Modeling and Simulation of the Hydraulic Clamping/Unclamping Systems Using Hydro-Pneumatic Accumulators

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Abstract: *This article highlights some methods for determining the optimal accumulator for the hydraulic units with accumulators used in the locking and clamping/unclamping systems for machine-tools. The mathematical models and the results of the simulations carried out for designing such units are shown below. The results of the research can also be applied in the case of the clamping/unclamping systems for the tool-holders of the machine-tools or similar systems.*

Keywords: *Hydro-pneumatic accumulators, clamping/unclamping systems, machine-tools*

1. Introduction [1, 2, 3]

The accumulators are hydraulic components that enable the reception, storage and transmission of the hydrostatic energy in the form of volumes of liquid under pressure. The low degree of compressibility of the liquids makes it difficult to store energy in small volumes, but allows the transmission of high efforts. Unlike liquids, gases have great possibilities in terms of compressibility, which allow them to store large energies in small volumes. The association of liquids and gases within special constructions led to the creation of the hydro-pneumatic accumulators**.** In the hydraulic clamping/unclamping systems [4, 5, 6, 7, 8] of the numerically controlled machine tools, the accumulators are the ones that ensure the necessary flow peaks in the case of frequent actuations.
As a rule, the accumulator of volume V_0 is charged with gas (nitrogen) at pressure p_0 and will operate between the pressures p_1 and p_2 $(p_1 < p_2)$. The volume of liquid circulated between the two states is ΔV. The nitrogen loading pressure, according to [7, 9, 10], has the expression:

$$p_0 = 0.9 \cdot p_1; p_0 > 0.2p_2 \tag{1}$$

For the isothermal transformation (usually along a few minutes), the necessary volume V_0 is obtained depending on the circulating volume ΔV:

$$V_0 = \frac{\Delta V}{\frac{p_0}{p_1} - \frac{p_0}{p_2}} \tag{2}$$

From the relations (1) and (2), after substitution, it will be obtained:

$$V_0 = \frac{\Delta V \cdot p_2}{0.9 \cdot (p_2 - p_1)} \tag{3}$$

In the general case, for a polytropic transformation or if the transformation is fast (adiabatic), it will be obtained:

$$V_0 = \frac{\Delta V}{\left(\frac{p_0}{p_1}\right)^{\frac{1}{n}} - \left(\frac{p_0}{p_2}\right)^{\frac{1}{n}}} \tag{4}$$

where $n = \gamma = 1.4$ in the adiabatic transformation.
The nitrogen effectively occupied (approximate) volume V_a is determined by means of the relation:

$$V_a \approx \frac{\Delta V}{\left(\frac{p_2}{p_1}\right)^{\frac{1}{n}} - 1} \tag{5}$$

Or according to the relation:

$$V_a \approx \Delta V \cdot \frac{(1-\tau)^{\frac{1}{n}}}{1-(1-\tau)^{\frac{1}{n}}} \tag{6}$$

In the relation above, τ has the expression:

$$\tau = \frac{p_2 - p_1}{p_2} = 1 - \frac{p_1}{p_2} \tag{7}$$

and it is the pressure drop coefficient.
In the specialized literature it is recommended: $\tau \geq 0.15 \div 0.2$ [10].
The pre-sizing calculations consider: $V_a = (9 \div 10)\,\Delta V$ [10].

2. Compensation of Flow Rate/Pressure Losses with the Help of Accumulators

There are flow rate losses in all hydraulic circuits. These ones, as a rule, depend on pressure (liquid leaks) and its variations (compressibility of liquids). If the values of these losses are large or they occur very quickly, they can be compensated by means of accumulators.
Assuming that the lost flow is Q_L, then the relation below must be satisfied in the time t:

$$Q_L = \frac{\Delta V}{t} \tag{8}$$

where ΔV is the volume of liquid supplied by the accumulator:

$$\Delta V = V_0 \cdot p_0 \left(\frac{1}{p_1} - \frac{1}{p_2} \right) \tag{9}$$

In the relations above, it is considered that the losses occur in times of the order of minutes, so the nitrogen undergoes isothermal transformations.
The volume ΔV provided by the accumulator must be greater or at least equal to the volume required in the unit after a certain actuation. The accumulator can be discharged towards a segment of the circuit that is under a certain pressure or towards a part of the circuit from which, in a previous stage, all the oil was removed [1]. The latter case is the one when the accumulator is stressed and this case will be studied further on.
The simple diagram in Figure 1 is considered as an example.
The pump P is driven by the electric motor EM and sucks the oil from the tank T. The maximum pressure is regulated using the pressure relief valve 1PV1. If the directional valve 1D1 is not actuated (1S -), the oil is sent back to the tank at a pressure practically equal to the atmospheric pressure. By actuating the directional valve 1D1 (1S +), through the check valve 1CV1, the accumulator is charged to the pressure set at the valve 1PV1. It is assumed that, after charging the accumulator, the directional valve 1D1 is no longer actuated (1S -). If the directional valve 2D1 (2S +) is actuated right now, the accumulator sends oil to the upper chamber of the cylinder 1C1 which is compressed against the springs. When the directional valve 2D1 is no more actuated, all the oil sent towards the cylinder, but also the oil contained in the discharge circuit of the cylinder, is sent

to the tank. This is the volume Δ*V* lost from the accumulator. This loss, if it is not covered by a new actuation of thedirectional valve 1D1 (pre-command) [2, 5], will lead to a decrease of the pressure.

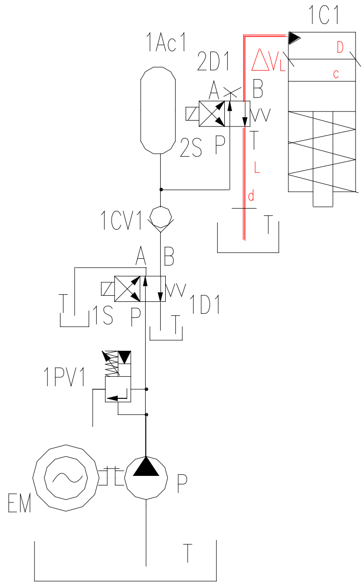

Fig. 1. Losses of flow (volume) in the circuit with accumulator

In this case, it is considered that the diameter of the cylinder piston is *D*, its stroke is *c*, the inner diameter of the supply/return pipes is *d* and the total length of these ones is *L*. If the compressibility of the oil and the deformations of the pipes are neglected, the lost volume ΔV_L can be calculated using the expression:

$$\Delta V_L \approx \frac{\pi}{4}(D^2 c + d^2 L) \quad (10)$$

Ideally, according to the relations above, the following condition should be met during the operation:

$$\Delta V \geq \Delta V_L \quad (11)$$

In reality, in the case of the numerically controlled machine-tools, the confirmations of the clamping/unclamping states are performed at a pressure p_x lower than the minimum working pressure of the accumulator so that the equipment does not display errors during the machining operations. If the pressure in the system drops below this value p_x then the machine-tool becomes non-operational. In order to prevent the drop of the pressure below this value, it is recommended that the accumulator operate between the pressures p_1 and p_2. It is also recommended that the pressure in the spots where the pressure switches confirming the pressure p_x are located do not fall below this value, even after the discharges of the type presented above.

3. Hydraulic Unit for Locking and Unlocking Two Axes in a Numerically Controlled Machine-Tool

Figure 2 shows the hydraulic diagram of a numerically controlled drilling machine. In this case, the B axis is hydraulically locked, while the C axis is mechanically locked by means of spring disks and is hydraulically unlocked.
The pump P is driven by the electric motor EM and sucks the oil from tank T. The maximum pressure is adjusted by the pressure relief valve 1PV1 at the value p_{PV}. If the directional valve 1D1 is not actuated (1S -) the oil is sent back to the tank at a pressure practically equal to the atmospheric pressure. By actuating the directional valve 1D1 (1S +), through the check valve 1CV1, the accumulator is charged to the pressure adjusted at the valve 1PV1. The accumulator

1Ac1 has the volume V_0 and is charged with nitrogen at the pressure p_0. The charging and discharging pressures p_1 and p_2 are those set at the pressure switches 1PS1 and 2PS1. The cylinders for the locking of B and C axes are actuated by the directional valves 2D1 and 3D1. The existence of pressure in these cylinders is confirmed by the pressure switches 3PS1 and 4PS1, adjusted to the pressure p_X. This pressure is lower than the pressure p_1. To ensure an efficient charging of the accumulator, the pressure adjusted at the pressure relief valve p_{PV} will be higher than the pressure p_2. To avoid the complete emptying of the system, the check valve 2CV1 was assembled on the return.

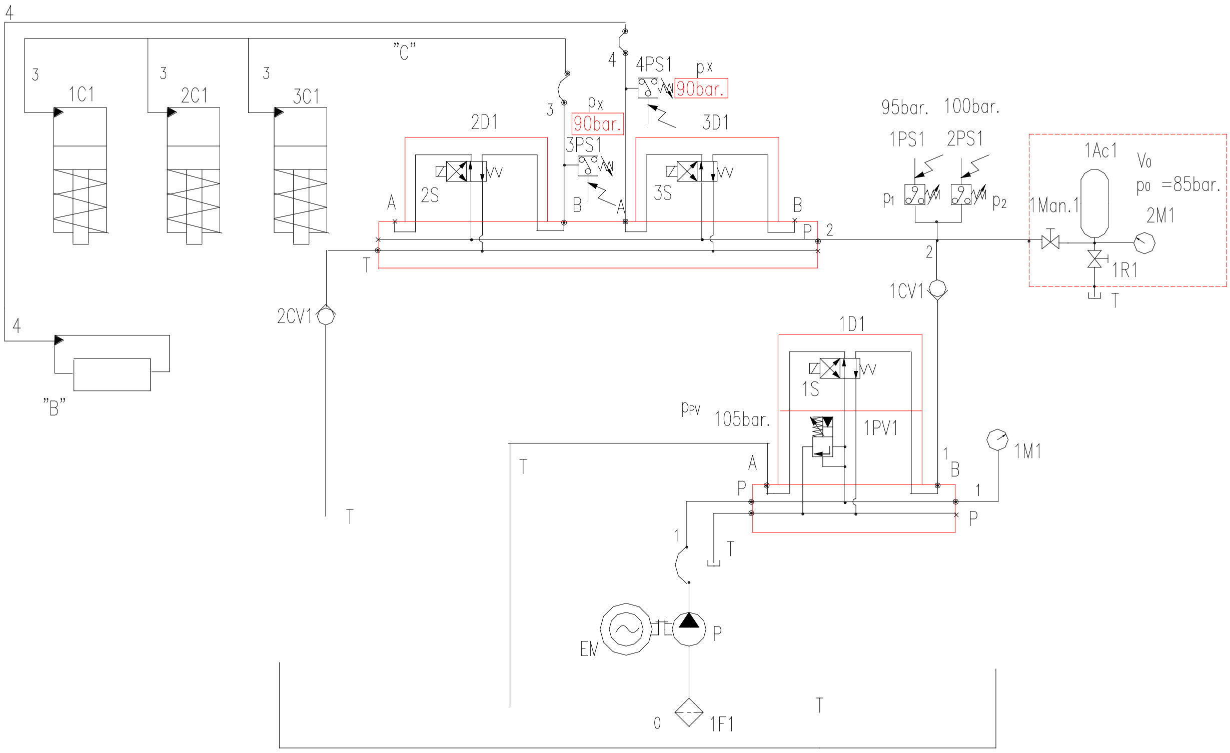

Fig. 2. Hydraulic diagram of the drilling machine

The operation of the system is also shown in the cyclogram in Table 1.

Table 1

No.	Phase	1S	2S	3S	1PS1	2PS1	3PS1	4PS1
1	STOP	-	-	-	(+,-)	(+,-)	-	(+,-)
2	START of circuit charging	+	-	-	-	-	-	+
3	Circuit charging	+	-	-	+	-	-	+
					+	+		
4	STOP of charging	-	-	-	+	+	-	+
5	Locking of C axis	-	-	-	+	+	-	+
6	Unlocking of C axis	(-,+)	+	-	+	+	+	+
7	Locking of B axis	(-,+)		-	+	+		+
8	Unlocking of B axis			+	(+,-)	(+,-)		-
$p_X < p_1 < p_2 < p_{PV}$								

There are three cylinders serving C axis: their diameter is D = 100 mm and the stroke c = 3 mm. The connecting pipe has the length L = 2.5 m and the inner diameter d = 6 mm. Under these conditions, the necessary volume is ΔV_L = 0.15 l.

If one considers that the discharge of the accumulator is made without actuating the pre-command, it is possible to obtain ΔV = 0.03 l by means of an accumulator with V_0 = 0.7 l and charged at p_0 = 85 bar, according to the relation (9). Therefore, the volume is insufficient. If an accumulator with V_0 = 2 l is used, it will be obtained ΔV = 0.18 l until the pressure p_X = 90 bar is reached. But, in reality, the pre-command is actuated when the pressure drops below the value p_1 = 95 bar. When this pressure is reached, the pre-command that will supply again the entire circuit is actuated.

4. Simulation of the Operation of the Locking/Unlocking System [4, 8]

To study the behavior in dynamic mode, it is possible to create models for the components of the hydraulic unit [11], which will be introduced according to the diagram, or to use specialized programs [12].
The diagram in Figure2 and the numerical values above-mentioned were used for the simulation.
Pump P is a gear pump that can provide a flow rate Q_P = 6 l/min. All the hydraulic devices have DN = 6 mm [13]. It was also considered that until the pressure value p_1 = 95 bar is reached, in a first situation, the pre-command is not engaged. The pressure is not allowed to drop below the value p_3 = 90 bar in the pressure switches 3PS1 and 4PS1. Any drop below this value is considered to be a clamping error and the machine is stopped. Then the simulation is resumed but, this time, when the p_1 pressure value is reached, the pump is switched on by actuating the pre-command. In the first phase, there are presented the results of the simulations performed for the accumulator with V_0 = 0.7 l.
Figure 3 shows the evolution of the pressures when the pre-command is not actuated, so only the oil from the accumulator is used.

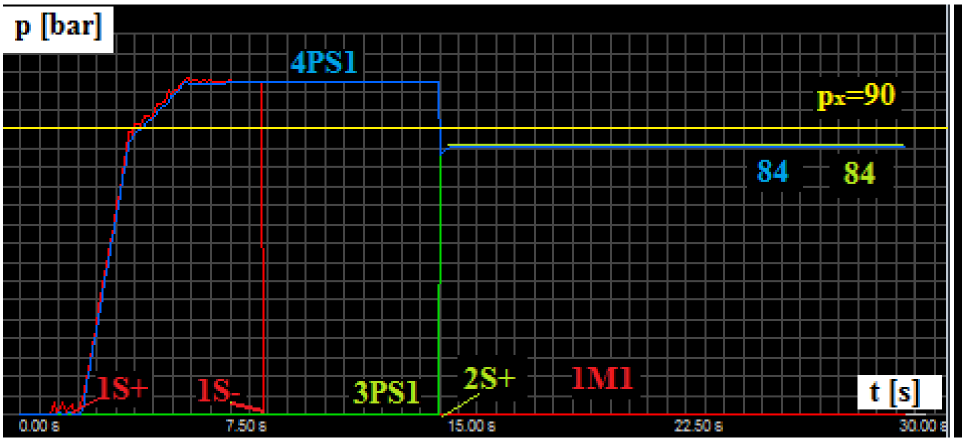

Fig. 3. Results of the simulation with an accumulator of volume V_0 = 0.7 l only

In this case, when the circuit (1S +) is charged, after about 5 s, the locking of the B axis is confirmed. If the supply of the accumulator is stopped (1S -) and the unlocking of the C axis (2S +) is commanded, the pressure drops to the value of 84 bar, below the minimum necessary pressure, p_X = 90 bar. This is equivalent to the occurrence of the locking/unlocking error.
If it is assumed that the circuit charging is not stopped, the evolution of the pressures is the one shown in Figure 4.
In this case too, when the circuit (1S +) is charged, after approximately 5 s, the locking of the B axis is confirmed. If the accumulator charging continues (1S +) and the unlocking of the C axis (2S +) is commanded, the pressure drops to the value of 84 bar for a short time, lower than the minimum pressure required, p_X = 90 bar. This means the occurrence of the locking/unlocking error. So, even if the pump is constantly supplying the circuit of the C axis locking/unlocking, errors may occur.

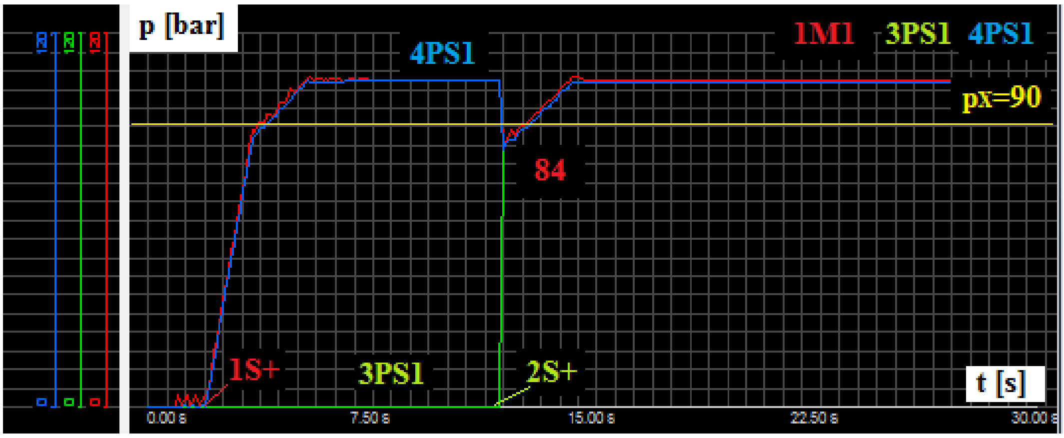

Fig. 4. Results of the simulation with pump and accumulator with volume V_0 = 0.7 l

In which case, the accumulator of 0.7 l was replaced with a 2 l one. Figure 5 presents the evolution of the pressures if the pre-command is not actuated, so only the oil from the accumulator is used.

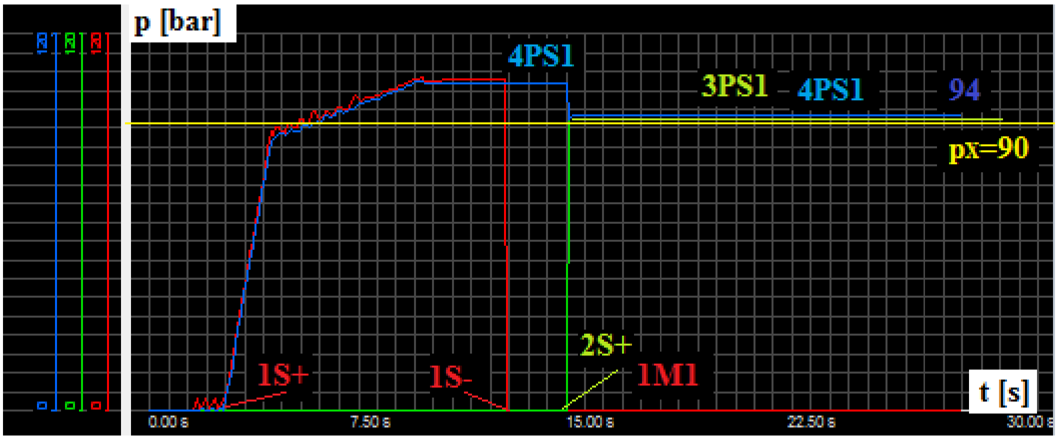

Fig. 5. Results of the simulation with an accumulator of volume V_0 = 2 l only

In this situation, when the circuit (1S +) is charged, after about 10 s the locking of B axis is confirmed. If the charging of the accumulator (1S -) is stopped and the unlocking of the C axis (2S +) is commanded, the pressure drops to the value of 94 bar, higher than the minimum necessary pressure, p_X = 90 bar. Therefore, the accumulator covers what is needed and the danger of a locking/unlocking error does not occur anymore.
If it is assumed that the circuit charging does not stop, the evolution of the pressures is the one shown in Figure 6.

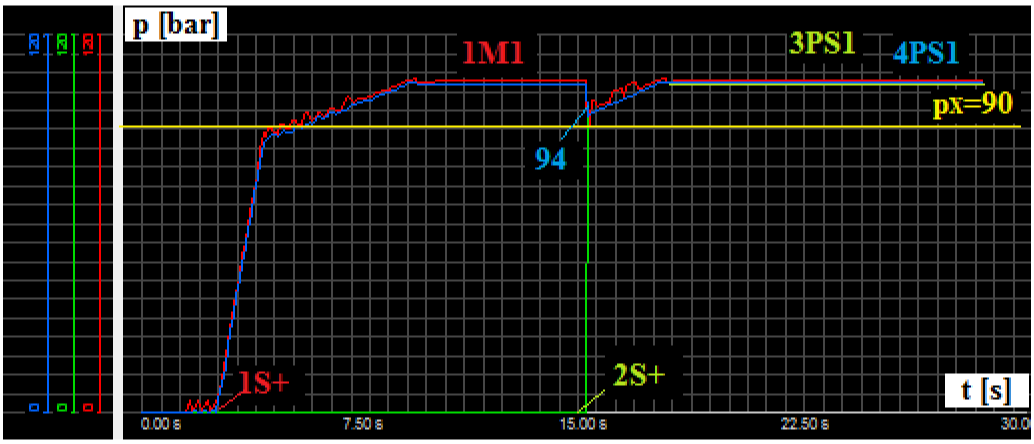

Fig. 6. Results of the simulation with pump and accumulator of volume V_0 = 2 l

In this case also, when the circuit (1S +) is charged, after 10 s approximately, the locking of the B axis is validated. If the accumulator charging is continued (1S +) and the unlocking of the C axis(2S +) is commanded, the pressure drops to the value of 94 bar for a short time, higher than the minimum pressure required, p_X = 90 bar, then increases to the maximum value. There is no more danger of error occurrence. The results are similar to the ones obtained through the calculations above. At the first actuation, the circuit reaches the intended pressure in 5 s if the accumulator has 0.7 l and in 10 s if an accumulator of V_0 = 2 l is used.

5. Presentation of the Actual Unit

The hydraulic unit intended for a NC drilling machine, made as per diagram in Figure 2, is shown in Figure 7.

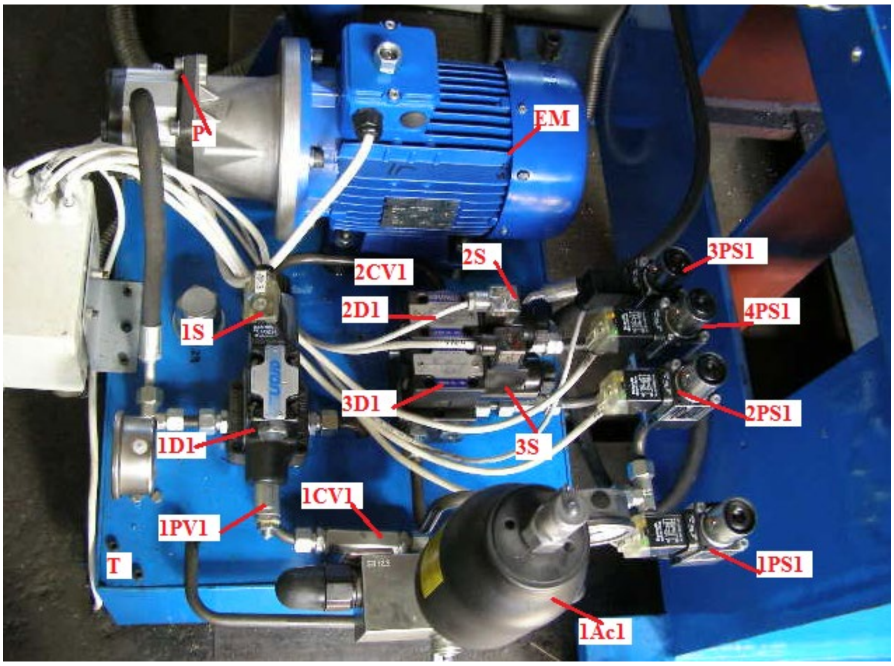

Fig. 7. Hydraulic unit

Figure 7 uses the same notations as in Figure 2. The tank T has the volume of 100 l. The accumulator shown in the figure is the one with V_0 = 0.7 l. This accumulator did not cope with the tests of the machine and was replaced with one of V_0 = 2 l. In this case, the pressure in the unit did not drop below the value of 95 bar, even during the switches. Thus, the equipment no longer detected errors and the operation of the machine was within the intended parameters.

6. Conclusions

The hydro-pneumatic accumulators used in the clamping/unclamping and locking/unlocking systems bring a series of advantages to these ones, such as:

- diminution of the electric power consumption;
- reduction of the noise during operation;
- reduction of the operating time of the pump under load;
- maintaining for a long time the regulated pressures.

The selection of the accumulator to be used and of the working pressures is made in conformity with the particularities of each system, following specific calculations that allow determining the flow rates or the volumes to be supplied.

There are simulation programs in dynamic mode that allow establishing the optimal accumulator. If the accumulator is too small, it will not cover the necessary flow rates (volumes). An accumulator that is too big takes longer to charge, increases the overall size of the system and the price of this one.

In such systems, especially in the case of the numerically controlled machine-tools, where the confirmations are electro-hydraulically performed (pressure switches), the accumulators will be checked in transitory mode too. Namely it will be verified to what extent they do not lose the pressure in the circuit, even for short periods of time, when activating the clamping/unclamping commands. In such cases, the simulation programs are really useful.

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