Discussion: Is the future of fluid power digital?

Imagine the scenario in which an electric motor company came to the (correct) conclusion that the power density of hydraulic pumps and motors is much higher than that of electric generators and motors. Then imagine that the board of this company gave the (wrong) instruction to the R&D department to utilize the concept of hydrostatic machines to develop electric actuators and pumps with the same power density as their hydraulic equivalents.

The reasoning of the board parallels the reasoning of the Forward Look article in which Rudolf Scheidl, Matti Linjama and Stefan Schmidt argue that the future of fluid power will become partly digital: “The overwhelming success of digital concepts in information, communication and power electronics, as well as the analogy between electrical and fluid power systems, suggest that digital concepts should be beneficial in fluid power”. Or, to recast this statement: “The overwhelming success of feathers for making birds fly, as well as the analogy between birds and fish, suggests that feathers should also be beneficial for fish”. In addition the authors emphasize that “the positive connotations of the word ‘Digital’ are good selling points”.

Do not be mistaken! I am a strong supporter of research in digital hydraulic systems, although I am not at all convinced that the future of fluid power will be digital. To quote Einstein: “If at first, the idea is not absurd, then there is no hope for it.” A lot of research in digital fluid power I consider to fall in the category ‘absurd’, in the sense of ‘out of tune’ or ‘dissonant’ with the ruling technology, and I am very curious to see what will be useful in the end.

The idea to copy successful electrical concepts in the design of hydraulic systems and components is as old as the hydraulic industry itself. Examples are ‘fluidics’ or ‘fluidic logics’ in which a fluid flow is directed in order to perform analog or digital operations, similar to electronic devices. The authors of the Forward Look article refer to another example, AC hydraulics, in which the principle of a three-phase a.c. network is converted to a three-phase alternating flow network.

Other examples are ‘switched reactance hydraulics’ and ‘PWM electrohydraulic control systems’. Aside from some niche applications, none of these promising developments has been applied successfully in the market.

In 2011, Linjama presented an overview of the state-of-the-art of digital fluid power. In that article he defined digital fluid power: “Digital Fluid Power means hydraulic and pneumatic systems having discrete valued component(s) actively controlling system output. Digital fluid power does not mean digital control of analogue components. Some borderline cases are the control of valve spool by using stepping motor or bang-bang positioning of actuators.”. Linjama furthermore distinguishes between “parallel connected systems” and systems based on “switching technologies”.

Wang, et al. classify three different digital hydraulic systems.

1. “The first type is the traditional on–off technology in which the system output has only two discrete values, such as pump/motor rotating or stopped, cylinder moving or stopped.”

2. “The second type is the digital hydraulic system consisting of parallel-connected on/off valves. The system is truly digital as the system output has only discrete values. The on–off valve development and the control technique have resulted in extensive research of this technology since 2000. The system is fault tolerant and the failure of a single valve does not prevent the use of the actuator. However, a rather complicated controller is required for the synchronous valve switching. Moreover, large numbers of valves are needed to achieve high flow rate resolution.”

3. “The third type is the switching hydraulic technique which imitates the principle of switch-mode power electronics. The switching technique relies on fast valve switching and the main benefits of this technique are continuous output and simple hardware. The purpose is typically to produce a smooth analog output by using high-speed on–off valves. Applications of the switching technique include ABS and fuel injection in modern vehicles and agriculture machinery. It has also found application in the fan drive system of mobile machinery.”

The Forward Look article significantly expands the world of digital fluid power. The authors seem to suggest that digital pumps, AC technology, and even conventional displacement pumps and motors could be regarded as digital systems or components.

I have always considered it difficult to judge the strength, weaknesses, opportunities and threats of digital hydraulics, without first making a clear definition of...
the term. I would certainly not include ordinary posi-
tive displacement pumps as a digital fluid power com-
ponent, simply because (as the authors suggest) the
principle is discontinuous. If this were true, then d.c.-
motors, having a commutator, would also be digital
electronics, which is obviously not the case. I would
also not consider a hydraulic pump, which incorporates
solenoid operated on–off valves for each cylinder, as a
digital pump, just because electronically controlled
valves replace the port commutation of a valve plate.

It would have been wise if the authors had stated a
clear definition of the term ‘digital fluid power’. It would
have been perfectly acceptable if they had adopted two
or more definitions, for instance, if they had followed
the distinction between ‘parallel connected on–off
valves’ and ‘switching hydraulic control’ systems, as
long as these different systems are treated as different
systems, having different opportunities and threats.
There seems to be a common, overlapping area, since
both systems rely on high-speed on–off valves. But the
operating frequency, the dynamic requirements and the
durability constraints are very different, depending on
the application for parallel-connected on–off valves or
for switching hydraulic control.

Parallel valve systems have been studied at Tampere
University of Technology: there is indeed an analogy
with the electronic system proposed by Flügge-Lotz and
Taylor. Both systems utilize a Boolean logic operating
system in which multiple, parallel-operated actuators,
with different gains can be switched in different logic
combinations. In the Forward Look article, the authors
claim that these combined valves can be manufactured
at a lower cost than proportional valves. They also state:
“switching valves have the potential to become very comp-
act and light components’. This is somewhat contrary
to Linjama’s article on ‘Digital fluid power – state of
the art’ in which he mentions that “physical size and price”
are at least a challenge. Furthermore he states that
noise and pressure pulsations, and the complicated
and non-conventional control, are challenges. I believe
the term ‘challenge’ is a euphemism. In terms of a
SWOT-analysis I would rather talk about weaknesses.

The second branch of digital hydraulic systems, as
defined by Linjama are analogous to switch-mode elec-
tronic systems, like switched reluctance motors,
switched-mode power supply and switched buck con-
verters. These systems rely on the availability of high-
speed, high frequency on–off valves. There are several
interesting valve developments, like the developments
at Linz University and at Minnesota University.
Switched-mode hydraulics are, for instance, applied in
the hydraulic transformer that was patented by
Dantlgraber. Hydraulic free piston engines, with
pulse–pause modulation of the piston frequency
could be considered to belong to this group.

One of the first research groups to investigate this
type of hydraulic system was the ‘Republic Aviation
Corporation’. In 1963 Pollard conducted research on
‘Hydraulic pulsation concepts’. This was an attempt to
utilize electric and electronic principles in the fluid
power domain: “The use of an electrical analogy was
considered as a basis of pulsating system analysis, and a
block diagram representation of a typical system was
derived.” A year later, the final report on the program
for “Research Investigation of Hydraulic Pulsation
Concepts” was published. The report outlines and
studies the basic principles of ‘pulsating hydraulics’,
including the use of high-speed alternating valves and
hydraulic transformers. Just like the authors of the
Forward Look, the report concludes that, “for the spe-
cific applications involved … pulsating hydraulics will
not only be more reliable and lighter in weight, but also
efficient than continuous flow systems.” However, the
authors also conclude “the system efficiency is very sen-
titive to the system load impedance.”

As mentioned earlier, the authors of the Forward
Look article do not clearly differentiate the advantages
of fluid power between parallel valve systems and
switched mode valve systems. It is, therefore, unclear if
the authors really intend to attribute all of the men-
tioned advantages also to this type of digital fluid
power. If that is the case, the authors are of the opinion
that systems based on high-speed, high-frequency
valves have a high reliability and robustness and are
insensitive to oil contamination. I have strong doubts
that this true. Impact wear and hammering of the valve
seats are enormous ‘challenges’. I am not the only per-
son with this concern. Linjama, one of the authors of
the Forward Look article, mentions elsewhere7 that
“durability and life time with switching technology” are
challenges. I would also not underestimate the cost of
the electronic drivers, sensors and actuators that are
needed for these systems. Linjama mentioned noise and
pressure pulsations as a challenge: I would add effi-
ciency as an additional challenge. In our own research
on switched mode hydraulic systems, we noticed how
critical the timing of the valve opening was with respect
to the pressure waves in the output line. Since in most
applications, for instance the arm cylinder of an excava-
tor, the load impedance changes constantly, it is
almost impossible to obtain a correct timing and, there-
fore, achieve a high efficiency.

In spite of these comments, I believe that the
research on digital fluid power will bear fruit. To
quote Einstein once more: “in the middle of difficulty
lies opportunity”. Digital fluid power could be very
beneficial for the control of variable displacement
hydrostatic pumps and motors (and transformers).
This was suggested by Sosnowski et al. in 1998. I
can also appreciate the benefit of having ‘hybrid’
solutions in which digital fluid power systems and
conventional continuous flow systems are combined.
In this respect I can agree with the final conclusion of
the Forward Look article.
P. Achten
Innas BV, Nikkelstraat 15, 4823AE Breda,
The Netherlands.
Email: pachten@innas.com

Authors’ Response

The authors welcome Peter Achten’s comments. They have initiated a thorough discussion which is a major purpose of a Forward Look article, and helped to bring more clarity to this subject. In response to Peter Achten’s critique we would add the following.

The authors did not intend to provide an article embracing clear terminology, definitions, and structure. For the time being and in view of the rapid development of digital fluid power (DFP), it may be more convenient to see what evolves and to make definitions and categorizations at a later date. A definition of DFP that represents the current state is, ‘Digital fluid power means hydraulic and pneumatic systems having discrete valued component(s) actively controlling a system output’. Ultimately, it is only relevant if all the R&D activities around DFP generate new solutions that solve some drive and actuation problems better than existing techniques.

It was not the intention of the authors to categorize conventional pumps as digital components. They just wanted to point out that sudden changes of states and structure are quite common in fluid power and these do not constitute an inherent weakness of DFP. Digital pumps, however, may be justifiably classified digital. A traditional pump rectifies flow by passive components. A digital pump-motor uses on–off valves actively to control the output of a system. Flow pulsations produced by pumping pistons can be rectified as in traditional fluid power technology; but this is one special case only. Digital control valves create great flexibility for a pump, allowing optimization at different operation points, also operation as motor, partial and idle strokes, faster response, etc. This calls for intelligent control.

A d.c. motor does not have any active discrete value component to control the system output, and no intelligent control. In this way it corresponds to a traditional hydraulic motor. An a.c.-motor with a frequency converter is digital, because it utilizes discrete valued power electronics together with intelligent control.

Looking for analogies and trying to transfer successful concepts from one field of engineering (electronics) to another (fluid power) is just an approach for finding new ideas. It does not guarantee success and requires considerable R&D work. Systems from different fields that employ analog principles may look quite different in detail and may require new component technologies. Employing Peter Achten’s bird and fish allegory: wings become fins and feathers fish-scales.

The statement that the success of digital electronics makes digital fluid power attractive to customers concerns only the marketing aspect, it is not seen as the guarantee for success. A high openness from potential end users was identified, e.g. in the four DFP workshops, organized so far. The authors are well aware that the fulfillment of these high expectations needs considerable R&D work. Systems from different fields that employ analog principles may look quite different in detail and may require new component technologies. Employing Peter Achten’s bird and fish allegory: wings become fins and feathers fish-scales.

References

The question of cost is presented in our paper and is basically the same as that offered by Achten when he discussed his floating cup principle in a SCIFP05 paper. To quote “The floating cup principle is designed as such that many of its components can be produced by means of deep drawing, extrusion, sintering and other modern, non-machining production technologies. A cost study, which has been performed together with the industry, has proven the strong cost reduction potential of the floating cup principle.” Every word is true for modern mass produced digital valves. They are already used in fuel injection systems of most cars.

There is a substantial efficiency gain for parallel connected valve systems, provided independent metering in and out is employed to minimize unnecessary back pressure and switch to a regenerative control mode, when possible. Studies predict 30%-60% reduction of valve losses.

Switching systems can be made durable and reliable, as shown by the fuel injection valves of diesel engines. They perform 100 million strokes per year, i.e. over a billion during the lifetime of a car. This happens for every cylinder and every car for pressures up to 2000 bar and at varying temperatures. Switching technology is the only fast, accurate and reliable approach for this application. Jumping from hydromechanical fuel injection to digital injection with intelligent control has resulted in great improvement in the performance, pollution and fuel economy.

M Linjama
Tampere University of Technology,
Tampere, Finland
R Scheidl
Johannes Kepler University Linz, Austria
S Schmidt
Bosch Rexroth, Lohr am Main, Germany
Email: rudolf.scheidl@jku.at