HYDRAULIC PRESSURE AMPLIFIERS INTEGRATED WITHIN THE HYDRAULIC LINEAR ACTUATORS

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The rated pressure of common hydraulic pumps varies depending on their principle and geometric displacement but generally doesn't significantly exceed 400bar threshold. While this is perfectly adequate for most industrial and off-highway applications, there are applications requiring very high force that cannot be achieved by the linear actuator supplied with common pump pressure due to the space constraints placed upon the actuator. Increasing the pressure by means of pressure amplification resolves this problem. This presentation deals with principle, design considerations, applications, and benefits of hydraulic cartridge pressure amplifiers integrated directly into the hydraulic linear actuators and developed by PistonPower. The resulting linear actuator with integrated pressure amplifier thus features higher power density compared to the conventional hydraulic linear actuators.

KEYWORDS
pressure amplifier, pressure intensifier, hydraulic linear actuator, cylinder, high pressure

1 STAUS QUO

1.1 Hydraulic energy transmission

Hydraulic circuits are a common way of energy transmission between the prime mover (internal combustion engine or electric motor) and desired machine function (linear or rotary movement) in the mobile off-highway and industrial machinery.

While energy transmission via electric circuits is possible for the same purpose, hydraulics currently offers unrivaled power density and has no alternative in medium to high power applications for the foreseeable future, especially when considering conversion of rotary movement of the prime mover into linear movement of the machine work function.

Hydraulic pump is the product converting mechanical rotary energy of the prime mover (defined by rpm and torque) into static and kinetic energy of the hydraulic oil (defined by pressure and flow). The rated pressure of common hydraulic pumps varies depending on their principle and geometric displacement but generally doesn't significantly exceed 400bar threshold.

While this is perfectly adequate for most industrial and mobile off-highway machines, there are applications that benefit from even higher pressure to achieve the force that cannot be achieved while supplied with common pump pressure due to the space constraints upon the actuator.
A typical example of such an application are hydraulic excavator attachments used in the demolition of buildings and infrastructure, i.e. demolition tools. They are used both for primary demolition i.e. tearing down the pieces of the standing building or other structures and for secondary demolition i.e. reducing large debris already on the ground to smaller pieces fit for the rotary crushers and screeners. Typical representative of such a tool is a concrete crusher used for primary demolition depicted in Figure 1.

Figure 1. Demolition tool - concrete crusher

The force between the jaws of this tool is essential for the demolition activity yet it cannot be easily increased by larger hydraulic cylinder because the size and weight of the hydraulic cylinder are heavily limited. The available space for the cylinder is constrained by the need for the maneuverability and limitations of the frame design and the weight is constrained by total permissible weight of the tool. This is important as these tools are used on the high reach excavators with extended booms and low tool weight is critical for the excavator stability and maneuverability during the job.

The requirement for high force combined with space and weight constraints placed upon the linear actuator can be resolved by increasing the hydraulic pressure above the level typically provided by hydraulic pumps by means of pressure amplification.

2 PRESSURE AMPLIFICATION

The hydraulic pressure amplifier is a device that converts the flow and pressure of hydraulic oil on a principle of differential area so that the amplified pressure is higher than the input pressure at the expense of output amplified flow being lower than input flow.

3 CARTRIDGE PRESSURE AMPLIFIER

3.1 *Operating principle*

The cartridge amplifier (CA) developed by PistonPower is a single acting oscillating pressure amplifier designed for integration into the piston rod of the hydraulic cylinder. The principle of pressure amplification is based on reciprocal movement of two connected pistons with different area.

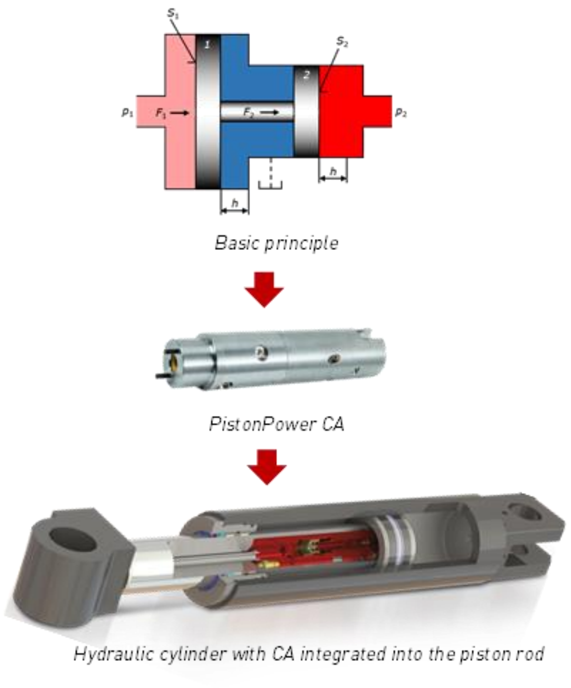

Figure 2. Principle of the cartridge amplifier

Input pressure p_1 acts on area S_1 of a large piston which is being moved to the end position by force F_1 . Since it is connected to a small piston, this is being moved to by a force F_2 generating higher output pressure p_2 and lower output flow on the small piston side. Afterwards the pistons move back to initial position and the amplification cycle repeats itself. Typical amplification frequency i.e. number of amplification cycles per second is 15-20Hz. In case of no flow demand (e.g. at the end stroke of the cylinder) the frequency of amplification decreases to 1-5Hz to cover the internal leakage in the CA and the cylinder in order to maintain the high pressure on the outlet side. Since the pistons are connected

$$F_2 = F_1 \tag{1}$$

$$p_2 \times S_2 = p_1 \times S_1 \tag{2}$$

$$\frac{p_2}{p_1} = \frac{S_1}{S_2} = i_{CA} \tag{3}$$

where i_{CA} is the amplification ratio of cartridge amplifier.

3.2 *Integration*

The innovation of the PistonPower cartridge amplifier (CA) is its integration into the piston rod of the hydraulic cylinder. The inlet port A1 and outlet port B1 of hydraulic oil are located in the piston rod eye. The oil is routed through the rod to the cartridge pressure amplifier (CA) and from the CA further to the desired cylinder side. The output from the CA A2 might be routed to the piston chamber, or to the rod chamber of the hydraulic cylinder, both shown in Figure 3.

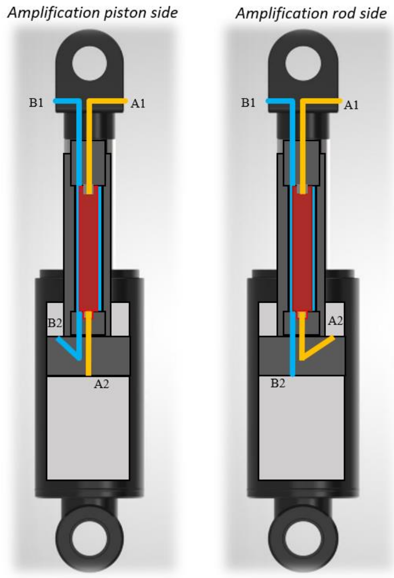

Figure 3. Options for connecting the CA output

The side determined by the application requirements, however in vast majority of the cases, the output from the CA is routed to the piston chamber, because the high force in usually required in the extension of the cylinder i.e. pushing direction.

3.3 *Functionality*

Besides the pressure amplification itself, the cartridge pressure amplifier also features the function of automatic activation and load holding, both provided by the respective valves built into the product, as shown in the schematic in Figure 3.

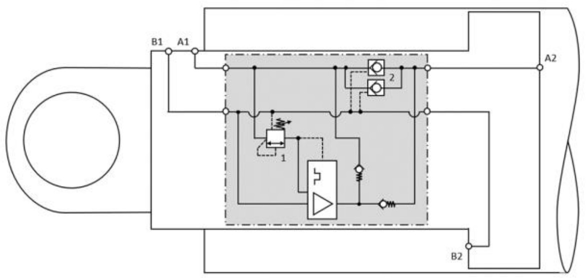

Figure 4. Hydraulic schematic of the cartridge amplifier

Sequence valve (Pos. 1 in Fig. 4) ensures automatic activation of the amplification process based on load. If the system pump pressure p_1 is sufficient to overcome load (represented by p_2) the amplification is not activated, and the oil passes freely from input A_1 through the by-pass channel and pilot operated check valves directly to output A_2. The cylinder works as usual, and this is called bypass mode, where

$$p_1 = p_2 < p_{SV} \tag{4}$$

Once the system pump pressure is not sufficient to overcome the load, the load induced pressure p_2 increases above the setting of the sequence valve p_{sv}, the valve opens and routes the flow to the amplification part of the CA. The amplification process starts and increases the pressure p_2 in the piston chamber to match the load requirements. This is called amplification mode, where

$$p_2 \geq p_{SV} \tag{5}$$

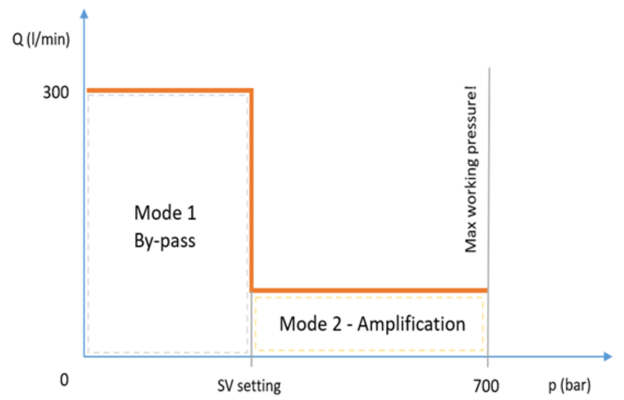

Figure 5. Simplified operating modes of CA

The pressure setting of the sequence valve is defined by the max. pressure capability of the system adjusted down by a safety margin to compensate for the valve characteristic and response time, e.g. for the system pressure of 200bar (setting of the main relief valve), the typical sequence valve setting is 160-180bar.

Pilot operated check valve (POCV) (Pos. 2 in Fig. 4) ensures load holding, i.e. holding of high pressure on the piston side of the cylinder during the stop of cylinder extraction and release of the high pressure on the piston side of the cylinder once the cylinder retraction is desired. POCV starts to open as soon as

$$p_{B1} \geq \frac{p_{A2}}{i_{POCV}} \quad (6)$$

where i_{POCV} is the pilot ratio of the pilot operated check valve. The POCV used in all CA models is double stage type i.e. with the pre-compensation. This is important because the sudden release of the high pressure by the single stage POCV create pressure shock that is both audible as intense sound of a shot and visible as the strong movement of hydraulic hoses. The pre-compensation of the double stage POCV helps eliminate this effect during the POCV release.

Real life example of a work cycle with pressure amplification is shown in Fig. 5, that captures the development of pressure on the piston side of the cylinder (pA2) in time during the cutting of the solid steel bar using a demolition shear attachment as shown in Fig.6 mounted on a mini excavator.

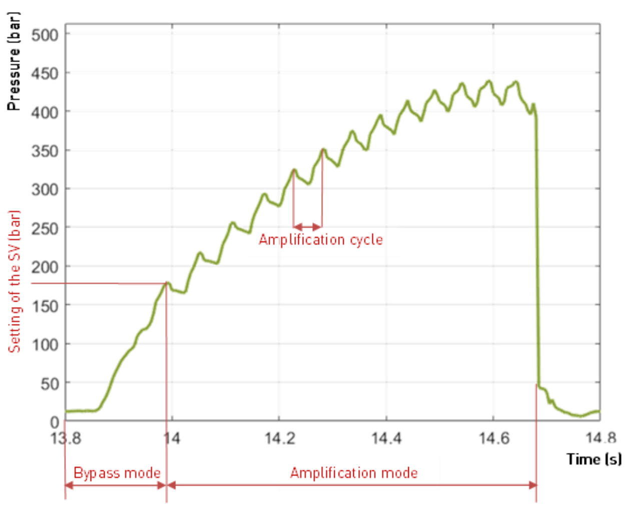

Figure 6. Example of a work cycle

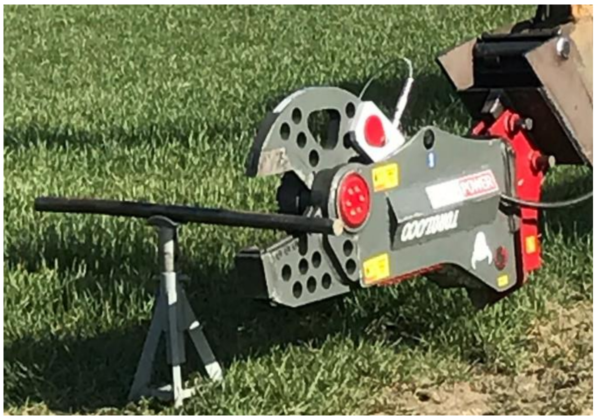

Figure 7. Demolition shear used for testing

4 BENEFITS

The benefit of integrating the hydraulic pressure inside the hydraulic cylinder is the compact package and increased safety thanks to the reduction of all external high-pressure hydraulic components (e.g. pipes, fittings).

The benefits of pressure amplification used in hydraulic cylinders vary depending on the design goals of the machines and thus also the cylinder.

4.1 *Maximizing force*

One design approach would be to maximize force. In such a case, the force of the hydraulic cylinder with integrated pressure amplifier would be the original force multiplied by amplification ratio, when compared to original standard cylinder with the same internal diameter.

Considering the amplification ratios i_{CA} range from 2.0 to 2.8, this extreme approach is not applied as 200-280% increase in force of the actuator would require total machine redesign.

4.2 *Maximizing speed*

Another design approach would be to minimize the dimensions and weight of the hydraulic cylinder with integrated pressure amplifier while maintaining the same peak force compared to original standard cylinder with the same internal diameter.

The main benefit of such an approach besides the dimension and weight reduction of the cylinder is the increased in cylinder speed and thus shortening of the machine working cycle. This is a byproduct of the cylinder bore decrease while the available flow remains the same.

In this design approach characterized by the same force and more speed, the CA is competing with the regenerative valve (also called speed valve) that are mounted on the cylinder and achieve similar benefit by different means.

4.3 *Combined approach*

The most common design approach in utilizing the CA technology is the combination of the two benefits mentioned above.

The cylinder with integrated CA is designed to have 15-30% more peak force compared to original standard cylinder with the same internal diameter, while being smaller and lighter (considering the amplification ratios i_{CA} from 2.0 to 2.8). This provides the benefit of higher force without the need for machine redesign together with the benefit of smaller and thus faster cylinder providing shorter machine work cycle.

4.4 *Downsizing of the hydraulic system*

Chapters 4.1., 4.2 and 4.3 deal with different approaches to design of a cylinder with integrated CA when used instead of a original standard cylinder. All these approaches assume no changes to the actual machine frame or hydraulic circuit since this is in most cases not desired.

If however a project is pursued on a machine in the transition between generations or in the beginning of a completely new machine design, the use of the CA has further benefit on the machine side i.e. the possibility to downsize the hydraulic system.

In the tradition system the max. operating pressure and flow of the pump and all other components in the circuit is defined by the needs of the most demanding consumer i.e. rotary or linear actuator. In a system where the most demanding consumer is a linear actuator i.e. hydraulic cylinder, the use of integrated CA in such a cylinder allows to define the max. operating pressure and flow of the pump by the other consumers and thus downsize the whole system while still delivering the required peak force and speed on the most demanding actuator.

5 APPLICATIONS

While the pressure amplification in general can be beneficiary in many applications, it is not suitable for all of them.

5.1 *Duty cycle*

Any pressure amplifier follows the law of energy conservation and acts as a hydraulic gearbox, having pressure p_1 and flow Q_1 as the inputs and providing pressure p_2 and flow Q_2 as outputs during amplification where

$$p_2 > p_1 \tag{7}$$

$$Q_2 < Q_1 \tag{8}$$

This implies the hydraulic cylinder equipped with pressure amplification is during the amplification process considerably slower compared to original standard cylinder of the same peak force.

Thus, the benefits described in chapters 4.2, 4.3 and 4.4 (specifically the shorter machine work cycle) are present only when the high force demand represent a small portion of the total cylinder stroke. The threshold for the benefits depends on the cylinder length and hydraulic system parameters but is generally in the range of 15-30% of high force demand i.e. amplification mode on the total cylinder stroke. The Figure 7 and Figure 8 show the threshold for the benefit of the pressure amplification in the example of specific cylinders from the application examples where the technology has established itself.

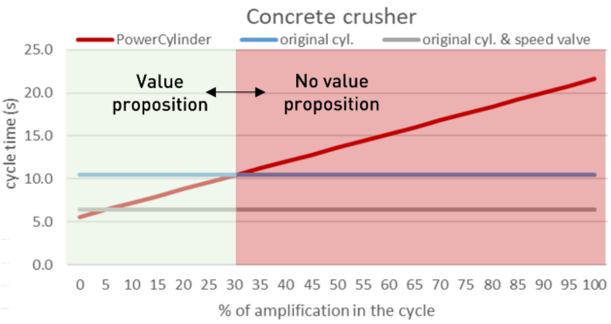

Figure 8. Benefit threshold for the concrete crusher cylinder

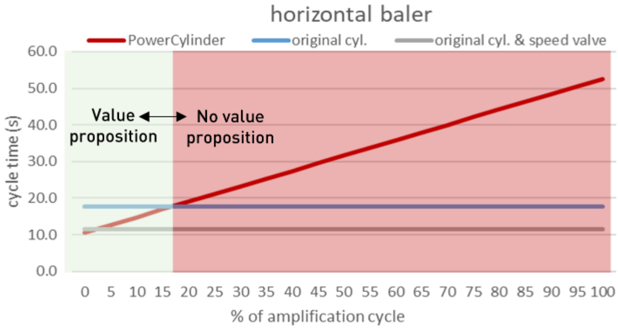

Figure 9. Benefit threshold for the recycling baler cylinder

The typical applications with the duty cycle that features high force requirement only for a short portion of the cylinder stroke and which thus benefit from the pressure amplification technology by obtaining benefits described in chapters 4.2, 4.3 and 4.4 are demolition attachments mentioned in chapter 1.1 and various kinds of industrial pressing machines.

The most typical representative of the second group is the baler or baling press, i.e. machine used in the recycling industry for compacting bulk waste or recyclables into compact bales for further transportation.

6 CONCLUSIONS

The technology of pressure amplification integrated into the hydraulic cylinder (CA) is and innovative use of well-known hydraulic principles increasing the possibilities, power density and value proposition of hydraulic linear actuators.

While not suitable for all applications of hydraulic cylinders, it has its firm place in the designer's toolbox for the applications with the suitable duty cycle in which major benefits in machine performance and productivity can be achieved.

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PistonPower proprietary technical literature

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