CLDP - Hybrid Drive using Servo Pump in Closed Loop

Dipl.-Ing. (BA) Bert Brahmer

Voith Turbo H+L Hydraulic GmbH&Co.KG (VTHL), Schuckertstr. 15, 71277 Rutesheim, Germany, E-mail: bert.brahmer@voith.com

Abstract

This paper presents an approach for energy efficient hydraulic drives. A differential pump is directly connected to a differential cylinder. By principle, energy losses and heating of the fluid are very low. Control loop design is surprisingly simple, because given technology and software from electromechanical drives may be applied. Finally, the approach is attractive because of the degree of freedom in mechanical layout and also because from the outside, the drive appears to be “non-hydraulic”. Ease of use and wide technology basis of electromechanical drives is combined with the ruggedness and overload proof of hydraulics.

KEYWORDS: servo pump, linear drive, hydraulic closed-loop, energy efficient hydraulic drive

1. Introduction

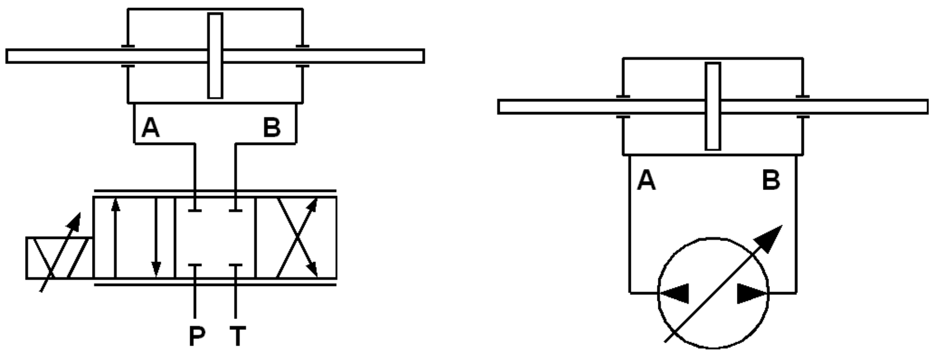
Hydraulic drives enabled industry to create versatile machine tools. In some cases - like machines for flexible punching/nibbling - only hydraulic drives enabled machine builders to translate customer requests into reality. Back in the 1970’s, many CNC machine tools were heavily relying on hydraulic drives, simply because electromechanical drives were not mature enough to “deliver” in a real world productive environment. Things have changed. Electromechanical drives are reliable, easy to use and their power density is ever increasing. Besides that, for machine tools, hydraulic drives are “out of fashion”. Still, hydraulic drives have inherent advantages which should not be dropped by machine builders: a cylinder is the most simple machine element to deliver a linear movement. With little effort, a hydraulic cylinder may be furnished crash-proof. Life time of a cylinder can be “endless”, compared to a heavily loaded ball screw drive. The objective of CLDP is to win back some of the application fields that have been lost against electromechanical drives. Ease of use, ruggedness and energy efficiency are considered the main market requirements that define the design goals.

2. General Concept of CLDP

As a basis for understanding, we divide hydraulic drives into two classes: hydrodynamic drives and hydrostatic drives. In hydrodynamics, energy is transported by means of the fluid's kinetic energy. The fluid's energy will be transformed into mechanical work by means of a turbine. While CLDP is targeted to high accuracy positioning and/or force control, hydrodynamic solutions are not a choice. In hydrostatics, energy is transported by the static energy (pressure) of the fluid. The fluid's energy will be transformed into mechanical work by means of a hydraulic motor, for example a cylinder or a rotational motor.

For hydrostatic systems, we find throttle control and displacement control. For throttle control, a pump will generate a constant pressure fluid supply. Using proportional valves, direction and flow rate acting on the hydraulic motor may be controlled. Hence, direction and speed/force of the hydraulic motor can be controlled. Example: pump with accumulator charging and a proportional valve driving a cylinder. Applying fast response valves, it is possible to setup high gain control loops, resulting in high quality force/ position control. Major drawback of throttle control is inherently low efficiency. By principle, energy is dissipated at the control edges of the valves, where we find a high pressure drop and flow rate, heating up the oil, but not contributing to output power.

A displacement control does not use a throttling device; either pump or motor must be adjustable in terms of direction of fluid flow and/or flow rate or pump displacement. Example: variable displacement pump, coupled to a linear cylinder. See **figure 1**.



a) Throttle control b) Displacement control

Figure 1: Hydrostatic drives

Applying this classification, CLDP is a hydrostatic drive with displacement control.

3. Design principle of CLDP

A 2Q/4Q pump is needed for bidirectional operation of the cylinder. This pump will have symmetrical displacement on ports A and B. While this will be fine for the displacement drive in figure 1 b), there will be a problem when using a differential cylinder. In a differential cylinder, piston side A will have a bigger effective surface compared to the surface of rod side B. **Figure 2** shows an example for this problem. The displacement / surface mismatch is addressed with additional valves (“Back pressure valve”). Even though the system generally is operating in displacement mode, these valves will cause additional energy loss, similar as found in throttle control systems.

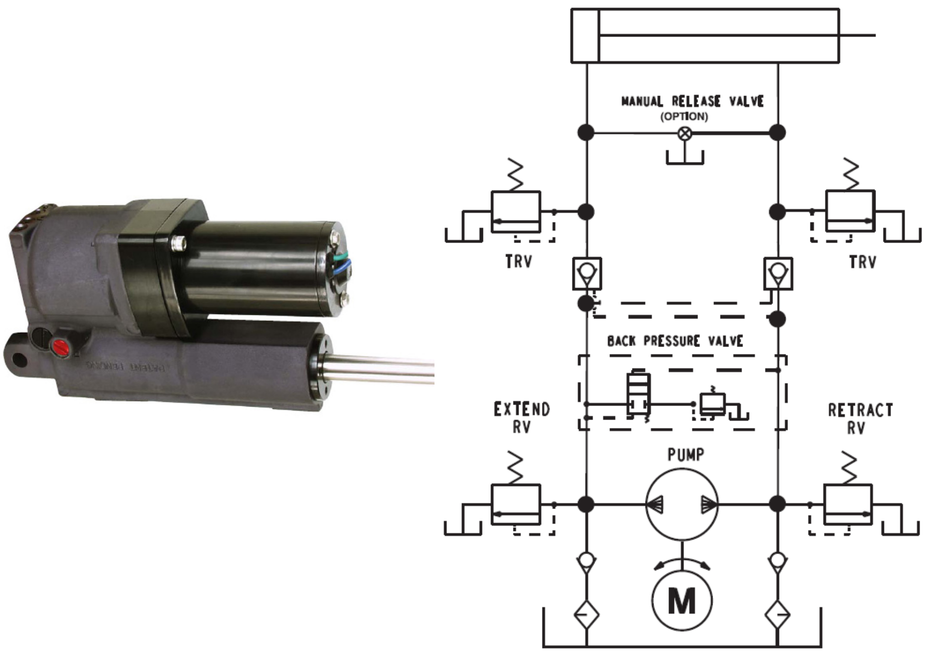


Figure 2: EHA with symmetric pump /1/

Several approaches may be found throughout industry to address the issue of surface / displacement mismatch when using a differential cylinder. A common feature of these approaches is to allow excess fluid from the bigger cylinder side (A) to drain back to tank. Major drawbacks of this approach are loss of efficiency and necessity for extra valves.

CLDP addresses this issue by implementing a “differential pump”. See **figure 3**. Servo motor 1 shall drive the pump 2 to create the desired fluid flow, driving the differential cylinder 3. Direction of flow and also the flow rate are a result of motor direction and motor speed. Pressure relief valves 4 and 5 are for overload protection. Check valves 6 and 7 allow compensation for leakage and compression or decompression of the fluid. Accumulator 8 is used as a tank. When cylinder 3 is extracted, more of the fluid will be stored inside the piston cavity A of the cylinder whereas more of the oil will be stored in the accumulator while the cylinder is retracted.

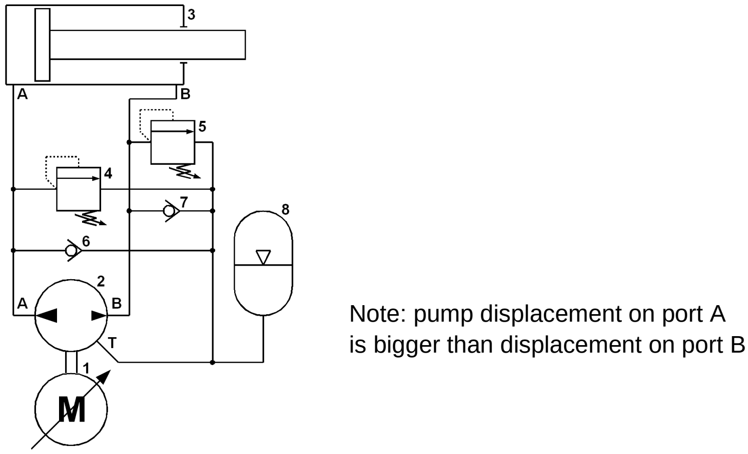


Figure 3: CDLP basic schematic

The ratio of displacement on ports A and B of the pump shall closely match the ratio of the cylinder surfaces in A and B.

$$\eta_Q = Q_A / Q_B \tag{1}$$

$$\eta_A = A_A / A_B \tag{2}$$

$$\eta_{Q} / \eta_A = 0.95 \dots 1.05 \tag{3}$$

To implement this differential pump, the basic principle of the internal gear pump was chosen. Advantageous characteristics of the internal gear pump are:

- High volumetric efficiency
- High mechanical efficiency
- Low noise
- Low pressure pulsation

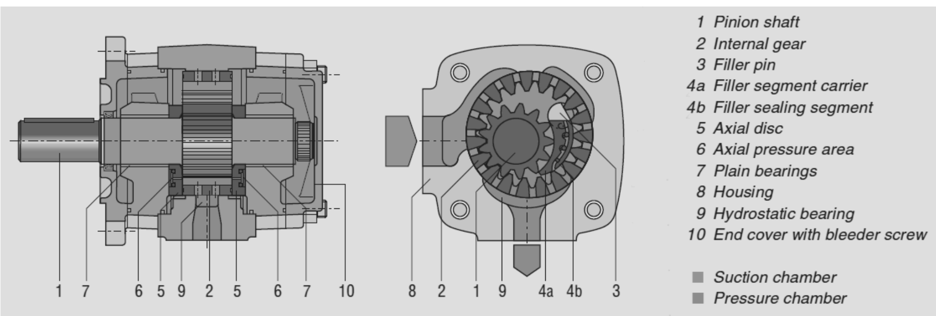
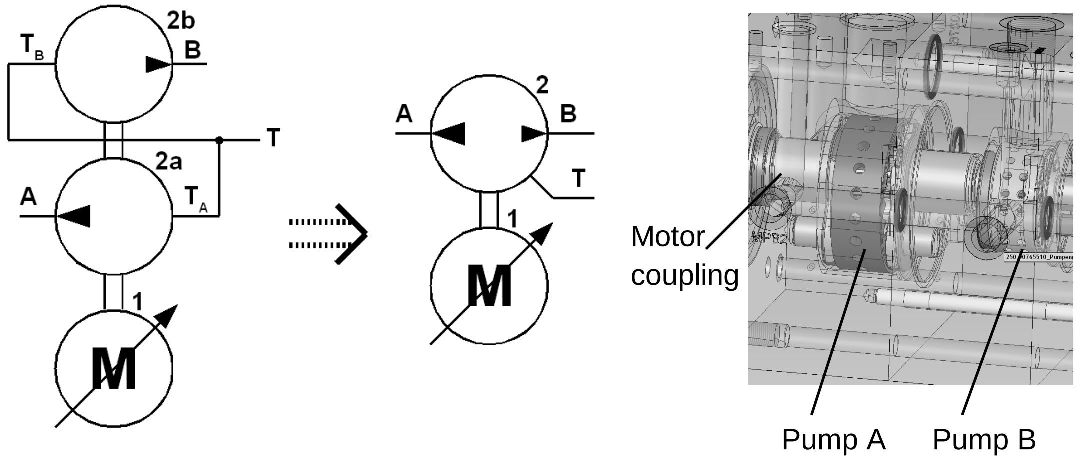


Figure 4: Internal gear pump /2/

Figure 4 gives a brief introduction for the design concept of an internal gear pump with radial and axial compensation. Two of such pumps, each with the desired displacement, may be combined to furnish a differential pump. **Figure 5** a) shows the functional symbol and 5 b) is a cross section of CLDP's pump module, which shows the approach for practical implementation of this concept.



a) Schematic Symbol b) Practical Implementation

Figure 5: Differential pump

4. Control Loop Design

Obvious reasons for the decreasing acceptance for hydraulic drives may be the extra effort for proper handling of the pressure fluid and the environmental problems caused by leakages. An other important issue is control loop design. Drive engineering and commissioning is often done by electrical engineers, well trained for electromechanical servos but often not so for hydraulics. CLDP may bridge the two worlds.

Figure 6 shows a "classical" linear drive, applying a spindle to translate the servo motor's rotation into linear motion. Rotating the spindle will linearly move the nut (nut must be rotationally fixed). Linear position will be known, because the rotational feedback of the motor encoder can directly be transformed into linear coordinates. In many systems, CNC/PLC and PID position controller are integrated in a single device.

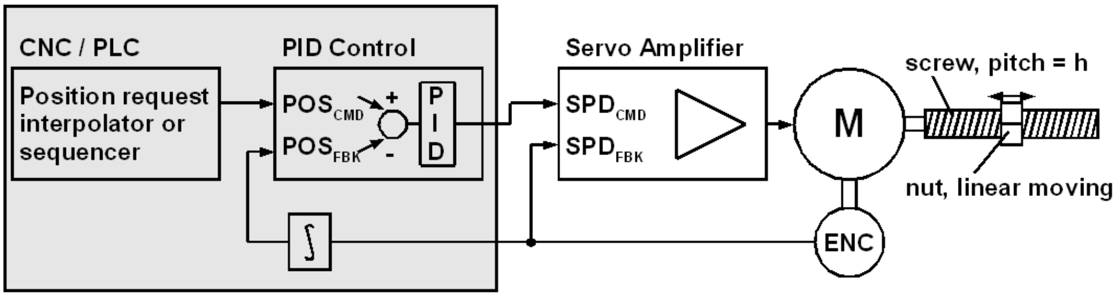


Figure 6: Classical PID for position control

The following figure shows the same application, now using CLDP for translating motor rotation into linear movement (CLDP schematic simplified).

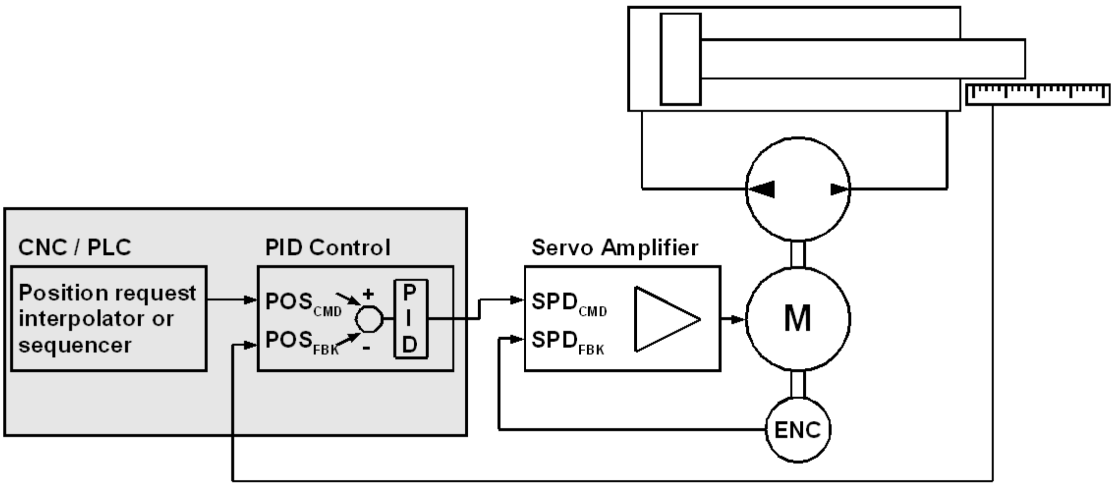


Figure 7: PID for position control with CLDP

Major structural elements remain unchanged, comparing figure 6 and 7:

- CNC/PLC will generate position command from interpolator or sequencer
- PID control will generate speed command
- Servo amplifier driving the motor using speed command and motor feedback

An important drive parameter is the pitch *h* (linear stroke per motor revolution). For the classical drive, this is a mechanical parameter of the screw system. For CLDP the pitch is derived from pump and cylinder data:

$$h_A = Q_A / A_A \quad (4)$$

$$h_B = Q_B / A_B \quad (5)$$

The above equations assume 100% pump volumetric efficiency, zero leakage in the cylinder and an incompressible fluid. Because this is not realistic, these losses will need to be compensated by the PID loop applied to CLDP. In figure 6, motor feedback may be used by position loop PID. For CLDP (figure 7), a direct linear encoder from the cylinder is needed. This direct feedback is necessary for three reasons:

- Pump leakage
- Compression of pressure fluid
- Cylinder leakage

The above effects will cause CLDP to behave like a spindle drive with inherent slip (caused by leakage) and non-ideal stiffness (caused by compression). These effects can be compensated very easily by the “I” (integral) factor of the PID position controller.

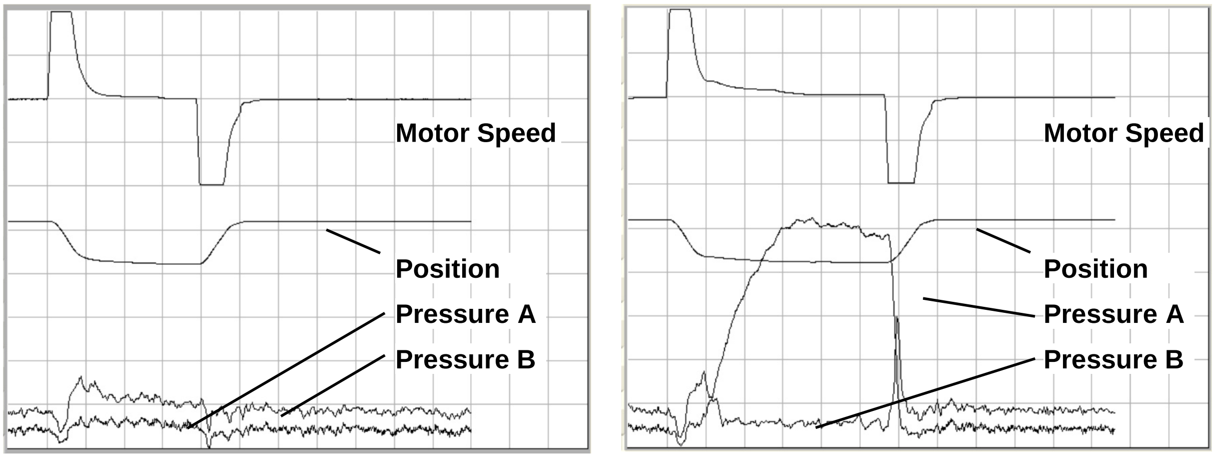
More sophisticated approaches will take into account the speed/pressure curve of the pump. A typical pump will need approx. 100 rpm to deliver full pressure, event when consumer flow rate is zero.

5. Operating Performance

For demonstration, CLDP performance will be shown for the following system (**table 1**):

Parameter	Value	Unit
Pump displacement, A	20,7	cm³/rev
Pump displacement, B	10,2	cm³/rev
Peak pressure	250	bar
Peak speed	3000	rpm
Cylinder piston diameter	100	mm
Cylinder rod diameter	70	mm
Forward pitch (A side)	2,64	mm/rev
Backward pitch (B side)	2,65	mm/rev
Pitch ratio (A/B)	0,99	
Peak speed (A side)	131,78	mm/s
Peak force (A side)	196,35	kN
Peak force (B side)	96,21	kN
Peak power	25,875	kW

Table 1: Evaluation data



a) load condition: 0 kN

X: 50 ms / DIV
S: 5 mm / DIV
PA: 40 bar / DIV
PB: 25 bar / DIV
Speed: 1500 rpm / DIV

b) load condition: 157 kN

Figure 8: Testing result

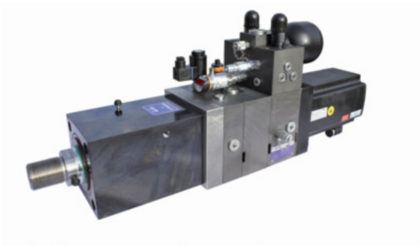
Figure 8 shows test results. “No load” chart shows the reference cycle. Total stroke is 4.8 mm. Rapid speed is approx 150 mm/s. There is 50 ms dwelling at target position. Such a cycle is typical for a forming application. A simple PID is used for position control. “Load” chart shows the same system’s behaviour (same PID parameters) when delivering 157 kN at 200 bar. The system needs approx. 100 ms longer to build up pressure and to reach the target position. Position error for 0 kN: +30 µm. Position error for 157 kN: -10 µm. Repeatability is better than 10 µm. More elaborate control loops, taking into account the speed/pressure curve of the pump, can easily achieve a total error of less than 10 µm, under any load condition.

During evaluation and first projects´ experience, quality of pressure fluid turned out to be important. Because of the closed system nature of CLDP, it is desired to have a life time oil filling. For this purpose, we are evaluating a special pressure fluid that addresses these issues. Long time testing of this fluid is under way, with encouraging results so far.

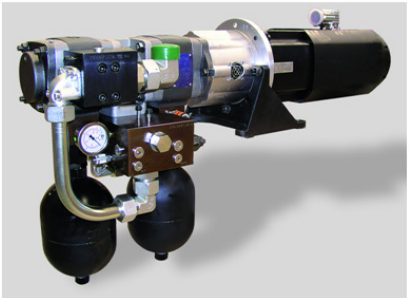
6. Application Examples

Several projects have already been realized. Applications include forming, cutting, punching, material handling and others. The following figure shows some of these examples.

Compared to “classical” drives using constant pressure supply and servo valves, all projects went through commissioning extremely smooth. Acceptance by design engineers, commissioning experts and maintenance people is very high. The following figure 9 illustrates some application examples.



a) Compact version

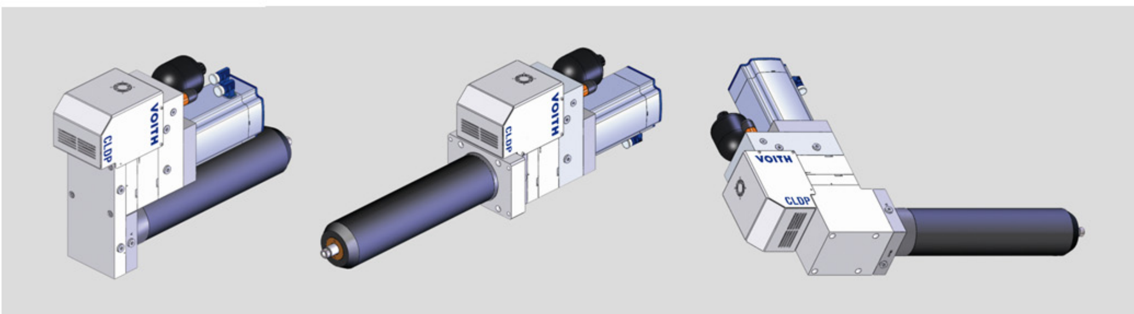


b) Split version with separate cyclinder

c) Double synchronous drive

Figure 9: Application examples

The modular design of CLDP can easily be adapted to mechanical requirements. Just by modifying the interface plate between pump/valve block and cylinder, various design options are possible (**figure 10**).



a) folded

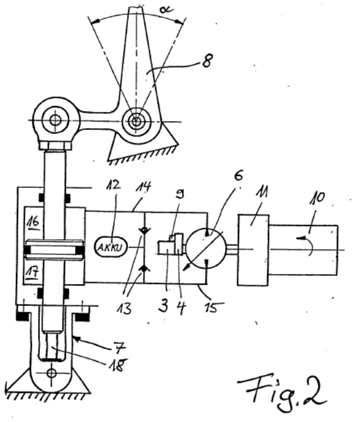
b) straight

c) right angle

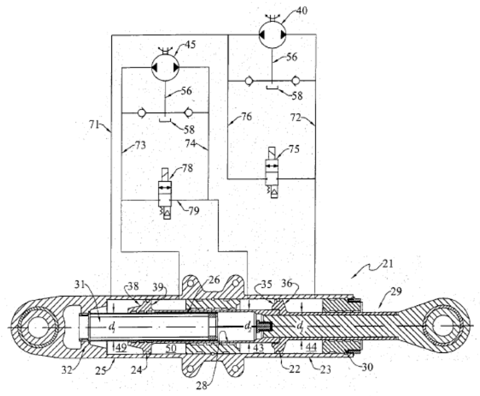
Figure 10: CLDP design options

7. Conclusion

Applying a pump to directly drive a linear actuator is not new. Besides the example of figure 2, other examples can be found in aircraft applications. **Figure 11** shows two principal drawings of applications from Liebherr /3/ and Moog /4/.



Liebherr EHA /3/



Moog EHA /4/

Figure 11: Known closed loop applications

By using a differential pump, major drawbacks caused by surface / displacement mismatch are resolved. Resulting CLDP systems are very compact and rugged, compared to electromechanical drives. Due to simple control loop setup, commissioning is easy. Extra valves for volumetric compensation are not necessary. Experience so far has shown that pump performance in terms of volumetric and energetic efficiency is key to system performance. Future focus of development will be on long life pressure fluid and machine specific optimizations.

Some of today's machine OEMs´ requirements may be summarized:

- Ruggedness for harsh environment
- Insensitive to mechanical overload - „crash proof“
- Simple control loop design
- Simple commissioning
- Avoid hydraulics. If not avoidable: build a closed system

Positively addressing these requirements, CLDP may help to win back some of the „lost applications“ against electric servos and also to keep the existing ones.

8. References

/1/ Parker catalogue “Compact EHA”, 2011

/2/ Voith catalogue “High Pressure Internal Gear Pumps”, 2009

/3/ Liebherr, DE3640082, 1986

/4/ Moog, US20040163386, 2003

9. Nomenclature

Q	pump displacement	cm^3 / rev
A	cylinder surface	cm^2
η	ratio: pump displacement, cylinder surface	1
h	pitch	cm / rev