# ENERGY EFFICIENCY OF HYDRAULIC SYSTEMS WITH SHARED DIGITAL PUMPS

**Stefan Heitzig, Sebastian Sgro and Heinrich Theissen**

*RWTH Aachen University, Inst. for Fluid Power Drives and Controls (IFAS), Aachen (Germany)*
*stefan.heitzig@ifas.rwth-aachen.de*

**Abstract**

Conventional variable displacement pumps are being used instead of throttle controls if energy consumption of hydrostatic drives needs to be reduced. A new promising approach is the substitution of conventional "analog" pumps by digital pumps. A digital pump is composed of several parallel constant pumps and a number of switching valves. Digital pumps tend to have better efficiencies in partial load operation than conventional pumps.

In addition, digital pumps offer new concepts to supply several actuators in parallel without requiring throttle controls. The shared use of a digital pump for several actuators at once, compared to separate digital pumps for each actuator, tends to further reduce energy losses because of smaller installed total power and reduced partial load operation.

A study of digital pumps in a velocity control circuit is presented here with simulation results, comparing separate analog and digital pumps for each actuator vs. shared use of one digital pump for several actuators.

**Keywords:** digital fluid power, digital pump, constant pump, variable displacement pump, axial piston pump, radial piston pump, gear pump, hydraulic transformer, position control

## 1 Introduction

Fading fossil energy resources, rising fuel prices, and more and more restrictive emission standards cause developers of hydraulic systems to think about energy saving alternatives. In mobile equipment, displacement controlled hydraulic pumps operating hydraulic cylinders directly, and eliminating many of the throttling losses occurring in load-sensing or other valve controlled systems have been studied by Williamson and Ivantysynova (2010), and Zimmerman and Ivantysynova (2011).

Digital hydraulics is another new alternative, offering two different concepts of flow control: pulse width modulated systems (PWM) as presented by Ploeckinger et al. (2010) and by Long and Lumkes (2010), and pulse code modulated (PCM) concepts as presented by Linjama (2011). The second concept with several pumps operating continuously in parallel is the background for the study of digital pumps presented here.

During the last years, digital valve concepts have been investigated where proportional valves have been replaced by several simple on/off-valves in parallel, combining their individual flows in a stepwise, but almost continuous characteristic, for example by Linjama et al. (2009), Huova et al. (2009), Ijas et al. (2009), Juhala et al. (2009), and Lähteenmäki et al. (2010).

Digital pump concepts have been analyzed before where single cylinders of piston pumps are switched with valves, allowing the distribution of flow in intervals between several outlets or idle, by Ehsan et al. (1996), Salter (2005), Linjama (2009), Rampen (2006 and 2010) and Holland et al. (2011). Several studies about digital hydraulics have recently also been presented in a special issue of this journal (IJFP, Vol. 11, No. 3, Nov. 2010).

An array of continuously running pumps connected through a number of directional valves to several control valves and actuators has been patented by Schienbein and Kanter (2003). A pump-motor-transformer combining several continuously operating pumps of different sizes with a number of outlets was presented by Linjama and Tammisto (2009). In this system, the pumps are repeatedly switched on and off to achieve a desired mean pressure at the outlets, where a capacitance volume is located to equalize pressure and provide a continuous flow towards the valves controlling cylinder movement. A second output was connected to an accumulator to allow energy recuperation and power

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equalization. Linjama and Huhtala (2010) give a comprehensive overview over the different possibilities to establish digital pump structures, including a variant where output flow is directly coupled to multiple actuators without intermediate control valve.

## 2 Scope of this Study

The study presented here is based on simulations made at IFAS and analyzes digital pumps consisting of several rotating constant displacement pumps of different sizes, working continuously in parallel at constant speeds, e. g. with a common mechanical shaft. The flow of the individual pump "slices" contributes to the total flow of the digital pump through a matrix of on-off-valves. The combined flow is used to control one or more cylinder drives directly, not requiring intermediate capacitance or control valves other than the matrix valves.

A special focus has been on transient valve overlap effects when changing flow rates, on selecting suitable gradations for a double output digital pump, and on reducing energy losses during motor-mode.

Dynamic pump behavior has been analyzed by computer simulation with the simulation software DSH*plus*® (Fluidon, 2011).

## 3 Structure of Digital Pumps

The digital pump discussed here consists of an array of several constant displacement pumps, usually of different sizes, working in parallel. The individual pumps can be switched between load and idle by means of a matrix of on-off-valves when flow requirements change. An example is shown in Fig. 1. To avoid confusion with the different meanings of "pump", the following terms will be used in this study:

- Digital pump: Array of individual pumps ("slices") and a valve matrix.
- Shared digital pump: One digital pump supplying two or more actuators simultaneously.
- Slice or slice pump: One individual constant pump as part of a digital pump.
- Analog pump: Conventional variable displacement pump.

In principle, any pump type can be used to build a digital pump, as long as a suitable gradation of volumes is available. Designs that allow several units on the same shaft would be preferred. Since a digital pump consists of at least three and up to seven or more slices, it is certainly convenient to use pump types with a short axial dimension, e. g. gear or vane types. These allow an easier modification of volume, but are limited in pressure. Radial piston pumps are also suitable and would also allow higher pressures. A new radial design – not yet in volume production – that seems to be very promising for this application is the RAC radial piston pump, since it is short and the shaft is free from forces other than those related to torque transmission, allowing simple stacking on a common shaft (Berbuer and Schulze Schenking, 2012).

For a systematic comparison of concepts, all valves in this study are 2-way valves. Each row of the valve matrix is assigned to one of the slice ports, and each column of the matrix to one of the cylinder ports.

Digital Pumps can be designed for both open and closed circuit operation. A digital pump system with three slices driving one cylinder in an open circuit is shown in Fig. 1. Of the eight 2-way valves, six are needed to connect the three slices to either side of the cylinder. Two additional valves are required to facilitate return flow from the cylinder to tank, or to set slices into idle mode. If the slice pump volumes are gradated in a binary scale, e. g. (1, 2, 4), then seven flow rates from one to seven can be combined in both directions, plus two zero positions (floating and one side blocked).

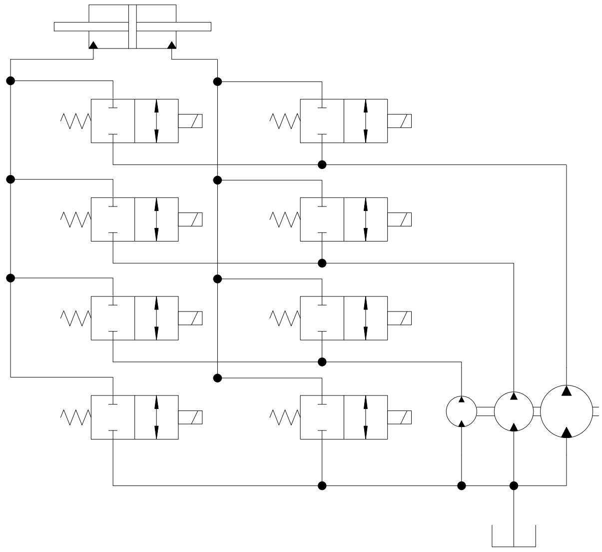

**Fig. 1:** *Digital pump in an open circuit*

Figure 2 shows the same pump and cylinder configuration as in Fig. 1 but in a closed circuit. It can be seen that now twelve valves are required to realize all potential connections. Again, seven flow rates can be chosen in both directions, plus two zero positions (blocked and floating). The closed circuit also allows four-quadrant operation.

Adding more valves creates a larger valve matrix and opens a potential for multiple outlets of a digital pump. The idea of a valve matrix as a control intermediate between pumps and actuators is very old (Nelson 1885). It has been used to allocate flow from a multi-pump supply to multiple actuators by Schienbein (2003) and by Rampen et al. (2008), with additional valves used to control pumps or actuators. The idea to use the valves in the matrix as integrated control instruments without any additional directional or control valves outside of the matrix has been described by Theissen (2009). One digital pump can then supply and control more than one actuator at a time with a minimal number of valves in each flow path and without adding up major pressure drops. This shared use of a digital pump will be analyzed further in this paper. It should be mentioned that conventional variable displacement pumps (analog pumps) do not offer this feature.

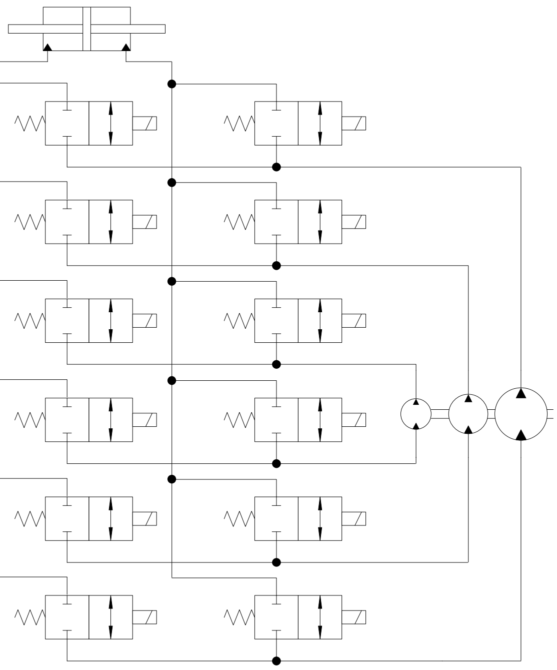

**Fig. 2:** *Digital pump in a closed circuit*

Asymmetric (differential) cylinders can be operated in closed circuits when pump sizes are graduated according to the area ratio of the cylinder, and need an additional column of valves for tank connection and volume balance. This also allows a fast forward mode for the cylinder.

## 4 Operation and Efficiency

It is assumed that the slice pumps within the digital pump are all driven with the same shaft speed. For control, 2-way on-off valves in a matrix layout are used. According to the position of the valves, each pump can be operated in three modes, as shown for one pump in Fig. 3. In pump mode, flow goes to the actuator moving it into the desired direction. In idle mode, fluid is circulated preferably at low pressure, either in a closed circuit or via tank. The third mode is motor mode: here the pump receives fluid from the high pressure side and acts as a motor on the common shaft. This mode can be useful in certain configurations to create more flow steps, subtracting certain amounts from the total flow. Efficiency of the digital pump, however, will deteriorate if some of the slice pumps operate in motor mode. The total flow of the digital pump is the sum of all individual flows multiplied with + 1, 0, or - 1 respectively.

In a closed circuit, switching between modes requires operation of two or four valves simultaneously. When two valves in the same matrix row connected to one of the pump ports are switched at the same time, they will open a temporary connection between two columns with different pressure levels, causing an undesired short circuit flow from the high pressure column to the low pressure column while partially opened. This short circuit is not only a loss of energy, it also disturbs the movement of the corresponding actuator. On the other hand, switching both valves consecutively will temporarily block the corresponding pump port, causing pressure peaks or cavitation. During the simulations it was found that a partial delay between the two valves would optimize pressure peaks, energy loss, and actuator movement. In this case with 50 ms total valve switching time, the best performance was found if the opening valves had a 42 ms (= 84 %) delay behind the closing valves. This is equivalent to a small underlap if multi-way spool valves should be used instead of seat valves.

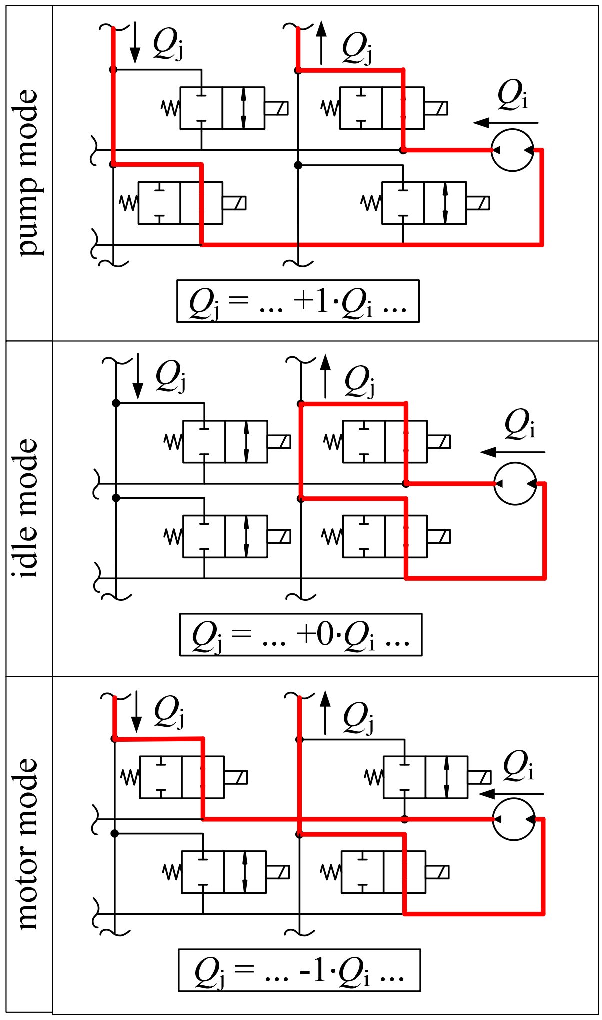


**Fig. 3:** *Pump and motor modes*

To demonstrate the dynamic effects, the actuator in Fig. 4 follows a sine course at 100 bar (10 MPa) load pressure. In the upper velocity graph both valves of a matrix row operate simultaneously, causing the temporary short circuits and severe drops in piston velocity. In the lower graph, these disturbances could be minimized by applying the above mentioned delay to the opening valve in each row. With lower load pressures, short circuits become smaller and valve delays could be reduced to minimize oscillations (Heitzig and Theissen 2011). This variable delay option has not been installed in the simulations in this study. Short circuits could also be reduced by additional check valves if these were ideal valves, but real check valves would also need time to react and further add to the pressure drop.

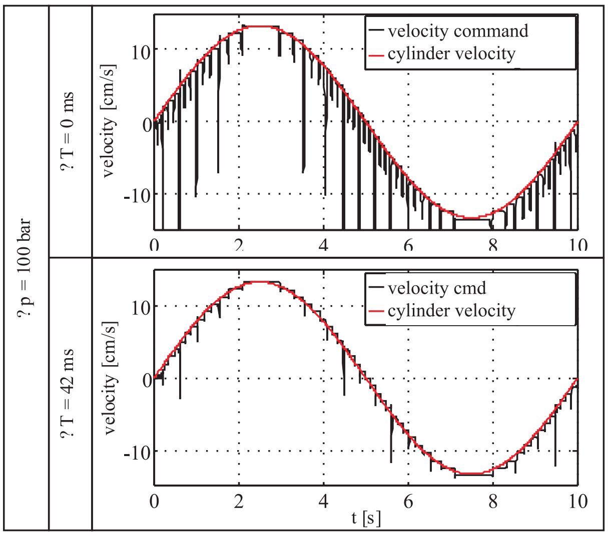


**Fig. 4:** *Piston speed at different valve delays (p = 100 bar)*

Analog variable displacement pumps have relatively high losses under partial load operation. Compression losses can even be higher than under full load. In digital pumps, in contrast, losses that depend on pressure like leakage or friction are reduced under partial load, because unused slice pumps are in idle mode running at low pressure. Hence, both pressure and flow reductions tend to reduce volumetric and mechanical losses here. An overview over these tendencies is given in Table 1.

**Table 1:** Loss tendencies of analog and digital pumps

| pump type | analog | digital |
|---|---|---|
| reduction of flow | | |
| volumetric losses | ⇨ | ⇩ |
| hyd.-mech. losses | ⇨ | ⇘ |
| reduction of pressure | | |
| volumetric losses | ⇩ | ⇩ |
| hyd.-mech. losses | ⇩ | ⇩ |

Figure 5 shows the efficiency characteristics for a binary-gradated digital pump and for an analog variable displacement pump at 2000 rpm. In this study, in order to be able to compare digital and analog pump efficiencies, data of a recent commercial axial piston pump are used for simulation in both cases. Both diagrams are based on data of a swash plate axial piston pump as supplied by a manufacturer. For comparison, the digital pump graph uses the maximum volume curve of the same pump as in the analog graph for all sizes of slice pumps. Any efficiency advantages that a constant pump may have over a variable pump were not considered in the comparison. Pressure drop losses ocurring in the valve matrix were also included at one bar (0.1 MPa) per valve.

The highest efficiency of the analog pump at full load is two precentage points better than that of the digital pump. This difference is due to the digital pump's valve losses. At partial load, the digital pump is better, especially at lower flow rates. This is due to the pressure relief of all unused slice units of the digital pump.

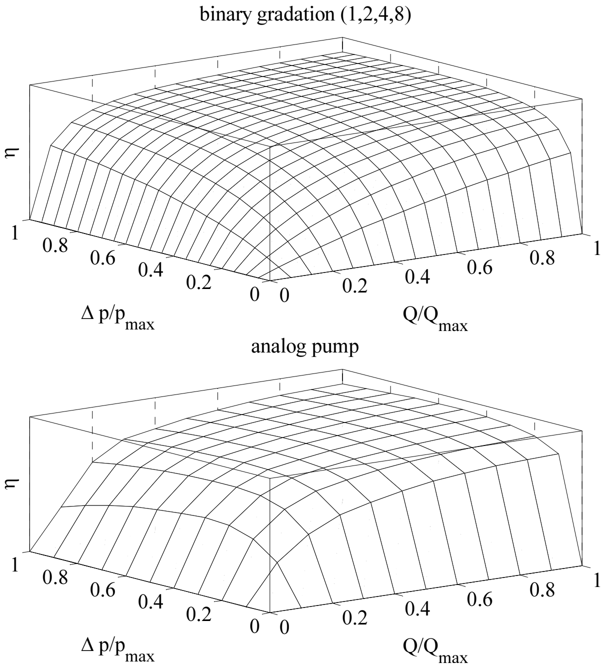


**Fig. 5:** *Efficiency characteristics of digital and analog pumps*

## 5 Separate and Shared Use of Digital Pumps

In contrast to analog pumps, digital pumps can either be operated as separate pumps for separate cylinders, or as one pump shared by two or more cylinders. Figure 6 shows two digital pumps separately controlling two cylinders. In Fig. 7, one digital pump controls two cylinders (shared use) via a valve matrix. The slice pumps can be connected to both actuators in a flexible way. It is important to note that the valves are either closed or fully open. Pressure drop in the valves thus depends on the size of valve chosen, but there is no intentional pressure drop as in a proportional valve.

The characteristic differences between both concepts will be studied. In the simulation model, two actuators move an object over a quarter circle path with different speeds. It is assumed that actuator 1 has a pushing load and actuator 2 a drawing load, opening a potential for partial energy recovery in simultaneous operation which is similar to excavator applications. This allows a demonstration how energy returning from actuator 2 can be used to help drive actuator 1. In this case, the shared digital pump acts as a hydraulic transformer and at the same time as a pump.

As has been mentioned before, in a digital pump only those slice pumps contributing to flow output operate at high pressure, while others run in idle with lower losses. This reduces the amount of partial load energy losses.

A further improvement can be obtained by shared use of a digital pump. For separate use, all pumps need to be dimensioned according to the maximum power requirement of the corresponding actuator. Shared pump operation allows a reduction of installed power yet maintains maximum power available to individual actuators. This increases the utilization of the pump and minimizes partial load operation.

Shared pumps also require less slice pumps, but need more valves to connect to the actuators, as can be seen comparing Fig. 6 and 7.

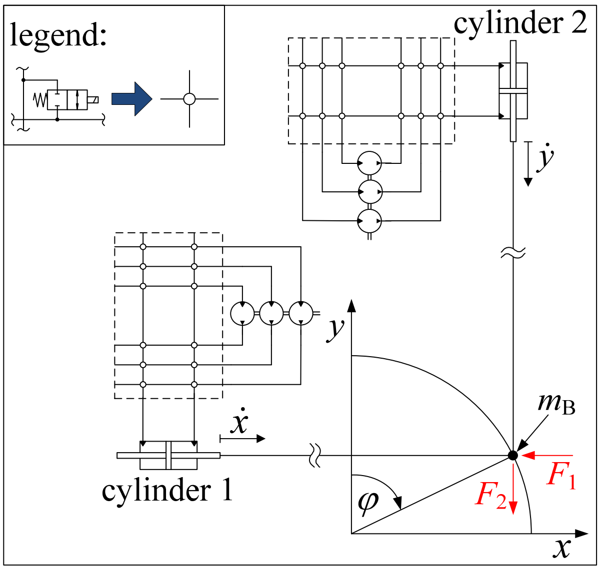


**Fig. 6:** *Simulation model for two separate digital pumps*

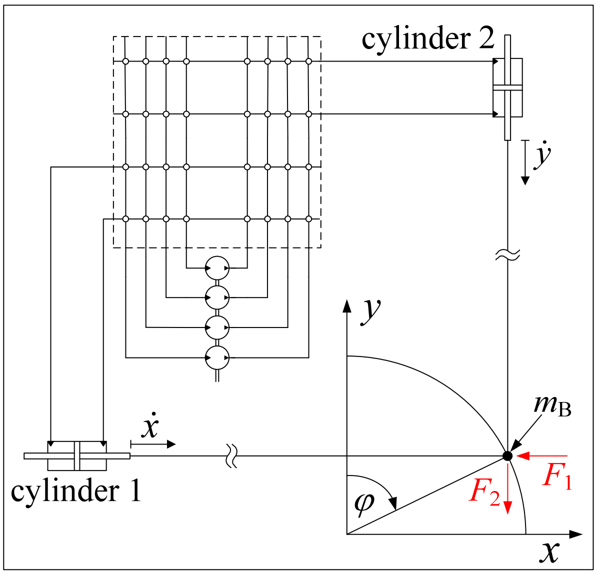


**Fig. 7:** *Simulation model for one shared digital pump*

## 6 Gradation and Resolution

By selecting the number and sizes of the slice pumps, the number of different total flow rates can be optimized, improving thus the resolution of the digital pump. A vast number of combinations is possible and a best selection must take into account the typical work cycle of the actuator. For the general study in this paper, simple mathematical sequences are preferred for the pump sizes, like binary (1, 2, 4, ...) or ternary (1, 3, 9, ...).

For separate use, ternary gradation provides a good resolution with fewer slice pumps than with binary gradation, but it requires some pumps to operate in motor mode for certain flow rates. This reduces the total efficiency at these flow rates, since pumps in motor mode generate losses without contributing to the output flow. If motor mode shall be avoided completely, then binary gradation is the best choice for resolution and efficiency.

Operating ranges of two systems with different gradation are shown in Fig. 8, one with four binary slice pumps (1, 2, 4, 8; 1, 2, 4, 8) per digital pump in box A, and one with three ternary pumps each (1, 3, 9; 1, 3, 9) in box B. Both systems achieve similar resolutions, ± 15 and ± 13. The little squares in the graphics represent one simultaneous combination of flows $Q_1$ and $Q_2$ each that can be addressed by switching the valves in the matrix. Since both pumps work independently, all combinations are possible.

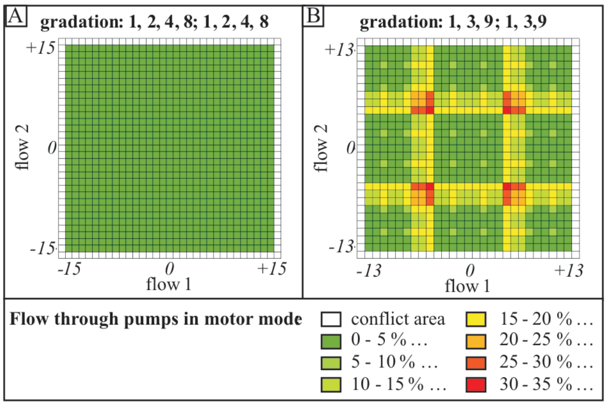


**Fig. 8:** *Operating range for two separate digital pumps*

The color coding stands for the amount of output flow of pumps in motor mode in relation to maximum flow, indicating reduced efficiency in this point. Figure 8 shows that the binary pump can cover the whole range without motor mode. The ternary pump in contrast can cover the range only partly in pure pump mode. Some areas have to rely on motor mode. For example, a flow of 5 would require slice pump size 9 to run in pump and slices 1 and 3 to run in motor mode.

As mentioned before, the binary pump is therefore more efficient, but requires more pump and valve components. In the analysis the ternary pumps will be used for a comparison of performance with the shared pump.

For a shared pump, the operating range is larger than for two separate digital pumps with the same rating, as can be seen in Fig. 9. The darker triangles in the diamond shaped graphic represent the gained operating possibilities. If one cylinder is requiring little flow or even stopped, more pumps can be assigned to the other cylinder.

While separate pumps have their resolutions available over all conditions, shared pumps have to be planned with more precaution. Since all slice pumps of a shared pump can be assigned to all actuators, but cannot drive two actuators at the same time, assignment conflicts occur in certain areas. The conflict areas where a certain combination of $Q_1$ and $Q_2$ is not possible are symbolically indicated in the graphic to the right in Fig. 9.

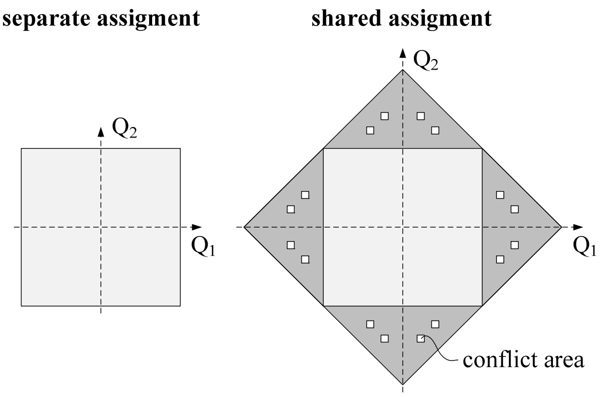


**Fig. 9:** *Operating range of separate and shared digital pumps*

Figure 10 shows a development of diamond shaped operating ranges for different gradations. With seven slice pumps in shared use and a double binary gradation as (1, 1, 2, 2, 4, 4, 8), a maximum resolution of ±22 can be reached (see box A). There are no conflict areas in this combination and no motor modes. This is a much better picture even with one pump less than in the comparable binary eight slice arrangement shown in Fig. 8 (box A).

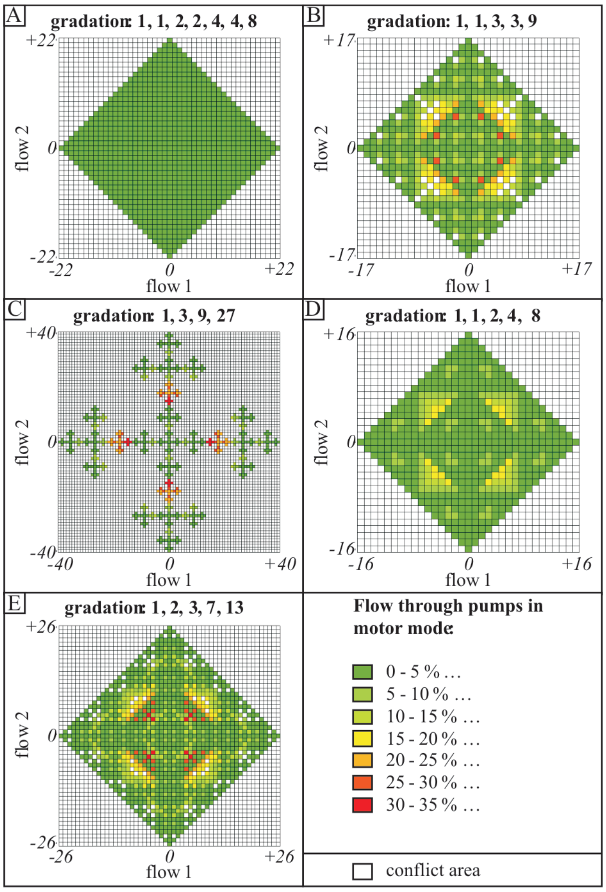


**Fig. 10:** *Operating ranges of shared digital pumps, different gradations*

Reduction of the number of slice pumps from seven to five with double binary or double ternary gradation not only reduces resolution but also requires motor mode fields in the diamonds (Fig. 10, boxes B and D).

A four slice pump ternary configuration as in box C, however, lacks redundancy and results in an operating range with large conflict areas, making simultaneous movements almost impossible. Only when one of the actuators is stopped, a good resolution on the other is obtained.

Leaving the simple binary or ternary sequences behind, a new combination of (1, 2, 3, 7, 13) was found to be a good compromise between resolution, efficiency and number of components. It is represented in box E in Fig. 10. This combination will be used for analyzing and comparing efficiencies between separate and shared pumps. The instances of motor mode are acceptable with 4.5 % in average. With only five constant pumps, 1309 different combinations of flows $Q_1$ and $Q_2$ can be addressed.

## 7 Path Control Challenges

To study simultaneous movements with two actuators driven by digital pumps, an object is moved along a quarter circle. Both cylinders are driven in an open loop control to understand the effects of limited resolution of the digital concept. For this purpose, a sine and a cosine curve are used as speed values for both cylinders, respectively. The path is followed at low speed (4 cm/s) and at high speed (13 cm/s). For the separate pumps case, the ternary configuration (1, 3, 9; 1, 3, 9) is used, and for shared use the configuration (1, 2, 3, 7, 13) is used.

Since some points in the operation range include motor mode with higher losses, an optimal operation point i* has to be found between the best points for low velocity error and high pump efficiency. This can best be achieved by minimizing a cost function C:

$$C = K_{CTR} \cdot \left\{ \left| \frac{\dot{x}_{cmd,a} - \dot{x}_{cmd,d}(i)}{\dot{x}_{max}} \right| + \left| \frac{\dot{y}_{cmd,a} - \dot{y}_{cmd,d}(i)}{\dot{y}_{max}} \right| \right\} + K_{EFF} \cdot \frac{Q_{Motor}(i)}{Q_{max}} \quad (1)$$

In this equation, $K_{CTR}$ is the weight factor for velocity error, and $K_{EFF}$ for efficiency. $\dot{x}_{cmd,a}$ and $\dot{y}_{cmd,a}$ are ideal (analog) values for velocities of pistons 1 and 2, $\dot{x}_{cmd,d}(i)$ and $\dot{y}_{cmd,d}(i)$ are the velocity set points for the digital pumps in a certain operation point $i$, and $\dot{x}_{max}$ and $\dot{y}_{max}$ are the maximum possible velocities of pistons 1 and 2 arising from the maximum output flow $Q_{max}$ of the digital pump. $Q_{Motor}$ ($i$) is a measure of losses and is the flow through pumps in motor mode in a certain operation point i. Modifying the weight factors allows to shift between energy optimized and precision optimized operation. For every time step, the optimal operation point i* is found by minimization of the cost function $C$. In the simulations shown in the following the focus has been on precision optimized operation.

The quarter circle is followed by the actuators on a polygon path, as shown in Fig. 11 at low speed. The angle of vectors from one point to the next is determined by the ratio of flow rates of both cylinders, which again depends on the point selected from the available operation range. At slow speeds the resolution of digital pumps is low, as only the inner portion of the operating range can be used. The polygons have 4 switch points for the separate pumps and 11 for the shared pump. Having only a small number of vector angles available, the error between circle and polygon is very visible, especially in the separate pumps system.

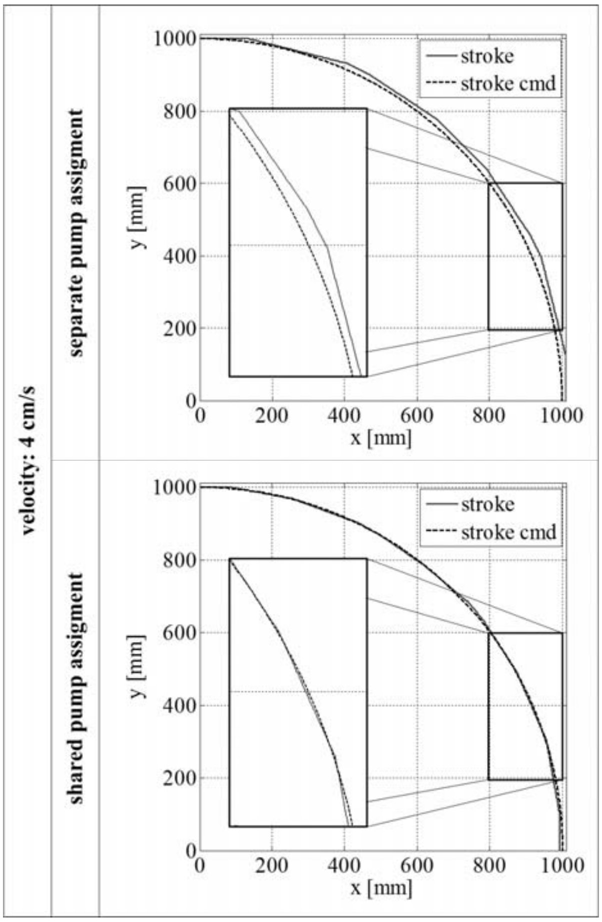


**Fig. 11:** *Precision of path control, separate vs. shared pumps at slow speed 4 cm/s*

Figure 12 shows the same situation as before, but with higher speed. In the outer portion of the operating ranges, more points are available for selection, and the number of switch points in the polygons is much higher (26 and 39), and the polygon is closer to the ideal circle.

A higher actuator speed allows a closer control, since more slice pumps are participating in the movements. At low actuator speeds, some pumps are permanently in idle mode, reducing the relative resolution and the number of choices for the controller. For future improvements, a proportional or switching bypass-valve could be used at vey low speeds as an option to support small movements without significantly sacrificing energy efficiency.

Since the purpose of the study was to understand the limits of the digital pump, all above simulations were performed in an open control loop. Closed control would enhance precision, of course. It would try to stepwise approximate the circle line, but also increase the number of valve movements.

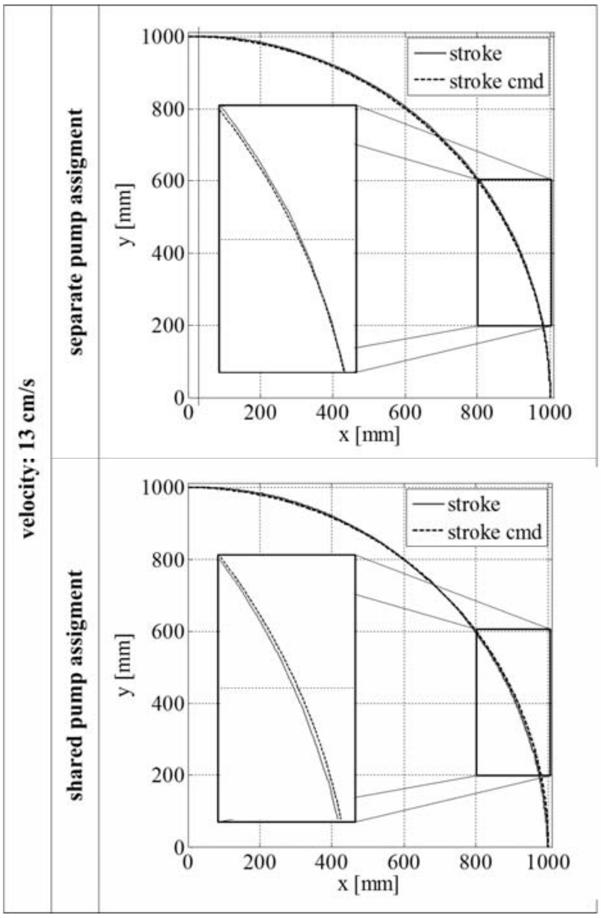


**Fig. 12:** *Precision of path control, separate vs. shared pumps at high speed 13 cm/s*

## 8 Energy Consumption Digital vs. Analog

A comparison between separate and shared operation with digital pumps has shown that the shared system is between 5 to 10 % more energy efficient than the separate pump system.

For an energetic comparison of digital and analog displacement control, the same quarter circle setup and data were used as in the previous chapter. The forces on the two actuators, one pushing and one drawing, were chosen to generate half maximum pump pressure (200 bar) in the cylinders. The energy returning from the actuator drawn outward is recovered and made available for the pushing actuator via the pump shaft.

Efficiency curves for all pumps were as shown previously in Fig. 5. Since an analog pump does not allow shared use, one analog pump was assigned separately to each actuator. These separate pumps must each be able to cover the maximum power requirement of the corresponding actuator. For the digital setup, one shared digital pump consisting of five slices with a gradation of (1, 2, 3, 7, 13) was used. The slices were modeled as constant axial piston pumps with the same efficiency characteristic as the variable pump, as has been shown in Fig. 5 at maximum displacement.

Figure 13 shows amount and structure of energy losses for analog and digital pumps at low and high piston speed. To perform the quarter circle path at low speed, the analog pumps require a total amount of

232 kJ mechanical energy input at the shaft, while the shared digital pump requires 145 kJ, which is a reduction of 38 %. A closer look at the structure of energy losses reveals that hydraulic-mechanical losses are the largest loss in the analog system. These are reduced in the digital system by approx. 60 % for two reasons: unused slice pumps run at low pressure with less friction, and the total installed power and hence pump size is less because of the shared operation. Volumetric losses are also reduced by 35 % in the digital system, because unused slice pumps idle at low pressure. On the other hand, the digital pump has additional pressure drop and switching losses in the valve matrix, totaling to 26 kJ.

At higher speed, the digital system also requires less energy, but the savings are much smaller than at low speed, as can be seen in Fig. 13. This confirms the assumptions made before, that digital pumps, especially in a shared configuration, have their main advantages at partial load operation.

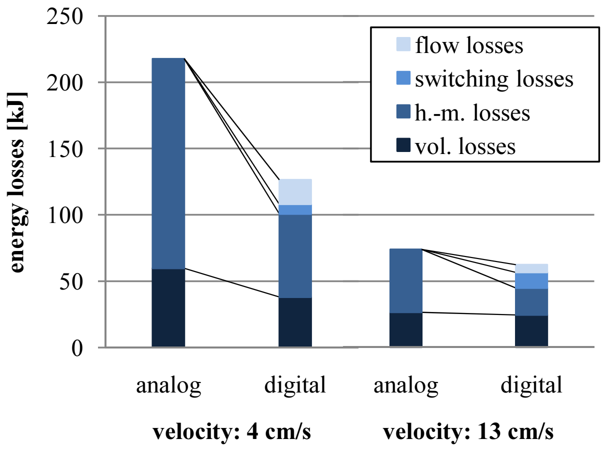


**Fig. 13:** *Structure of losses in analog and digital systems at different speeds*

## 9 Conclusions

Digital displacement controls with separate or shared assignment of pumps are a promising concept to improve energy efficiency of hydraulic drives. The number and gradation of individual pump slices in a digital pump are important factors influencing energy consumption and performance. Switching losses can be minimized by partial overlap of opening and closing movements of valves. The energy savings potential of digital pumps vs. conventional variable displacement pumps is especially high in work cycles with high amounts of partial load or low speed movements. In the simulations, a 38 % reduction could be observed.

Challenges worth further study are energy losses, pressure peaks, and oscillations caused by valve switching between the steps. Also, the resolution of speed steps can be poor at low speeds as less slice pumps are available, which could be addressed with proportional bypass valves for small flow rates. Efficient control algorithms have to be found to manage the complex decisions for step selection, optimizing between energy and precision.

The large number of frequently switching valves in the valve matrix can be a prohibitive cost and reliability factor, creating a demand for new low cost valve designs in the future. Noise issues could not be observed in the simulation study.

## Nomenclature

| | | |
|---|---|---|
| $C$ | cost function | [-] |
| $i$ | field number index | [-] |
| $K$ | weight factor | [-] |
| $p$ | pressure | [bar] |
| $Q$ | volumetric flow rate | [L/min] |
| $\Delta t$ | valve delay time | [ms] |
| $x$ | displacement co-ordinate | [mm] |
| $y$ | displacement co-ordinate | [mm] |
| $\eta$ | Efficiency | [-] |

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**Stefan Heitzig**
Received his Dipl.-Ing. in 2011 and is a member of scientific staff and Ph.D. student at IFAS. In 2009 won first prize in the "Fluid Power 2020" student contest. His diploma thesis was on comparing different digital pump concepts for position control.

**Sebastian Sgro**
Received his Dipl.-Ing. in 2007 and is a member of scientific staff and Ph.D. student at IFAS. His research interests include innovative concepts for energy recuperation in mobile applications and energy efficient working hydraulics.

**Heinrich Theissen**
After receiving his Ph.D. at RWTH Aachen University in 1983 under supervision of Prof. Backé, joined several companies in the manufacturing industry in Germany and in the U.S. In 2000 returned to IFAS to support the German Government's biobased lubricants program. Currently scientific director at IFAS, his main research interests are innovative energy conservation concepts for fluid power.