WHAT MAKES NEW IDEAS IN FLUID POWER SUCCEED?

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INTRODUCTION

The field of fluid power components and systems is characterized by a continuous evolution, intended to improve functionality, to reduce constructional effort and thus costs. In many cases, these improvements are due to advances in related technologies, such as electrics, electronics, computer science, control technology, or material sciences.

During the decades in which fluid power has been used, completely new ideas and innovations have appeared every now and then that seemed capable of accomplishing certain tasks in a better way. Any innovative new design must not only fulfil a particular task, it must do it at a better price than extant technology, or else it must offer additional functionality in order to justify higher prices.

After mentioning some flops in the history of Fluid Power this paper shall chart the reception that some new ideas and develpment have received. Examples treated here are:

- Secondary control
- Free piston motor and hydrotransformer
- Valve actuation
- Noise reduction
- Bus technology
- Fuel cell

Of course there are some more important new developments in Fluid Power, for instance Servopneumatics or Functional Fluids (ERF, EMF or ECF). But not all of them could be treated.

FLOPS IN THE HISTORY OF FLUID POWER

There are periods in the evolution of fluid power during which an effect will suggest itself for tackling particular tasks. Once other technical means allowing those tasks to be accomplished in a superior manner appear, the effect will soon be forgotten. One example to be mentioned is fluidics.

In the 1960s and early 1970s, Fluidics appeared, an approach realizing binary switching functions or steady control functions through the mere interaction of air jets, without any moving parts. [1] [2]

Figure 1 shows some effects utilized for this purpose: the Coanda-effect, the disturbance of a laminar jet, or the vortex-chamber effect. At that stage, whilst transistor technology still was in its infancy, one was of the opinion that the packing density of pneumatic logic elements could exceed that of transistor circuits. However, soon the trend towards miniaturizing electronic components started, which continues to the present day and which has led to incredibly high packing densities.

One of the main disadvantages of fluidies was the low signal propagation speed. Although considerable investments were made into this technology, hardly any remnants are to be found today. Another idea that didn't gain acceptance in practice was the ''Alternating Flow Hydraulics'' (AFH).

That was the attempt to make fluid power mirror the shift from direct-current to alternating-current energy transmission that took place in the electrics.
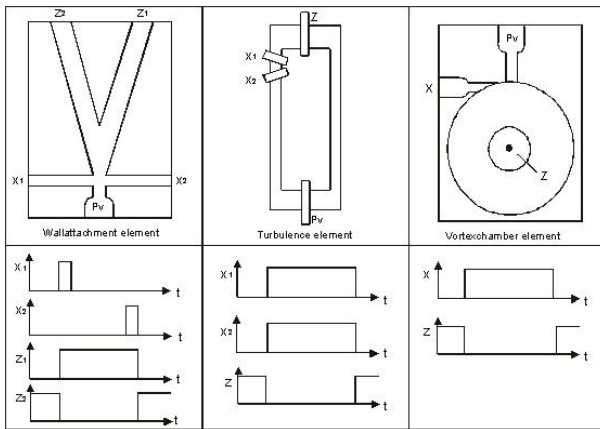

Figure 1: Fluidic elements

SECONDARY CONTROL

In the late 1970s and early 1980s, two institutions (Rexroth and IHP, now IFAS) independently developed the so-called secondary control. [6] [7] It occupied the hitherto-empty field (IV) in the methodology classification scheme for the control of fluid power energy (Fig. 2). It represents a displacement control with impressed pressure.
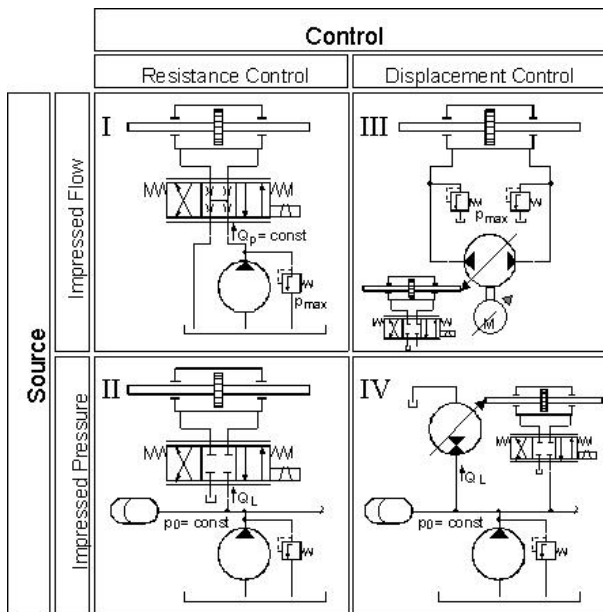

Figure 2: Methods of controlling hydraulic power

As Fig. 3 shows, an internal control loop is required for the various control tasks such as speed-, position- or torque-control, which ensures that the motor is stroked

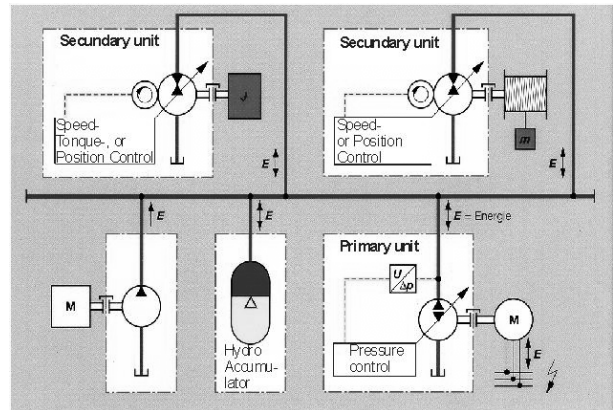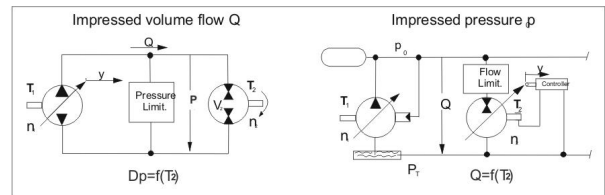back under decreasing load, to prevent it from picking up unlimited high speeds.

Figure 3: Secondary controlled displacement unit at a net of impressed pressure, (Source: Kordak, Rexroth)

Figure 4 lists the characteristics of displacement controls with variable pump and impressed volume flow and of displacement controls with impressed pressure:

- Singel Drive
- Closed Loop
- $n_2 = Q/V_2$ fixed
- Fourquadrant Drive in closed Loop
- Dynamics determined by hydraulic and mechanic Time constants
- Overload Security by pressure Limitation

- Energy recuperation in Gyroaccumulator/ Electr. Net

- Multiple Drive
- Open Loop
- n_2 determined by control
- Fourquadrant Drive in open Loop
- Dynamics determined by mechanic Time constants
- Overload Security by Flow- or Speed-Limitation
- Energy recuperation in Hydroaccumulator

Figure 4: Characteristics of drives with displacement control

Based upon this comparison in fig. 4, one might assume that both systems are equally likely to be used. Yet the variable motor attached to the constant pressure net has a number of drawbacks limiting its applicability.

- It is not suitable for the direct control of cylinder drives, because a variable displacement motor is required (variable cylinder drives are still waiting for a brilliant inventor).
- For drives that frequently stand still or are charged only with low torques, more leakage oil occurs than would be the case with the hydrostatic transmission. In the latter, the pressure drops whenever it is idling, and little leakage occurs.
- Furthermore, an internal control of the displacement volume is required in every case.

This is not the case with pump control (impressed volume flow).

One typical application, in which the constructional effort can be considerably reduced, is the bucket-wheel excavator, which often runs with high loads over a long period.

An interesting new application is the Flap Power Control Unit of the Airbus A 380. This unit, schematically depicted in Fig. 5, actuates the plane's flaps within a closed position-control circuit by means of 2 variable motors and a planetary transmission, via shafts and gears. With a supply pressure of 5000 psi, the all-in weight of the unit is approx. 58 kg, including the planetary transmission and the safety brakes. Through the use of variable motors in secondary control (VDHM), the efficiency could be increased by approx. 30 % over the valve control of constant motors (FDHM).
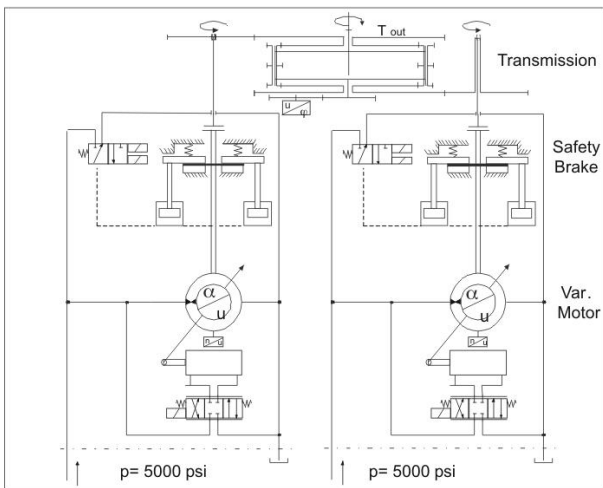

Figure 5: Flap power control unit, Airbus A 380, (Source: Liebherr)

FREE PISTON MOTOR AND HYDROTRANSFORMER

In mobile machinery, the diesel engine serves as the primary energy source, powering rotating pumps for the wheel drive and the working hydraulics. Early on, the idea was mooted to transform the energy of the combustion engine's piston into hydraulic energy by means of a linear motion, without any rotating parts. Such a free piston engine might be used to feed a constant pressure net required for the secondary control with variable motors. Several institutions are currently engaged upon developing different concepts for free piston motors, shown in Fig. 6. As the free piston motor only conducts a single displacement stroke per working stroke, the irregular volume flow that it delivers has to be smoothed by means of accumulators on the pressure- and suction side, as shown in Fig. 7 for the twin-piston

motor. That motor oscillates with the system's natural frequency. [8]

1. Combustion Chamber
2. Compression-Cylinder
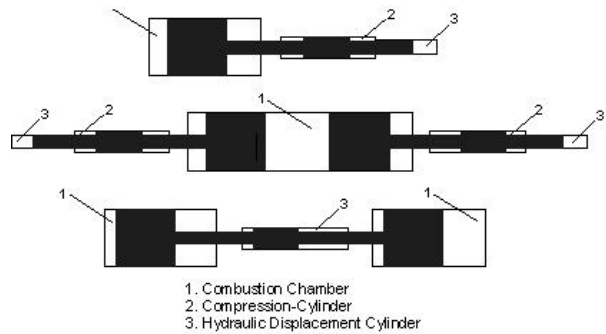3. Hydraulic Displacement Cylinder

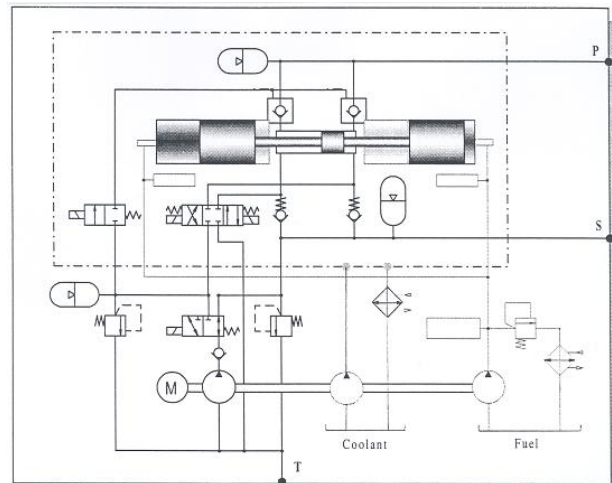Figure 6: Concepts of free piston engines, (Source: Tikkanen, Vilenius)

Figure 7: Schematic drawing of a dual hydraulic free piston engine unit, (Source: Seppo Tikkanen)

As already mentioned, it is impossible in secondary control to generate longitudinal motion via pistons and cylinders, because one requires a variable displacement unit. If energy for the actuation of cylinders is extracted from the constant pressure net through valves, high throttle losses occur within the valves.

Even during the development of the secondary control, the idea of a hydrotransfomer enabling the extraction of a controlled oil flow from the pressure net without incurring large valve losses was pursued.

Such a hydrotransformer consists in two coupled displacement units, of which at least one is variable and speed-controlled. Figure 8 shows such a conventional hydrotransformer. The company INNAS [9] succeeded at integrating the functionality of a hydrotransfomer into a single displacement unit. A prototype of that transformer is shown on the left-hand side in Figure 9.

The transformer is adjusted by turning the port plate, which in this case has three rather than two control kidneys.
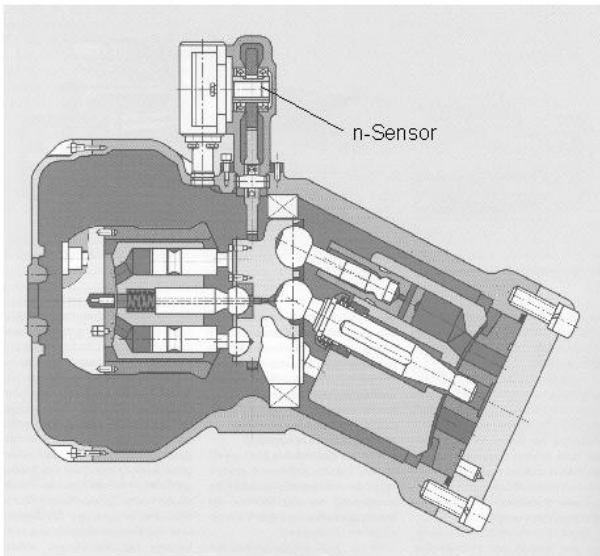

Figure 8: Hydraulic transformer with bentaxis displacement units (Source: Mannesmann-Rexroth)
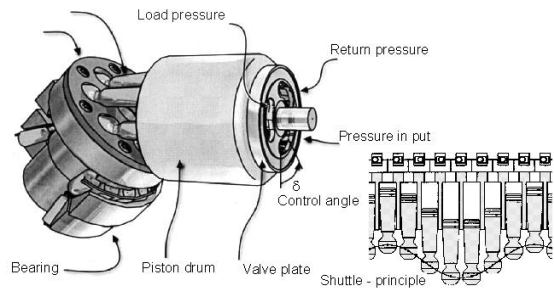

Figure 9: Prototype of a hydraulic transformer (Source: INNAS)

The key problem associated with these new transformers, i.e., the fact that the piston must be commutated during the stroke movement, appears to have been solved through the shuttle-principle. While the piston is commutates, a shuttle piston accommodates the compression oil, as shown in Fig. 9 on the right.

Figure 10 shows what the drive of a lift truck with a free piston engine might look like. Both the wheel drive and the working hydraulics are controlled by means of hydrotransformers. [10]
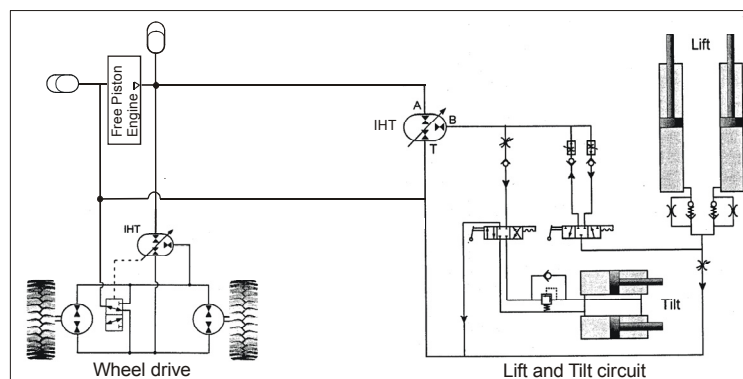

Figure 10: Drive of a lift truck with free piston engine and hydraulic transformer, (Source: Peter von Achten, INNAS)

It is not easy to predict whether this type of energy generation by means of a free piston motor will ever establish itself against the strong competition represented by the established volume flow generation through rotating displacement units. The most likely application scenario would be in mobile applications, because this energy source is reputed to be far more lightweight than the diesel engine with variable pump. However, switching to this new method of energy generation involves a far-reaching economic decision, because one cannot fall back upon proven designs.

VALVE ACTUATION

Whereas one had to work with unsteady valves actuated by switching solenoids in the early days, the 1960s saw the rise of the proportional solenoid. As shown in Fig. 11, in a proportional solenoid, the force generated remains constant over the stroke and proportional to the coil current within a certain range. If the proportional solenoid works against a spring, one achieves linearity between current and stroke. The proportional solenoid has been refined over the decades, such that the static and dynamic behaviour of proportional valves nearly matches that of servo valves. [11]
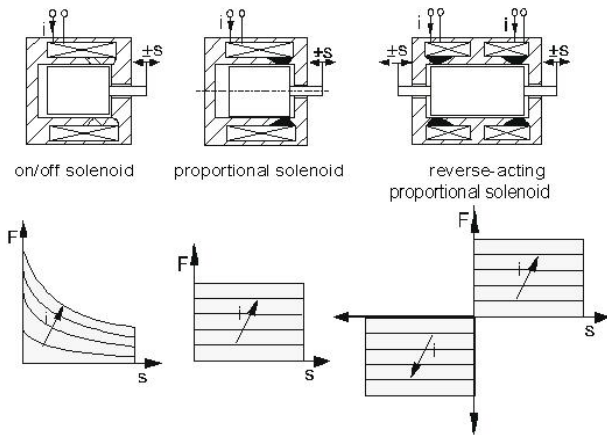
Figure 11: Valve actuators – solenoids

The proportional solenoid's shortcoming is that it can only generate forces in a single direction, so that a spring has to take care of the reverse movement. Hence, the failsafe position must be identical with the end position of the spring actuation, which can cause circuit design problems. Actuation becomes much more complex with a bipolar reverse-acting solenoid capable of exerting force in both directions, as shown on the right-hand side in Fig. 11. However, owing to the additional constructional effort required, that variant has not generally succeeded in the marketplace.

The moving-coil principle was first used in Germany for steady controls (Fig. 12, left). In the 1950s, the so-called moving coil controller (AEG Tauchspulenregler) was popular, predominantly in heavy-duty machinery, where the piloted version was most frequently used. [12]
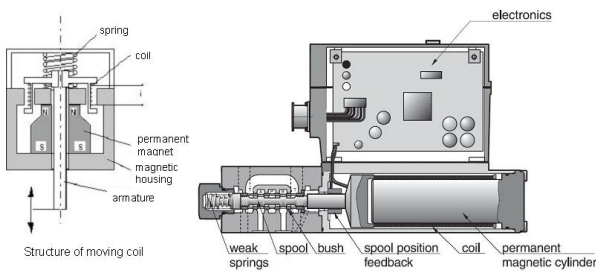

Figure 12: Moving coil design, (Source: Parker Hannifin)

In its new valve DF*plus*, the Parker company has revived the moving coil principle. As the right-hand side of Fig. 12 shows, the valve spool is directly actuated by the moving coil, which is wound around a thin-walled plastic pipe moving within the magnetic field of a strong, rod-shaped permanent magnet. Integrated into the valve is an inductive spool position feedback serving the valve spool's position control. If

the actuation should fail, the valve is moved to the fail-safe position in the middle by weak spring, (left side).

As evinced by the table in Fig 13., the moving coil can generate much larger forces than the proportional solenoid. In the open loop with an 100 % - signal at 250 Hz, a stroke of 0.2 mm was attained. The moving coil is more than twice as fast as the proportional solenoid. However, its power consumption is twice as high.

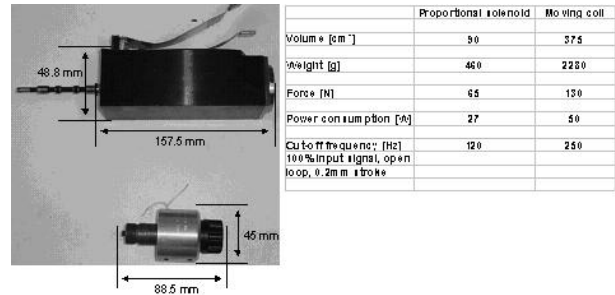|	Proportional solenoid	Moving coil
Volume [cm³]	90	375
Weight [g]	460	2280
Force [N]	65	130
Power consumption [W]	27	50
Cut off frequency [Hz] 100% input signal, open loop, 0.2mm stroke	120	250

Figure 13: Comparison: proportional solenoid vs. moving coil, (Source: Parker Hannifin & Magnet-Schultz Memmingen)

A further advantage is shown in Fig. 14. Within the closed position control, the moving coil can exert such high forces that it is able to counteract the flow forces up to a pressure difference of 350 bar at the valve. By contrast, the pressure difference at a proportional valve is limited, because the flow forces close the valve against the actuation force as pressure differences rise.
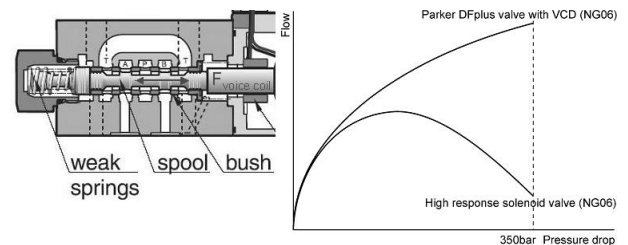

Figure 14: Application limits, (Source: Parker Hannifin)

One drawback of the new type of valve actuation shown in Fig. 13 is the weight, which is approximately five times as high as that of the proportional magnet. This will be primarily due to the heavier permanent magnet, which is, however, firmly attached to the valve housing. The moved masses are very low. This valve is at a disadvantage in applications where low valve weight and small volume are necessary. Its good static and dynamic behaviour may help find it wider usage elsewhere.

NOISE REDUCTION THROUGH PRE-COMPRESSION VOLUME

For many years, measures intended to reduce the noise emissions of piston pumps centred upon a soft pressure commutation, so as not to excite the pump's structure into emitting structure-borne noise. Towards that end, the port plate was equipped with a combination of pre-compression and suitable commutation bores or notches. However, these measures were only effective within a limited operating range in terms of pressure level, speed, and displacement volume.

In 1992, first reports concerning research conducted at the University of Linköping, Sweden (Professor Palmberg) appeared, which intended to reduce volume flow pulsations using a pre-compression capacity (pre-compression chamber). [14] These volume flow pulsations lead to pressure pulsations which excite attached components and systems into radiating noise. The idea is sketched in Fig. 15.

During the commutation phase of Piston 1 the piston volume is closed to the suction kidney and not opened to the pressure kidney. During the time Δt the piston volume is fed from the pre-compression chamber which is charged with high pressure. As the compression oil is not with drawn from the delivered volume flow the flow pulsations are reduced.

When the piston volume (1) opens to the high pressure kidney the pre-compression chamber is filled again through a wider orifice 0_1 from the high pressure kidney over a longer period.

Through a very narrow orifice 0_2 the pre-compression chamber can be additionally filled from the high pressure side constantly.
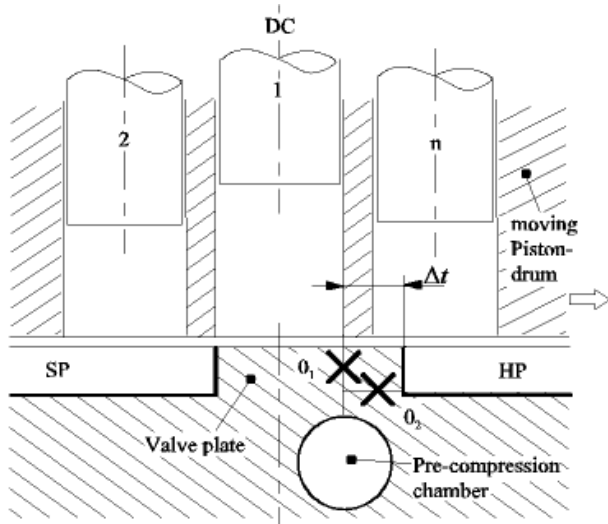
Some years passed before – encouraged by work done at IFAS (dissertation M. Jarchow 1997) – this operating principle was used in a production pump. [15] The left-hand side of Fig. 16 schematically depicts the arrangement of the Linde company's pre-compression volume, which is continuously fed from the high-pressure side as well as from the charged piston volume. The pre-compression volume principle was then adopted by two further major manufacturers of axial piston pumps. Figure 16, right-hand side, shows the pre-compression volume arrangement of the company Parker. Through this measure, reductions in pressure pulsations of between approximately 40-60 % are attained in practice. Moreover, that reduction is far less dependent on the operational parameters pressure, speed, and displacement volume than was the case with previous compensation methods. [16] [17]

Figure 16: Arrangement of pre-compression chambers
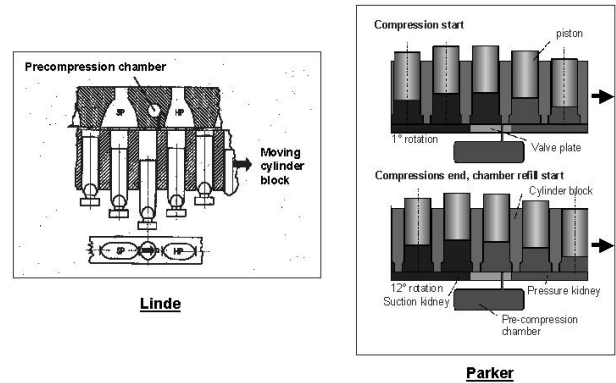
Figure 17 shows pulsation measurements conducted by the Rexroth company at a pump in an open circuit. Integrated into a complete system, the lower pressure pulsations can lead to a reduction in system noise of between approx. 3 to 5 dB (A).
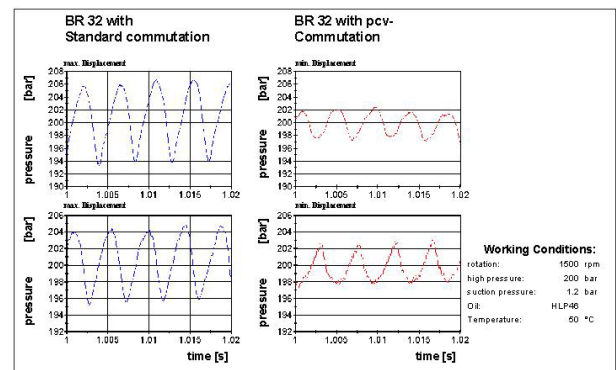

Figure 17: Pressure pulsation of an axial piston pump, (Source: Rexroth)

Figure 15: Pulsation reduction by pre-compression chamber

The constructional effort required for this pre-compression volume, which can be cast into the cover, is relatively low. The only disadvantage registered is the somewhat steeper pressure gradient during commutation, which leads to a slight increase in the pump's primary structure-borne noise.

In summary, the pre-compression volume is a development with little extra constructional effort and significant advantages to be achieved. It has led to a major decrease in the noise levels emitted by mobile machinery, for example. Hence, this idea quickly met with wide acceptance.

BUS TECHNOLOGY

The evolution of electronic control technology and the availability of affordable microcontrollers has enabled a new type of control circuitry.

Figure 18 illustrates the evolution from the parallel wiring of fluid power components to the field bus concept. Instead of laying some wires from the control electronics to each valve, which results in complex controls and thick wiring harnesses, the bus system relies upon a single signal line, which connects each valve or valve island in series. A processor on each valve island extracts the relevant information for each valve from the serial instruction set. These processors may contain decentralized intelligence, inasmuch as they can execute control tasks, e. g., for valves, variable pumps, or linear axis-drives. Often, the processor for the intended control tasks is integrated into the valve. For pneumatic valve islands, programmable sequence controls may be installed decentrally. The decentralized processors are remote-controlled via the bus by the superordinate control.
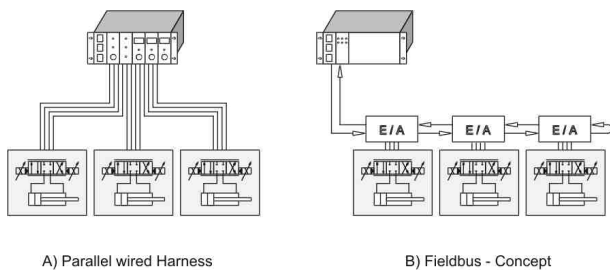
Figure 18: Development from the parallel wired harness to fieldbus-concept

Figure 19 shows the CAN-bus-control of a mobile working machinery. The bus transports the reference variables for the axis drives and for variable-pump control with short cyclical intervals (1-2 ms). Moreover, sensor output is transmitted onto a status- and diagnosis-terminal. In this manner, the machine operator is constantly kept informed on all ongoing machine functions. [18]
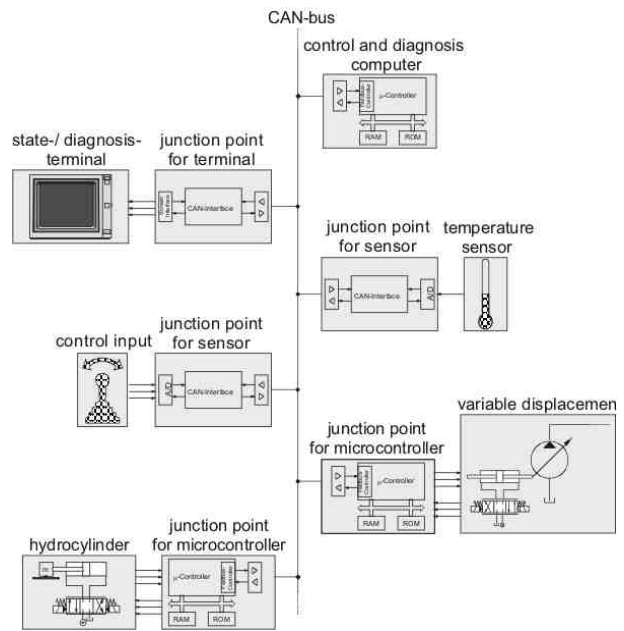

Figure 19: CAN-Bus for mobile hydraulics

In addition, acyclically and with longer reaction intervals (10 to 100 ms), condition-monitoring information is transmitted, which allows for the machine's condition to be diagnosed. Those data greatly simplify the maintenance and repair of complex drive systems. The drive manufacturer can even remotely diagnose the drive by logging on to the control computer.

Some exemplary advantages of bus technology would include: [20]

- smaller wiring harness and reduced wiring effort
- transparency of controls in planning machines and plants
- unproblematic system expandability
- interchangeability of standardized bus components
- comprehensive information available for diagnostic purposes
- quick setting of parameters for component functions
- enhanced user benefit through the integration of functions into components
- reduced incidence of malfunctions during start-up

Particularly for complex machine- and plant controls, the aforementioned economic and functional benefits far outweigh any other considerations. Accordingly, bus technology is fully accepted in that area and continues to gain ground vis-à-vis the conventional wiring technique.

FUEL CELL

The fuel cell represents a primary energy source that might alter the competitive situation in favour of electrical drives. In a PEM-technology (polymer-electrolyte membrane) fuel cell, the chemical energy of a gas (H_2) or fuel (methanol) is directly transformed, without combustion (by means of an ion-conducting membrane between anode and cathode), into electrical energy.

It is estimated that fuel cell technology will have matured within between one to two decades. [21]

At present, the competitive situation between electrics and fluid power in regard to the supply of primary energy for stationary and mobile applications is as shown in Fig. 20. For stationary applications, electrical power offers the advantage of allowing direct access to the primary energy source, via the electrical grid and a wall socket. By contrast, fluid power first has to create a pressure net with an electric motor and a pump, which entails greater expenditure for stationary application.. It takes specific requirements for fluid power to be utilized in spite of this comparatively higher cost: forming machines, for example, demand very high forces, for the generation of which fluid power is most suitable.
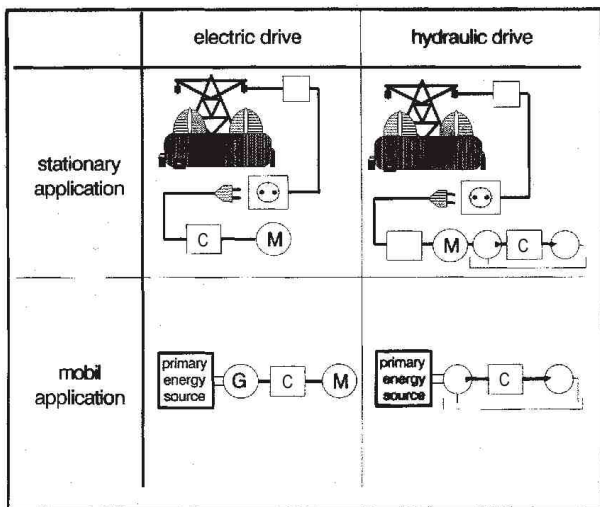

Figure 20: Present-day competitive situation: electric versus hydraulic

The situation is different in mobile applications. There, electrics and fluid power are on a level playing field. The primary energy source – most commonly a diesel engine – powers a generator or a pump to convert the mechanical energy into electric or hydraulic energy. Owing to its inherent advantages, particularly the higher power density, fluid power is the preferred choice for mobile applications today.
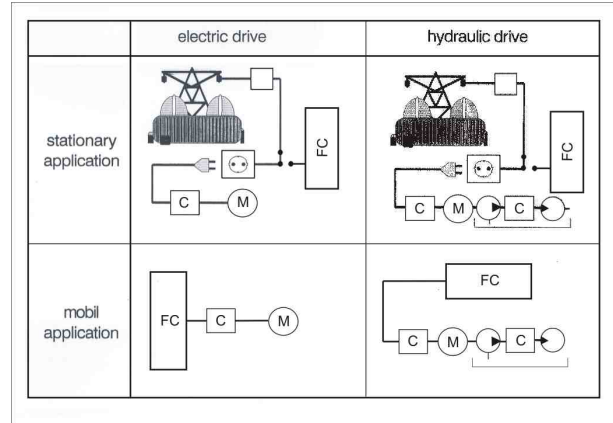

Figure 21: Competitive scenario after the introduction of the fuel cell

As Fig. 21 shows, this competitive scenario, particularly in mobile applications, might change in some decades. The fuel cell integrates the primary energy source (hitherto the diesel engine) and the generator into a single unit. Of course, this presupposes that it will become possible to develop sufficiently robust and powerful fuel cells offering a high power density at a low price.

What impact might such a development have on fluid power?

The competitive framework for stationary applications would remain unchanged, because it doesn't matter whether the primary energy is extracted from the power grid or from a fuel cell. However, the conditions for mobile applications would change: electric motors could be fed directly from the fuel cell, without the need for a diesel engine and a generator, whereas fluid power would still require a hydraulic pressure net to be built up, entailing comparatively greater expenditure.

Notwithstanding the aforementioned advantage of electrical power transmission, it is to be assumed that the working movements of mobile machinery will continue to be implemented using fluid power technology. Concerning translatory and swivelling motions, one major advantage is the easy transmission and distribution of hydraulic energy amongst several consumers through affordable cylinder drives. Furthermore, the force- and energy density of these drives is much higher than that of electromechanical drives with ball-thread drives or linear motors.

And what about rotatory movement, e. g., for the wheel drive? Whenever high power output is required from the electric motor, it has to run at high speeds. Thus, in order to generate the necessary low speeds with high torque at the wheels, speed transformers are required, for which purpose the proven hydrostatic transmission suggests itself. Applications most likely to migrate towards the electric drive are those in which the wheel

rotation merely serves to move the vehicle – as, for example, in a lift truck.

The fuel cell is a novel development, and its impact upon fluid power drive technology cannot yet be fully assessed. Nor can one predict whether fuel-cell technology is suitable for the rough operational environment of mobile working machinery. It is clear, however, that fluid power requires sustained further development in order to keep pace with electromechanics.

CONCLUDING REMARKS

Whether or not a novel idea will meet with wide acceptance in the field of fluid power depends upon a multitude of criteria. The overall technical and economic advantages of a fresh solution outweighing its shortcomings is the crucial determinant deciding whether it will be successfully applied within a particular area or whether it will be forgotten. Citing a number of examples, the likely prospects of some relatively recent ideas were discussed.

	Fluidics	AFH	Secondary Control	Free Piston Engine	New Valve-Actuation	Pre Compr. Chamber	Bus Technology	Fuel Cell
Acceptance in Practice	No Acceptance	No Acceptance	Acceptance for special Applications	Acceptance difficult to assess	Acceptance for special Applications	Acceptance	Acceptance	Acceptance difficult to assess
Functional Reasons	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗
Economical Reasons		⊗		⊗		⊗	⊗	⊗

Figure 22: Summary

From Fig. 22 we see that not all of the treated new ideas were successful and gained acceptance in practice:

- Some are fully accepted as the Pre-Compression Chamber and the Bus Technology.
- Some gained acceptance only for special Applications as the Secondary Control and the New Valve Actuation.
- And for some the acceptance is difficult to assess. That is true for the Free Piston Engine and the Fuel Cell.

The future will tell whether they become successful.

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