always subject of a sound system analysis which needs a profound expertise of high dynamic (partly nonlinear) hydraulic phenomenon.
But once such an application is designed a number of advantages can be exploited. Examples for such applications are given below.

2.2.1 Gap control in rolling mill applications and paper mills

Hydraulic gap control is nowadays done with highly accurate servo valves which need to have high oil cleanliness and suffer on high leakage losses (80% to 90 % of the consumed power). Avoiding all the mentioned losses and the high effort of oil filtering legitimates to think on new solutions. Digital hydraulics can avoid both problems, and in case of a parallel architecture can give a higher robustness which is one of the biggest demands on hydraulic systems in steel mill applications. It was possible to show that the required performance can be achieved with digital hydraulics.

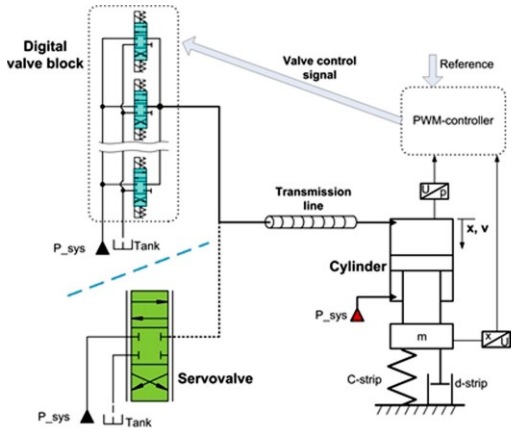


Fig. 3: Schematics of a hydraulic gap control actuator (digital- and servo-hydraulic) [11]

In Fig. 3 the schematics of gap control with analogue and digital principles is shown. For the digital version, a currently merchantable valve (Bosch Rexroth WES) which is qualified for digital applications was considered in this case to show the feasibility of the concept with state of the art components. The moderate nominal flow rate requires six of these valves to achieve the required positioning speed. The performance is comparable to that of servo valves with the expected benefit of higher robustness, longer lifetime, and considerable energy savings [11].

For paper mills a similar approach based on a PCM architecture has been developed by Tampere University of Technology and brought to market by Valtra.

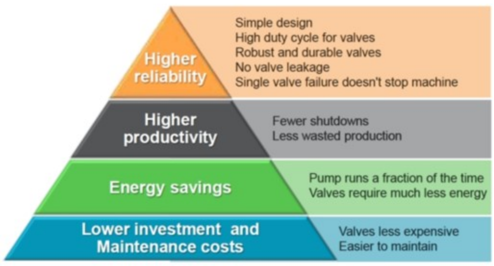


Fig. 4: Proven benefits of digital hydraulics compared to conventional hydraulics [12]

Fig. 4 shows the benefits identified by the customer after several years of operation. Lower investment costs are mostly a consequence of the low energy consumption compared to servo valves. This reduces the size of the supply unit dramatically and typically no coolers are needed anymore. Small supply units and a reduced demand on oil cleanness enables completely new system architectures, often the supply unit can be arranged directly at the drive what in turn piping and additional rooms for the former big supply units unnecessary.

2.2.2 Digital hydraulic tilting system for the Pendolino

At the Tampere University of Technology a new solution for the tilting drive of the finish Pendolino trains has been introduced 2 years ago [13]. Now after a long testing period the advantages of a digital hydraulic solution has been proven so far. One central requirement has been a higher availability of the drive system at lower energy consumption.

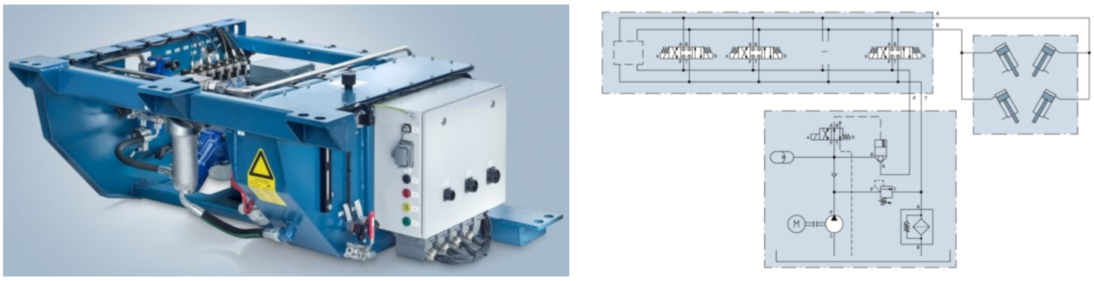


Fig. 5: Digital hydraulic drive system of the new Pendolino (Bosch Rexroth)

Fig. 5 shows the solution which consists of an axial piston pump, seven fast switching valves (SEC6) and some additional hydraulic components. The digital valves are operated via a standard series power electronic device. Due to the redundant architecture of the system a defective valve does not reduce the base functionality. Thus the valve can be replaced in a normal maintenance cycle.

Also the extreme conditions during the test phase from minus 30°C up to 25°C led to no problems. Due to the low energy consumption and the low maintenance costs the overall life-cycle costs of the system can be reduced significantly.

2.2.3 High performance digi-actuator

Some completely new approaches have been introduced in the latest digi-actuator of LCM.

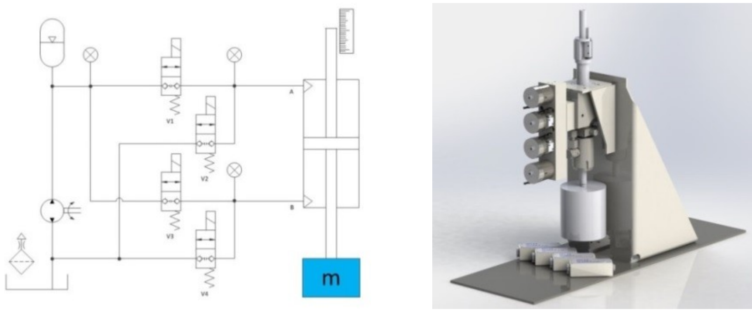


Fig. 6: left: hydraulic scheme, right: CAD-design of the demonstrator

In order to reduce the noise emission of digital hydraulic drives (LCM's switching valve FSVi can be driven up to 200Hz (ordinary switching mode, 500Hz max. ballistic mode)) the idea is to phase shift the valves at the opposite metering edges during control [10]. If the basic frequency is 200Hz (5ms period duration) and the nominal duty cycle is set to 50%, the specific valve on side "A" will be in "on-state" for 2.5ms, after that, the valve on side "B" will be switched. This leads to a frequency doubling effect in excitation of the system. Thus the movement of the cylinder is forced by the compressibility of the oil. As a result the amplitudes of the pressure peaks in the cylinder chambers A and B are reduced significantly what leads to a smoother movement and less noise. The controller was implemented such that both duty cycle and frequency can be changed simultaneously, so to say a "Pulse Width Modulated control with Variable Carrier Frequency" (PWMVCF).

An additional Advantage of this type of control type is, that the generated noise can be shifted into a frequency of some surrounding noise source so that the digital hydraulic drive cannot be recognized anymore. This was successfully tested in the lab of LCM.

2.2.4 Digital Displacement Machines

Digital displacement machines are playing a big role in digital hydraulics. Meanwhile highly attractive applications like wind power [14], wave energy [15] or automotive applications [16] are in a test phase. One of the main issues for DDM's is still a reliable long life time of the needed fast and big switching valve. Advances in valve development has been made recently [17], [18], [19].

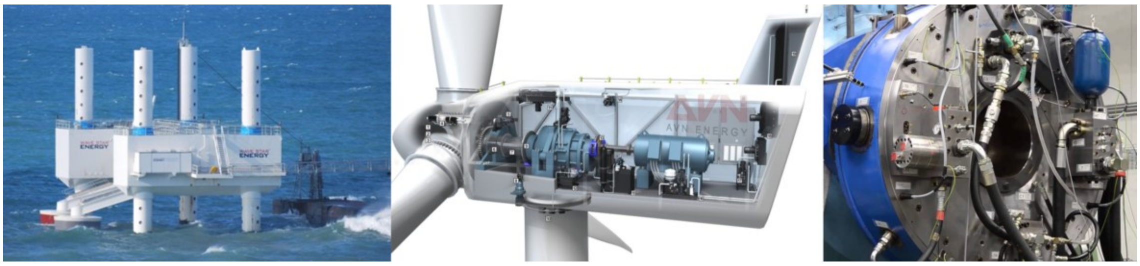
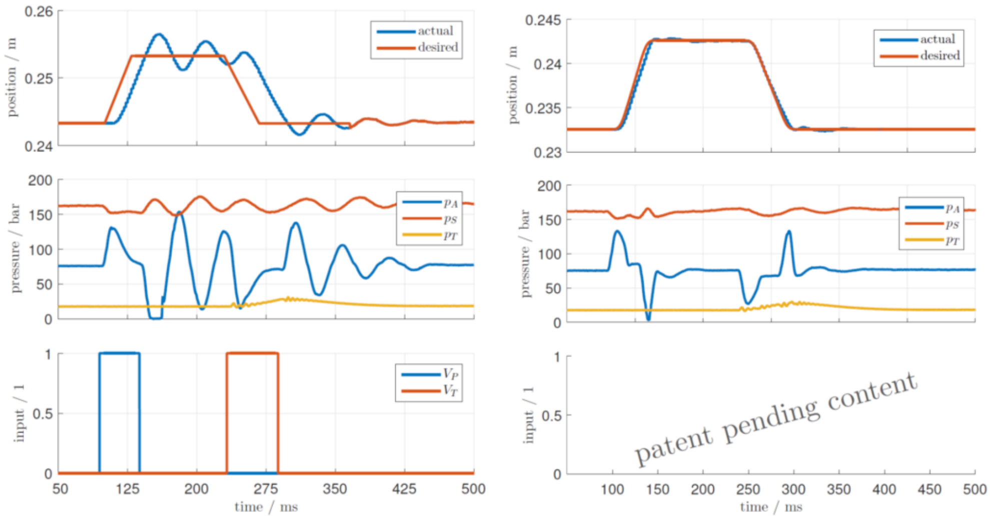


Fig. 7: Digital Displacement Technology in Wave and Wind Power

2.2.5 Optimized dynamic control of digital hydraulic drives

As already mentioned in case of high dynamic digital control pressure pulsations and consequently noise is a well-known problem which can only be reduced - but typically not completely fixed - by a sound and holistic system approach which causes some additional development effort. Additionally, hydraulic cylinders combined with servo valves are often used for linear drive actuation of heavy loads because of their high force density and good performance. Huge loads cause low natural frequencies of the drive, what slows down the closed loop response.

In some cases a very promising solution to overcome these problems is the so called High Dynamic Digital Control (HDDC) [20]. Such a digital valve control achieves the maximum physical dynamic response of a linear hydraulic drive. The feedforward control strategy is designed – it is generated some digital switching pattern - to the natural frequency of the drive in order to eliminate almost all oscillations of the hydraulic drive.



(a) Single Pulse Control (b) Optimal high dynamic digital control

Fig. 8: Measurements on a linear test rig

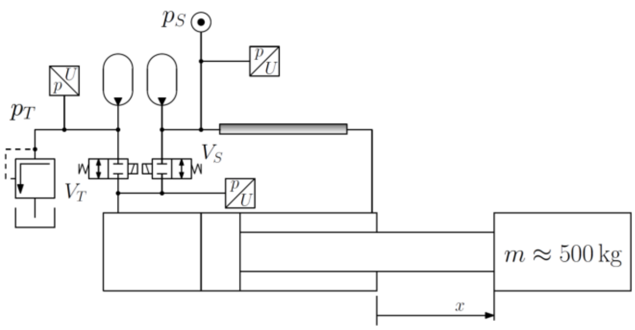


Fig. 9: Corresponding test rig

Measurements on a laboratory test rig (see Fig. 8) show a significant improvement in the dynamic response with the High Dynamic Digital Control (HDDC) compared to a digital single pulse control.

Due to confidential reasons (pending patent) detailed information will be delivered in upcoming publications.

2.3 Energy efficient position and pressure control exploiting converter principles or multi-chamber or multi-pressure actuators

2.3.1 Converter principles

The original idea of digital hydraulic was to transfer energy efficient switching techniques which have been used for decades in electrical engineering (switch-mode power supply units) into hydraulic drives in order to make hydraulic drives simpler, cheaper, more robust and to raise energy efficiency compared with resistance control.

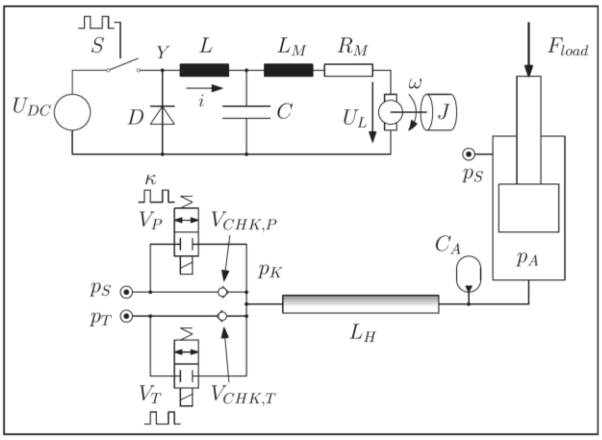


Fig. 10: EBC (Electric Buck Converter) and HBC (Hydraulic Buck Converter) schematics

Under some circumstances the tracking behaviour of the HBC is as good as that of a conventional hydraulic servo-drive, but the energy consumption is approximately only one half. One of the big advantages of such a converter is the possibility of energy recuperation.

Though, such converter principles (here just the Buck Converter is mentioned) are still not on the market, the author is convinced that such solutions will play a role in future hydraulic drive technology when energy efficiency of hydraulic drives in general will be a bigger issue.

2.3.2 Digital hydraulic multi-pressure actuator

A second approach to realize an energy efficient digital hydraulic system is the so called multi-pressure or multi-chamber principle. One of the latest publications [21] deals with the multi-pressure approach. The goal is to realize an energy-efficient digital hydraulic actuator by storing hydraulic energy locally at the actuators and charging the energy storage from the mean power supply line.

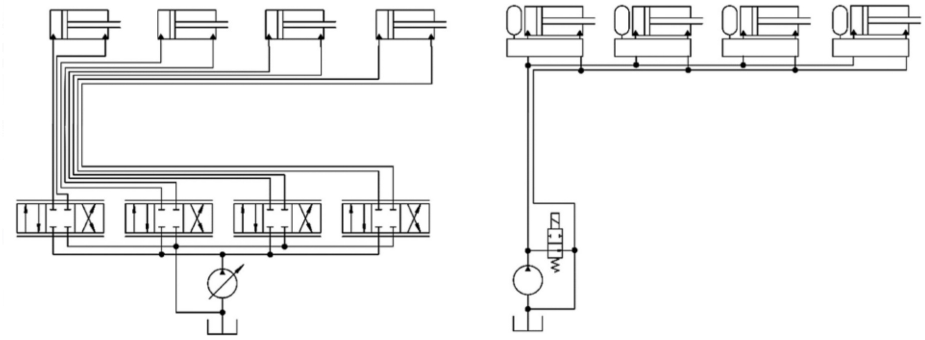


Fig. 11: Conventional drive concept (left) and digital hydraulic multi-pressure actuator (right)

In this system the supply unit can be sized according to the mean power of the actuators what reduces the size and costs of it often dramatically. Especially in mobile hydraulics, this is a promising approach.

2.4 Special purpose applications

Due to its high flexibility and range of functionality digital hydraulic can be implemented in a big variety of different solutions. Below some of these solutions are presented.

2.4.1 High accuracy sensorless hydraulic stepping actuator

Precise position control is a core function in a wide range of industrial systems. To realize a high precision normally a sensor in combination with a closed loop control is needed what. As a consequence costs for such a precise positioning system are quite high. Thus the avoidance of sensors without loss of accuracy is often required. Besides the sensor also cabling, connectors, and controller hardware drives the costs and risk of failure. Though, modern systems fulfilling needs on I4.0 and smartness additional position control is a must.

LCM and JKU presented an alternative solution for a hydraulic stepping actuator [22].

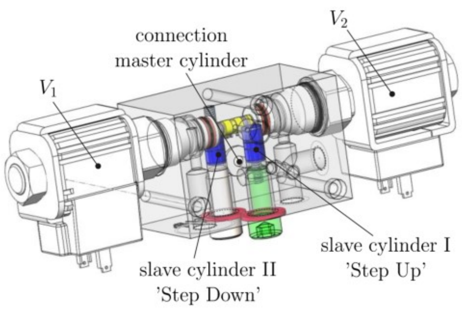


Fig. 12: Realization of the stepper unit

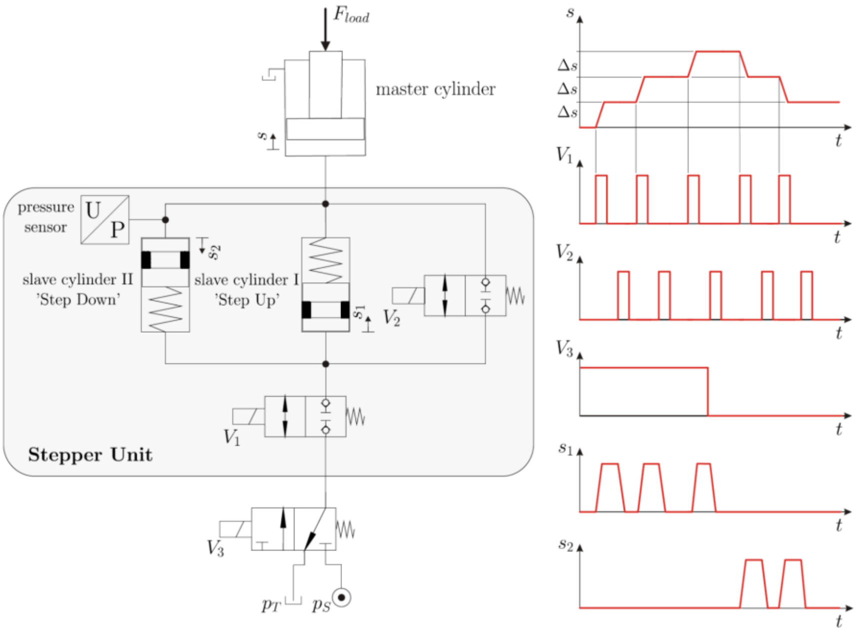


Fig. 13: Schematic and operation diagram of the hydraulic stepper unit

The position error is within ±0.8 µm and the relative error is less than 0.17 %. The new pressure compensated sensor-less stepping actuator meets typical design goals of hydraulic positioning systems. For low end applications the system is ready to market. In case of high end application some additional engineering is needed. The stepper drive uses leak tight seat type valves instead of proportional or servo valves. This results in a remarkably low energy consumption. Numerous applications like synchronization of cylinders, mobile application for construction machines and agricultural machines and also a huge number of industrial drives can take advantage of this technology.

2.4.2 Synchronization of serially driven hydraulic motors

One application which is now on its way to the market (market launch Q1/2018) is shown below. In this drive system two serially supplied hydraulic motors (motor 1 and motor 2) have to be kept exactly in phase to each other without a significant loss of energy efficiency.

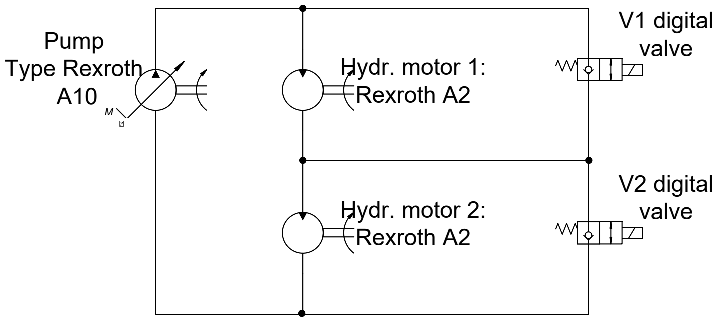


Fig. 14: Schematic of a synchronized dual-motor concept

This means that the by-pass flow over each motor lies in the range of their internal leakage and is quite low. Also in this case, seat type digital valves can be sufficiently accurate combined with lowest energy loss. Due to confidential reasons we have here also to refer on future publications for detailed information.

2.4.3 Digital hydraulic system for a magnetic refrigerator

Meanwhile digital hydraulics finds also attention in completely new fields. In case of cooling, digital hydraulics can be a promising technology for controlling the flow of the coolant. Projects with quite excellent results have been done at LCM for control of the CO2 coolant in new automotive climate control systems.

A group in Brazil [5] investigated digital hydraulics to control the coolant of refrigerators.

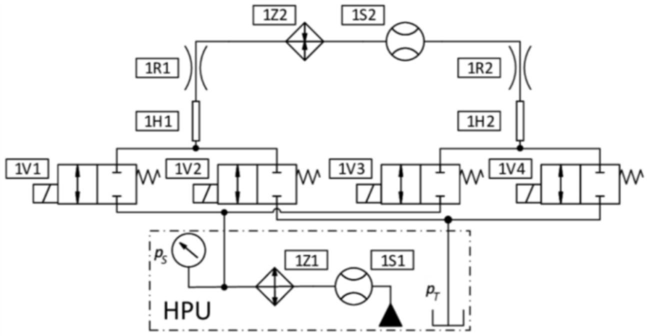


Fig. 15: Hydraulic system of the refrigerator

The power consumption of a solenoid switching valve system that would substitute the traditional rotary valve shows lower power consumption und thus improves the energy efficiency significantly.

3 COMPONENTS

To bring digital hydraulic forward not only new promising concepts are crucial but also new market ready components like digital valves, actuators and supply units are needed. In the last years more and more vendors are offering suitable valves which can be applied in digital hydraulics.

3.1 Digital hydraulic valves

In digital hydraulics the number of valves and their number of switching cycles is often high. Switching cycles in the order of 1.10^9 per year are quite common [23]. Additionally, for the power electronic devices also challenges in terms of mean power and peak current are given.

As already mentioned in the chapter 2, in most applications it is crucial when the used valves are leak tight.

Additionally, valves should be compact to limit the space requirement in case of multiple valves or to avoid parasitic hydraulic capacitances and inductances which might cause dynamic problems of the system.

Below the mentioned requirements are listed:

- High durability (switching cycles in the order of 1.10^9)
- Low cost by design suitable for mass production
- Low mean power consumption (<20W)
- Low peak currents (<20A better <10A)
- Cost efficient parallel power electronics
- Suitability for easy integration of a condition monitoring system
- Low leakage (best: zero leakage valves)

- Compact design

The Table below shows the ready to market valves for digital hydraulic applications.

	SUN DLV	Rexroth SEC6	Rexroth WES	Parker GS02-73	LCM FSVi4.1	Bucher WS22GD
						
Ts	10 ms	7-10 ms	5 ms	5 ms	< 3 ms	5-30 ms
Q_{N5bar}	0,12 l/min	7 l/min	45 l/min	1 l/min	5 l/min	1 l/min
Q_{max}	1 l/min	25 l/min	200 l/min	- l/min	25 l/min	30 l/min
p_{max}	350 bar	420 bar	350 bar	210 bar	300 bar	350 bar
f_{max}	13 Hz	40 Hz	10 Hz	- Hz	200-500Hz	- Hz
€	~100	~600	-	~70	~1500	~150

LCM's FSVi can be ordered for test applications in the prototypal phase. For a digital hydraulic serial system this valve can be licensed to a potential customer.

With respect to digital hydraulics a very promising valve concept is presented by Paloniitty et al. [24].

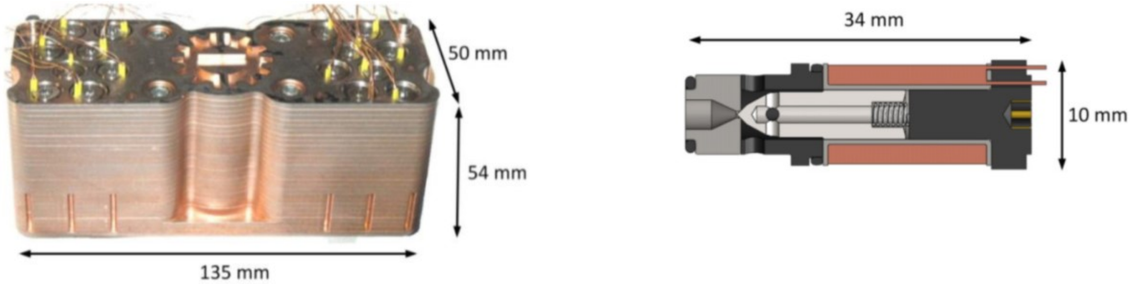


Fig. 16: Valve system prototype with CETOP 3 interface (left) and one of the implemented on/off valves (right)

Due to the sometimes high numbers of valves in digital hydraulics we suffer often by a big space requirement and also complex block design. Here such solutions will bring a big step forward.

3.2 Digital hydraulic actuators

Besides digital hydraulic valves one of the most interesting components is the so called multi chamber actuator (cylinder) to enable highly energy efficient digital hydraulic systems.

Fig. 17: Multi-chamber cylinder; simple approach by parallelization (IHA/L. Siivonen)

Multi chamber cylinders are basically cylinders with more than two active chambers. Additional chambers are typically used to realize a stepwise adaption of the process force on a constant pressure system.

4 CONCLUSION

Recent advances in digital hydraulics have mainly been made in the field of applications. In case of low dynamic high accuracy digital hydraulic solutions a number market ready solutions can be offered off the shelf. When it comes to high dynamic demands new promising methods (HDDC) addressing problems with noise and pulsations can be found in this paper. In case of components, manly for digital valves advances has been achieved in the last years. Due to the fact, that meanwhile very attractive solutions (Pendolino, digital hydraulic micro positioning, digital displacement units in wind power) have been implemented successfully in industrial applications, it can be detected that the interest of industry is constantly growing in this new technology. Besides this established applications a few new promising one are on their way to market products. This step by step increases the market share of digital hydraulics.

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