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Considerations on Flow Regeneration Circuits and Hydraulic Motors Speed Variation at Constant Flow

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Abstract: *The material shows a brief summary of simple practical applications of hydraulic drive systems that work on three principles: technology of regeneration of hydraulic motors feed flow, variation in steps of hydraulic motors speed at constant flow and control of vertical displacement speed of inertia loads. These applications have good energy efficiency, low price, high reliability and they are used to drive mechanisms that operate in several working phases, characterized by constant speeds within each phase, but different from one phase to another.*

Keywords: *flow regeneration, speed variation at constant flow, control of vertical displacement of inertia loads*

1. Introduction

An important method of increasing, at low cost, energy efficiency of hydraulic drive systems is to reduce the capacity of pumping systems, due to the use of flow "regeneration circuits" for working phases of mechanisms with high speeds and low loads. These circuits allow the transferring of flow, which in a "classical" way would circulate towards the tank, from the passive chambers of hydraulic motors to the active chambers of motors, which are powered by pumping systems [1]. In the case of a differential hydraulic cylinder, for instance, by using a regeneration circuit, established between rod chamber and piston chamber in order to obtain quick advance with no load, the pump feeds piston chamber with a lower flow, equal to the difference between the pump flow without regeneration circuit and the regeneration circuit flow.
Other methods of increasing, at low costs, energy efficiency of hydraulic drive systems [2] are: achieving three speed steps, at constant flow, of a mechanism driven by a differential hydraulic cylinder; achieving equal speed rates, in both directions, for a hydraulic cylinder fed at constant flow; achieving constant speed rates at variable load of hydraulic motors; control of vertical descent speed of inertia loads.
The described solutions represent a much simpler and cheaper alternative to the use of linear or rotary hydraulic drive servo-systems [3].

2. Circuits of flow regeneration

Advance high or low speed movements of some presses or mechanisms can be performed with small cylinders through the flow regeneration technique.
In regeneration or *differential* circuits, the fluid in the rod chamber of a differential cylinder is transferred to the piston chamber during the advance stroke, while in normal applications the fluid *regeneration* is addressed to the tank. In this way, according to the flow regeneration technique, Figure 1, the flow from the rod chamber is added to the flow delivered by the pump in the piston chamber. As a result, the piston speed increases significantly.

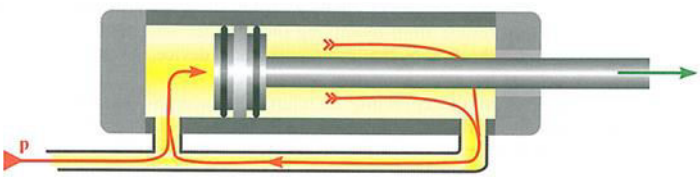


Fig. 1. Flow regeneration technique

At first glance, one might think that pump flow blocks the piston movement, because the fluid delivered by the pump is "pushed" over the two faces of the piston. In fact, the forces acting on the faces of a differential cylinder piston have different surfaces, because the rod area reduces effective surface of the piston face in rod chamber. *Regeneration technique* does not apply in the case of cylinders for presses or double rod cylinders.
Regeneration circuit effect can be demonstrated by the following simple sizing calculation:
There is given a piston with *2:1* ratio of areas. If the main area is equal to $S_1 = 150\ cm^2$, then the other area S_2 and rod area S_s measure *75* cm^2.

$$S_1\text{-}S_2 = Ss \text{ or } Ss = S_1\text{-}S_2 \quad (1)$$

With a stroke h of *50 cm*, maximum capacity V_1 and minimum capacity V_2 of cylinder chambers is

$$V_1 = S_1 \cdot h = 150 \cdot 50 = 7500\ cm^3 = 7.5\ l \quad (2)$$

respectively

$$V_2 = S_2 \cdot h = 75 \cdot 50 = 3750\ cm^3 = 3.75\ l \quad (3)$$

If the pump delivers a flow Q of *10 l/min* and is connected to the main chamber of the cylinder, in standard version the rod needs *45* seconds to travel the entire stroke.

$$t_{normal} = V_1 / Q = 7.5 / 10 = 0.75\ min \cdot 60 = 45\ s \quad (4)$$

For the case in which the cylinder is connected in the version with regeneration circuit, the fluid from the chamber V_2 enters the chamber V_1, and the rod reaches stroke end in *22.5* seconds (as long as there are no pressure drops that exceed the adjusted pressure of discharge valve).

$$T_{regenerative} = V_2 / Q = 3.75 / 10 = 0.375\ min \cdot 60 = 22.5\ s \quad (5)$$
$$t_{total} = t_{normal} - t_{regenerative} = 45 - 22.5 = 22.5\ s \quad (6)$$

A higher discharge speed can be obtained by reducing the diameter of the rod (if the peak loads allow): for example, with a ratio of the piston surfaces *4:1*, the rod has a flat surface S_2 of *37.5* cm^2 and needs *11.4* seconds to travel the entire stroke:

$$S_2 = S_1\text{-}S_2 = 150 - 37.5 = 112.5\ cm^2 \quad (7)$$
$$V_2 = S_2 \cdot h = 112.5 \cdot 50 = 5625\ cm^3 = 5{,}625l \quad (8)$$
$$t_{normal} = V_2 / Q = 5.625 / 10 = 0.56\ min \cdot 60 = 33.6\ s \quad (9)$$
$$T_{total} = t_{normal} - t_{regenerative} = 45 - 33.6 = 11.4\ s \quad (10)$$

A speed increase implies a reduction of the exerted force. The fluid flowing from one chamber of the differential cylinder to the other, through a regeneration circuit, reduces force resultant on the cylinder piston. If the safety valve is adjusted to 100 bar and if kept the same data used for a piston with a ratio of *4:1*, the forces F_1 on S_1 and F_2 on S_2 will be:

$$F_1 = p \cdot S_1 = 100 \cdot 150 = 15000\ daN \quad (11)$$

$$F_2 = p \cdot S_2 = 100 \cdot 112.5 = 11250\ daN \quad (12)$$

Since F_2 is opposed to F_1, then total force F_t is:

$$F_t = F_1 - F_2 = 15000 - 11250 = 3750\ daN \quad (13)$$

Thrust on the annular surface of the piston, inside rod chamber, is compensated by thrust on the other frontal surface of the piston, minus rod surface; as a result, the force exerted in a regeneration circuit is equivalent to the force on the rod surface S_s.

$$F_t = p \cdot S_s = 100 \cdot 37.5 = 3750\ daN \quad (14)$$

2.1. Check valves for flow regeneration circuits

Hydraulic cylinders fitted with a regeneration circuit usually work in three main phases: a rapid initial stroke, during which regeneration circuit functions, a terminal extraction phase, subjected to a maximum force and the return phase. In normal conditions, they obviously require quarter phase for resting. One 4/3 directional control valve, Figure 2, does not allow these conditions, unless give up one of these four phases.

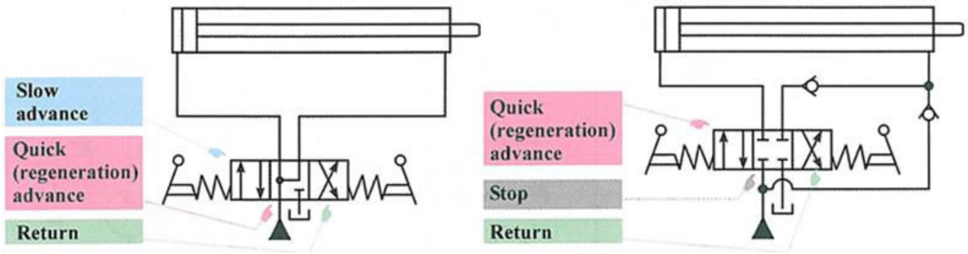


Fig. 2. Regeneration circuits with 4/3 directional control valves:
(a)=slow advance + quick advance (regeneration) + return; (b)=quick advance (regeneration) + stop + return

The most rational solution is given by a 6/4 directional control valve, Figure 3; it is possible to adjust the quick or slow advance movement, through a directional control valve manually driven. The size of the check valve does not depend only on the pump flow; it should be sized to pump flow plus regeneration flow.

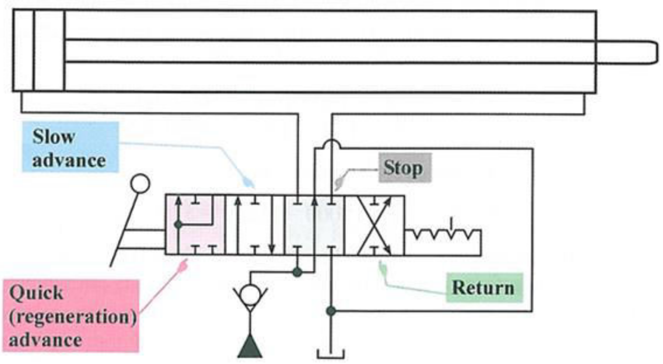


Fig. 3. Regeneration circuits with 6/4 directional control valves:
slow advance + quick advance (regeneration) and stop + return

2.2. Regeneration circuits with automatic slow or quick advance

Machines' operators cannot determine exactly the moment when they should turn from the quick regeneration advance to the completely slow regeneration advance. For this reason, the system is automated through a sequence valve, located between the 4/3 directional control valve and the hydraulic cylinder, Figure 4. The solution represents a much simpler and cheaper alternative to use of a linear hydraulic drive servo-system [3].

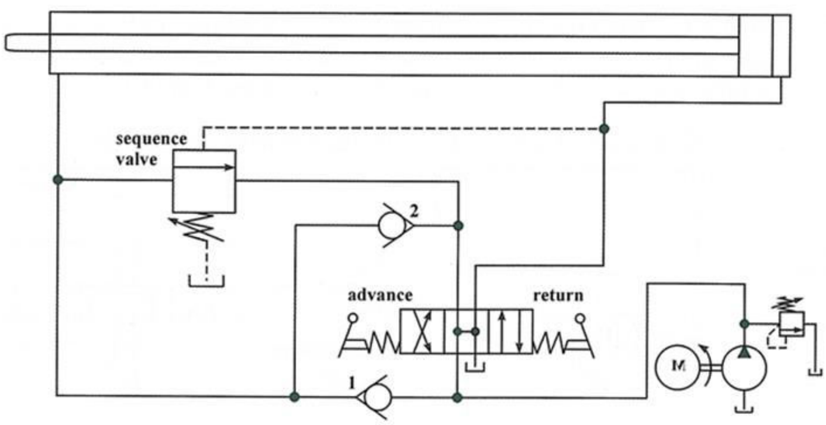


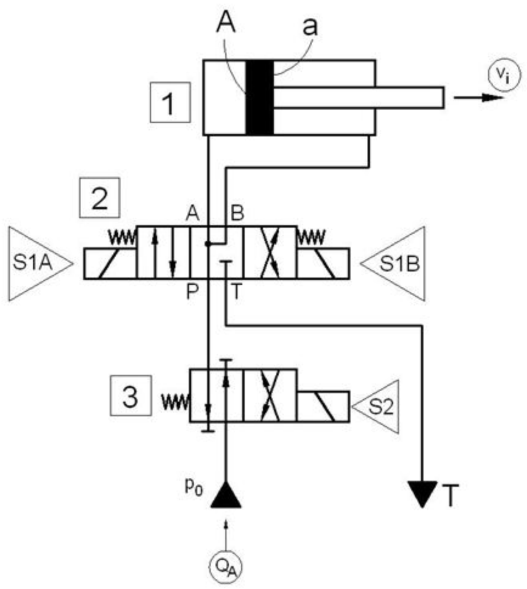
Fig. 4. Regeneration circuit with sequence valve

When the directional control valve is in the "advance" position, the quick advance stroke is supported by regeneration system; the fluid in the rod chamber is pushed through the check valve *1* and directional control valve to the piston chamber. Once there is developed a higher load on the rod, sequence valve normally closed, adjusted to that load, receives the pilot signal, opens and diverts the flow into the tank. In the regeneration phase, check valve *2* prevents the fluid from being conveyed to the tank and opens when the directional control valve is in the return position.

3. The speed variation in steps of hydraulic motors at constant flow

3.1. Drive of a differential hydraulic cylinder with three speed steps

Hydraulic drive diagram of a differential cylinder with three speed steps and ***stop*** phase is shown in Figure 5, and functioning cyclogram is shown in table 1.



Components and functional role:
1 = differential hydraulic cylinder; receives the flow provided by pump and runs three displacement speeds;
2 = 4/3 hydraulic directional control valve with electric drive; by switching determines the three speeds;
3 = 4/2 hydraulic directional control valve, 2 blocked ports, electric control; starts or stops oil supply to the hydraulic cylinder;
S_{1A}, S_{1B} = drive electromagnets acting by pushing the slide valve of the directional control valve *2*;
S_2= drive electromagnet acting by pushing the slide valve of directional control valve *3*;
T = tank.
Functional parameters:
A, a = large and small section of hydraulic cylinder piston;
$V_{i,\ i=1,2,3}$ = hydraulic cylinder speeds;
Q_A = flow; Q_A = const.

Fig. 5. Hydraulic drive diagram of a differential cylinder with three speed steps

TABLE 1: Functioning cyclogram of cylinder in Figure 5

Drive / Phase	S_{1A}	S_{1B}	S_2	Speed
Quick advance (with regeneration circuit)	-	-	+	$v_2 = \frac{Q_A}{A-a}$
Slow advance	+	-	+	$v_1 = \frac{Q_A}{A}$
Retraction	-	+	+	$v_3 = \frac{Q_A}{a}$
Stop	-	-	-	0

Caption: "-" = unpowered electromagnet; "+" = powered electromagnet.

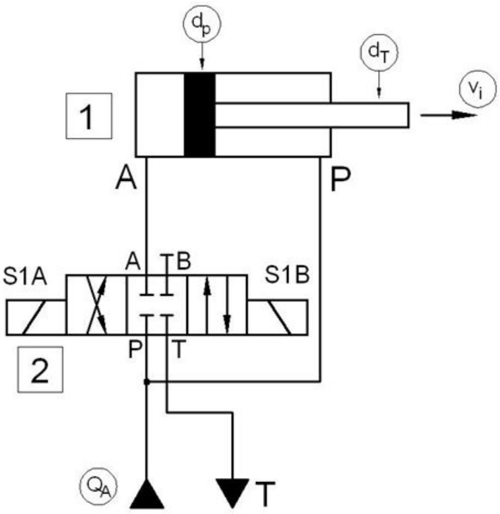
Between the three speeds of the cylinder, flow and piston sections the following relations are established:

$$v_2 = \frac{Q_A}{A-a}; \qquad v_1 = \frac{Q_A}{A}; \qquad v_3 = \frac{Q_A}{a}; \qquad a < A\ ; \quad v_1 < v_2 < v_3 \qquad (15)$$

These hydraulic diagrams are used to drive mechanisms component of small and medium power machines, which do not require speed variations during the same phase, only between phases.

3.2. Drive of a differential hydraulic cylinder with equal speeds in both directions

Hydraulic drive diagram of a differential cylinder with equal speeds in both travel directions and ***stop*** phase is shown in Figure 6, and functioning cyclogram is shown in table 2.



Components and functional role:
1 = differential hydraulic cylinder; receives the flow provided by pump and moves with equal speeds in both directions;
2 = 4/3 hydraulic directional control valve with ***B*** blocked port, closed center, electric control; changes cylinder travel direction; starts and stops cylinder movement;
S_{1A}, S_{1B}= electromagnets driving the slide valve of the directional control valve;
T = tank;
P, T, A, B = the 4 ports (connections) of the directional control valve, namely: pressure, tank, consumer A, consumer B.
Functional parameters:
d_p = piston diameter;
d_T = rod diameter;
Q_A = flow; Q_A = const.

Fig. 6. Hydraulic drive diagram of a differential cylinder with equal speeds in both directions

TABLE 2: Functioning cyclogram of cylinder in Figure 6

Drive / Phase	S_{1A}	S_{1B}	Speed
Left movement	+	-	$v_{stg} = \frac{Q_A}{A-(A-a)}$
Right movement (with regeneration circuit)	-	+	$v_{dr} = \frac{Q_A}{a}$
Stop	-	-	0

Caption: "-" unpowered electromagnet; "+" powered electromagnet

If between piston diameter and rod diameter we have the relation:

$$d_p = d_T\sqrt{2} \tag{16}$$

then the total and annular areas of the piston will be given by the relations:

$$A = \frac{\pi d_p^2}{4};\ a = \frac{\pi d_T^2}{4}; \tag{17}$$

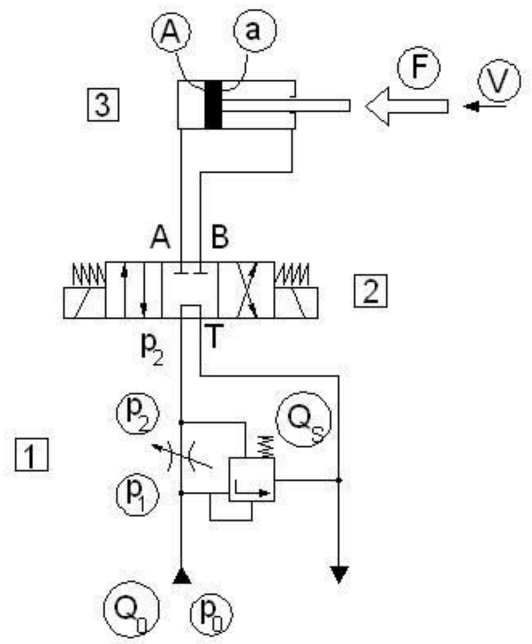
annular area of the piston being practically equal to area of the section rod, and the movement speeds to left/ right will be equal, respectively:

$$v_{stg} = \frac{Q_A}{A-(A-a)};\qquad v_{dr} = \frac{Q_A}{a};\qquad v_{dr} = v_{stg} \tag{18}$$

This type of driving can be found in mechanisms with oscillating motion in the structure of small power machinery.

3.3. Drive of a constant speed hydraulic motor at variable load

A linear hydraulic motor (cylinder) or rotary hydraulic motor can be actuated with constant speed or rotational constant speed, regardless of the force variation (at cylinder) or torque variation (at rotary motor) using a three-port flow regulator, placed between the constant flow hydraulic source and hydraulic directional control valve. Hydraulic drive diagram is shown in Figure 7.



Components and functional role:

1. Three-port flow regulator; maintains constant flow and speed regardless of load variation (force, at cylinder, respectively torque , at rotary hydraulic motor);
2. 4/3 hydraulic directional control valve with electric control; sets the travel direction, starts and stops hydraulic motor;
3. Differential hydraulic cylinder (or rotary motor); receives flow and performs linear or rotary motion.

Functional parameters:
A, a (q) = cylinder sections (or geometric volume);
F (M) = driving force (or torque);
p_1, p_2 = pressure drop across regulator;
p_0 = nominal pressure;
Q_0 = full flow;
Q_S = flow discharged through regulator valve;
V (n) = velocity (or rotational speed)

Fig. 7. Hydraulic drive diagram with three-port flow regulator of a differential cylinder

Between functional parameters there are established the following relations:
The flow on A and B consumer circuits of directional control valve are given by the relation:

$$Q_{A,B} = K_{AB}\sqrt{p_1 - p_2} \quad \begin{cases} \mathrm{p}_1 > p_2 \\ K_{AB} = \alpha_D \cdot A_0\sqrt{2/\rho} \end{cases} \tag{19}$$

where $K_{A,B}$ is a constant which takes into account a coefficient of losses by friction α_D, flowing area A_0, and working fluid (hydraulic oil) density ρ , and $Q_{AB} = Q_0 - Q_S$. Stationary characteristic $Q = f(\Delta p)$ is represented in Figure 8.

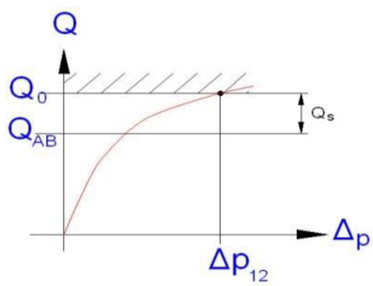


Fig. 8. Characteristic Q=f(Δp)

Relations between force/ torque and pressure, respectively speed/ rotational speed and flow rate are given by the expressions:

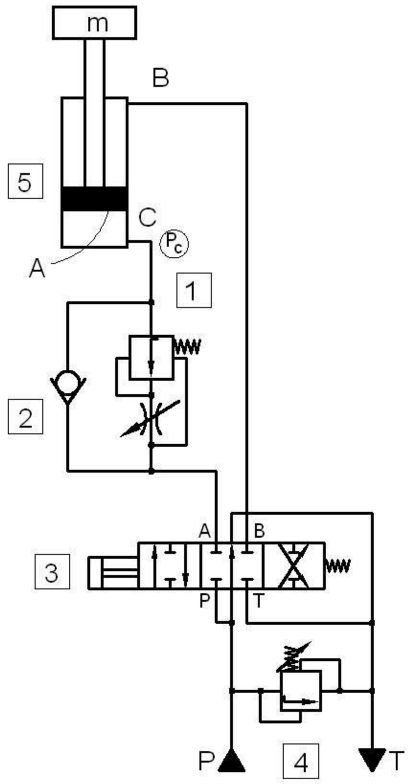
$$p_2 = \frac{F}{A}; \qquad \left(sau\,\mathrm{p}_2 \cong \frac{M}{q} \right); \quad v = \frac{Q_{AB}}{A} \left(\mathrm{sau\ n} = \frac{\mathrm{Q_{AB}}}{\mathrm{q}} \right) \tag{20}$$

This application is used to drive mechanisms component of small power machinery so that efficiency does not decrease below 65%.

4. Linearity of hydraulic motor speed under the influence of load

4.1. Control of descendent speed of a vertical load using the two-port flow regulator

Hydraulic drive diagram for lowering a vertical load at constant speed is shown in Figure 9.



Components and functional role:
1 = two-port flow regulator; maintains constant flow and speed regardless of load variation;
2 = bypass check valve; short -circuits the flow regulator in the load lifting phase;
3 = 6/3 distribution section of a battery directional control valve; reverses the travel direction of the hydraulic motor; starts / stops the hydraulic motor;
4 = input section of 6/3 battery directional control valve; contains safety valve of drive system;
5 = differential hydraulic cylinder (can be replaced with rotary hydraulic motor).
Functional parameters:
P_c = pressure upstream of regulator;
Q_c = flow upstream of regulator;
Δp_{CA} = load loss in regulator;
Δp_{AT} = load loss through directional control valve ($\Delta p_{AT} \leq 8$ bar);
Δp_{lin} = load loss on paths;
m = lowered / lifted mass corresponding to the load;
A = cylinder piston section;
P = connection (path) P (pump) of the directional control valve;
T = connection T (tank or reservoir) of the directional control valve;
A, B = directional control valve consumer connections;
C = connection of the cylinder in piston chamber.

Fig. 9. Hydraulic drive diagram with two-port flow regulator of a vertical differential cylinder

To lower the load, directional control valve is switched so as there are created $P \rightarrow B$ and $A \rightarrow T$ connections. The flow on C connection circuit of the cylinder is given by the relation: $Q_C = K_C \sqrt{P_C}$

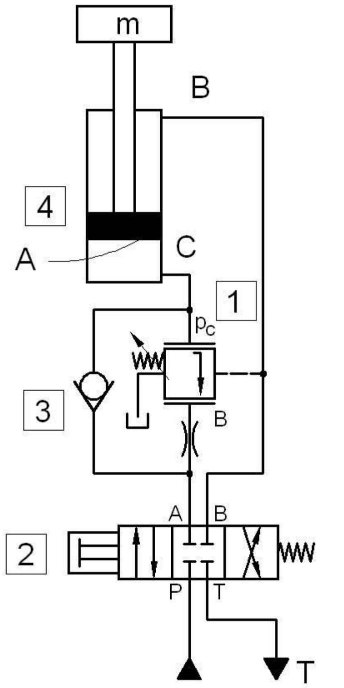
where $P_c = \dfrac{mg}{A} - \Delta p_{CA} - \left(\Delta p_{AT} + \Delta p_{lin}\right)$ (21)

This diagram is used to drive the mechanisms for arm and hook lifting at motor cranes for small and medium loads.

4.2. Control of descent of a vertical load through the speed limiting valve with external control

Hydraulic drive diagram for controlling descendent speed of a vertical load through a speed limiting valve with external control is shown in Figure 10.
The role of the two-port flow regulator is taken by a pressure limiting valve, with external control, acting as a valve that limits maximum flow which can cross the hydraulic resistance located upstream of the valve. In load lifting phase, the limiting valve and hydraulic resistance are short-circuited by a bypass check valve.

The directional control valve is so connected that there are created $A \rightarrow T$ and $p \rightarrow B$ connections.



Components and functional role:
1 = pressure limiting valve with external control; limits maximum pressure on C connection route of the hydraulic cylinder, respectively Δp by fixed hydraulic resistance, respectively flow in the outlet circuit of the piston chamber, respectively velocity of load lowering;
2 = 4/3 hydraulic directional control valve; changes the travel direction of the cylinder; starts / stops the hydraulic cylinder;
3 = bypass valve; short-circuits the hydraulic resistance and valve in the load lifting phase;
4 = differential hydraulic cylinder; receives flow and lifts / lowers the load.
Functional parameters:
p_C = pressure upstream of the valve;
Q_c = flow through the valve;
p_A = pressure downstream of the valve;
p_B = external control pressure;
m = mass lowered / lifted corresponding to the load;
A = cylinder piston section;
Δp = load loss on circuits.

Fig. 10. Hydraulic drive diagram of a vertical differential cylinder with speed limiting valve

Flow through the valve $Q_c = k\sqrt{p_1 - p_2}$, where $\begin{cases} p_1 = \dfrac{mg}{A} \\ p_2 = \Delta p_{AT} + \Delta p_{lin} \end{cases}$ (22)

This diagram is used as well to drive the mechanisms for arm and hook lifting at motor cranes for small and medium loads.

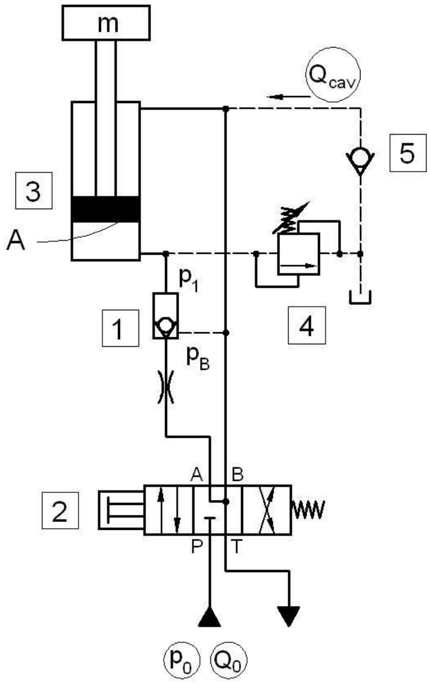
5. Canceling of the displacement speed under the influence of load

In the case of vertical displacement of a variable inertia load, upon accidental exceed of its maximum allowed value, during lifting or lowering phase, the load movement is canceled due to the opening of a safety valve, functioning as a shock valve, mounted in bypass on supply/discharge circuit of the hydraulic cylinder piston chamber.
Maintaining on an intermediate position of inertia load, located between the stroke ends of the hydraulic cylinder, is done in the center position of the 4/3 directional control valve, by means of an unlockable check valve fitted between the cylinder and connection A of 4/3 directional control valve.
The same shock valve does not allow lifting or lowering of inertia load, from an intermediate stationary position on the cylinder stroke (corresponding to the central position of the 4/3 hydraulic directional control valve) during exceeding its maximum allowed value.
Hydraulic drive diagram of vertical displacement of inertia load, with movement canceling at a maximum allowed value of load, is shown in Figure 11.
Relations between pressures are:

$$p_1(t) = \begin{cases} \cong p_0 \\ (1.25...1.35)p_0 \end{cases} ; \quad p_B=(0.5...0.9)p_0 ; \; p_{1\max} = \frac{mg}{A} < K \cdot p_0; \qquad K = 1.25...1.35 \tag{23}$$

The flow of displaced working fluid is given by the relation:

$$Q_{cav} = \frac{V}{\beta} \cdot \frac{dp}{dt} \begin{cases} \dfrac{dp}{dt} = \dfrac{p_{1\max} - p_0}{\Delta t} = \dfrac{(K-1)p_{nom}}{\Delta t} \\ V = \text{fluid volume in the circuit} \end{cases} \tag{24}$$



Components and functional role:

1 = unlockable check valve; ensures maintenance on position of inertia load in the center position of the slide valve of the 4/3 directional control valve, and by its unlocking in the right position of the slide valve, the load lowering;

2 = 4/3 hydraulic directional control valve with slide valve, diagram 02; ensures change of travel direction and also start / stop of hydraulic cylinder;

3 = differential hydraulic cylinder (can also be used a rotary hydraulic motor); ensures displacement of inertia load;

4 = shock valve; stops displacement of inertia load;

5 = anti-cavitation check valve; ensures filling of the cylinder rod chamber, during shock valve opening, in the center position of the slide valve of the directional control valve.

Functional parameters:

p_0, Q_0 = nominal pressure and flow;
A = cylinder piston section;
Q_{cav} = displaced flow; *m* = inertia load;
p_B = pilot pressure; *V* = fluid volume in the circuit;
β = compressibility of the working fluid.

Fig. 11. Hydraulic diagram of inertia load displacement with speed canceling under the influence of load

This application is used to drive the mechanisms for vertical lifting of inertia loads in technological equipment.

6. Conclusions

Flow regeneration circuits develop important applications for the efficient execution of fast or slow advance movements of differential hydraulic cylinders. With the help of sequence valves there can be developed a simple automation for passing from quick advance movement, with flow regeneration, to slow advance movement.

By use of a differential hydraulic cylinder and a flow regeneration circuit there can achieved three speed steps for cylinder rod, namely a fast advance, a slow advance and a return.

A linear or rotary hydraulic motor can be actuated with constant speed or constant rotational speed, regardless of load (force or torque) variation, if a three-port flow regulator is introduced in the drive diagram.

Control of vertical descent speed of inertia load can be achieved by use of a two-port flow regulator or an external control pressure regulating valve, located on the outlet circuit of a linear (differential cylinder) or rotary hydraulic motor.

Vertical displacement of an inertia load, by use of a linear or rotary hydraulic motor, is stopped at accidental increase in load beyond the allowed limit, by means of a shock valve.

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