Modeling and Simulation of the Operation of the Hydro-Pneumatic Accumulators

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Abstract: *This paper introduces some mathematical models and simulations of the operation of the hydro-pneumatic accumulators from the hydraulic actuation systems. There are presented static but also dynamic models that can be used in the design of the hydraulic units. The operation in dynamic mode was simulated by means of specialized programs such as Matlab/Simulink and Automation Studio. A real, numerical example, which was the basis for the achievement of a hydraulic unit intended for machine-tools, was also presented.*

Keywords: *Hydro-pneumatic accumulators, modeling, simulation, hydraulic drives*

1. Introduction

The hydro-pneumatic accumulators, performing different tasks, are frequently used in the hydraulic units of machine tools, presses, plastic injection machines etc. [1, 2, 3, 4].
Regardless of its role fulfilled in the hydraulic unit [1, 2, 5], one can consider that the hydro-pneumatic accumulator operates according to the representation in Figure 1.

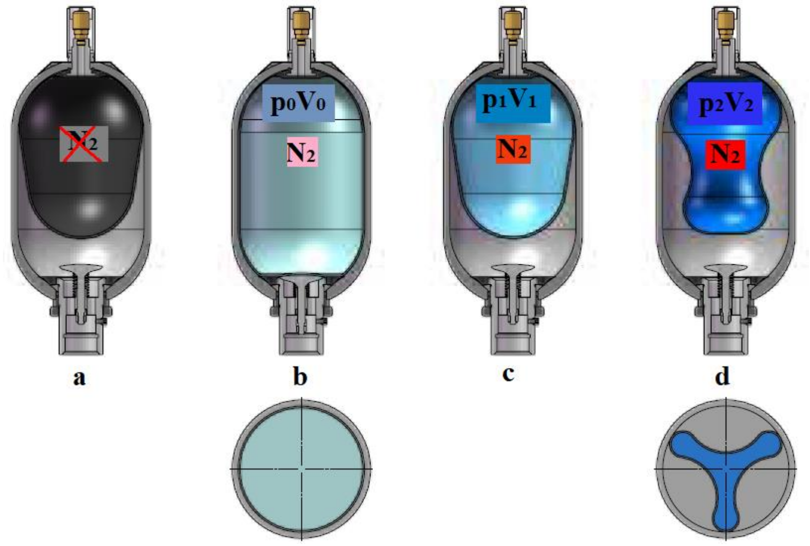

Fig. 1. Different states of a hydro-pneumatic accumulator

At the moment of its purchase, the accumulator is considered not charged, as shown in Figure 1a. It will be charged with nitrogen (N_2) by means of special devices [1, 3]. If the accumulator has the volume V_0, the charging is regarded as completed if the indicated pressure p_0 is achieved in this volume, as in Figure 1b.
Depending on the destination of the accumulator, this pressure represents a corresponding percentage from the minimum operating pressure of the unit p_1 [1, 2, 3].
When pressure p_1 is reached, the volume of nitrogen corresponds to volume V_1, in conformity with Figure 1c. When the maximum pressure is achieved in the unit, denoted by p_2, according to Figure 1d, the volume of gas is V_2.
The difference between the volumes V_1 and V_2, further denoted by ΔV, represents the volume of liquid entering or leaving the accumulator, depending on the operation phase.

2. State transformations underwent by the gas in the hydro-pneumatic accumulators

Immediately after charging with nitrogen at the pressure p_0, the oil sent by the pump gets into the accumulator located in the hydraulic unit, where it will reach the maximum pressure p_2 for the first time. In this case, it can be considered that the gas undergoes an isothermal transformation, as per the relation below:

$$p_0 V_0 = p_2 V_2 \tag{1}$$

Next, the accumulator is charged and discharged according to the operation phase. If these phases take place during "long" times, namely during minutes, it can be still considered that the transformations undergone are isothermal. Thus:

$$pV = p_1 V_1 = p_2 V_2 = ct. \tag{2}$$

In the above relation, it was also noted: V - instantaneous volume of the gas ($V \in [V_1, V_2]$) and p - instantaneous pressure of the gas ($p \in [p_1, p_2]$).
If the times for carrying out the operating phases are "short", of the order of seconds, it will be considered that the transformations are adiabatic ones, without heat exchange:

$$pV^{\gamma} = p_1 V_1^{\gamma} = p_2 V_2^{\gamma} = ct. \tag{3}$$

Besides the already known notations, it will be also considered the $\boldsymbol{\gamma}$ – the adiabatic coefficient specific to nitrogen, having the value 1.4.
By deriving the relations (2) and (3) as a function of time, the flow rates entering or leaving the accumulator will be obtained, in the case of isothermal (ΔQ_I) and adiabatic transformations (ΔQ_A):

$$p\frac{dV}{dt} + V\frac{dp}{dt} = 0 \tag{4}$$

$$\Delta Q_I = \frac{dV}{dt} = -\frac{V}{p}\frac{dp}{dt} = -\frac{pV}{p^2}\frac{dp}{dt} = -\frac{p_0 V_0}{p^2}\frac{dp}{dt} \tag{5}$$

$$p\gamma V^{\gamma-1}\frac{dV}{dt} + V^{\gamma}\frac{dp}{dt} = 0 \tag{6}$$

$$\Delta Q_A = \frac{dV}{dt} = -\frac{V}{p\gamma}\frac{dp}{dt} = -\frac{pV}{p^2\gamma}\frac{dp}{dt} \sim -\frac{p_0 V_0}{p^2\gamma}\frac{dp}{dt} \tag{7}$$

In the phases when the accumulator is charged, the useful flow rate Q_U will be lower than the flow rate of the source (Q_S) and when the accumulator is discharged, the useful flow rate is higher than the flow rate of the source. In the relations below, ΔQ_I and ΔQ_A are positive or negative, depending on how the pressure changes:

$$Q_U = Q_S + \Delta Q_I \tag{8}$$

$$Q_U = Q_S + \Delta Q_A \tag{9}$$

The following frequently encountered variants will be taken into account [6] as sources of pressure:

- constant flow pumps with pressure relief valve;
- variable flow pumps with pressure control valve.

The flow rate of the source is defined as:

$$Q_S = \begin{cases} Q_P; p \le p_{11} \\ Q_P \frac{p_{12}-p}{p_{12}-p_{11}}\ ; p_{11} < p \le p_{12} \\ 0; p > p_{12} \end{cases} \tag{10}$$

In the relation above it was also noted: Q_P – maximum flow rate of the source; p_{11} – pressure at which the pressure valve or the pump control valve will start to discharge; p_{12} – the pressure at which the entire flow is discharged to the tank if the pump is a constant flow one or if the flow pressure provided by the variable flow pump is zero.
If the operating pressures of the accumulator check the relation $p_1 < p_2 < p_{11}$, then it can be considered:

$$Q_S = Q_P \tag{11}$$

3. Determining the required flow rate at the pressure source in the hydraulic systems with hydro-pneumatic accumulator

It will be taken into account the diagram in Figure 2.

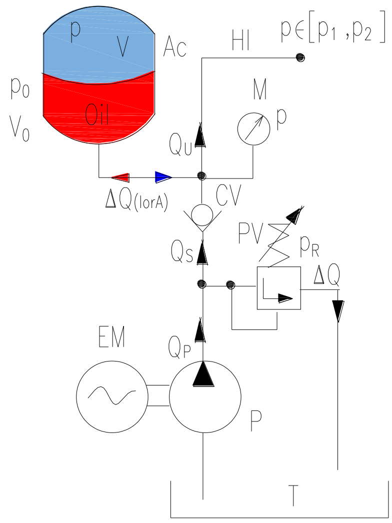

Fig. 2. Installing the hydro-pneumatic accumulator in the hydraulic unit

Pump P, driven by the electric motor EM, sucks the oil from tank T. The pressure relief valve PV is adjusted at the pressure p_R ~ p_{11} ~ p_{12}. The oil is sent to the hydraulic unit HI and to the accumulator Ac through the check valve CV. The accumulator has the volume V_0 and is charged with nitrogen at the pressure p_0. In the hydraulic unit, the pressure varies in the range [p_1, p_2], increasing and decreasing alternately. The instantaneous pressure p can be permanently viewed on the manometer M. The flow rate of the source Q_S is equal with the flow rate of the pump Q_P. The useful flow rate Q_U is the one that results according to the relations (8) and (9).
The necessary flow for the unit changes over time as per Figure 3.

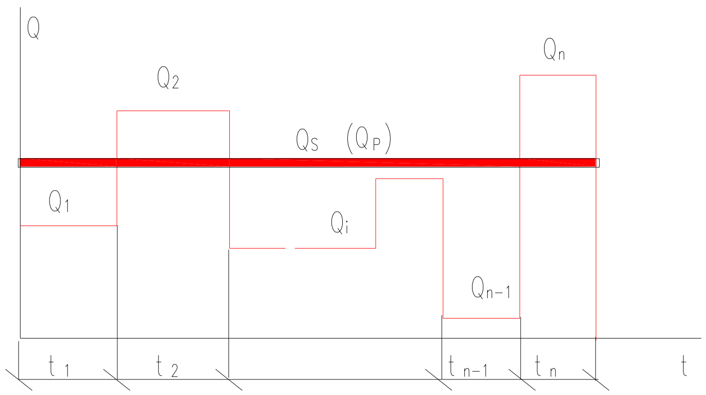

Fig. 3. The necessary flow for the unit

In each phase that lasts a time t_i, a flow rate Q_i is necessary, where i ϵ {1, 2,...n}, n being the number of phases. In a unit without accumulator, one must choose a possible source (constant flow pump) able to fulfill the condition:

$$Q_P \geq \max Q_i \,; i \in \{1{,}2..n\} \quad (12)$$

If the unit has an accumulator, the following relation is recommended for choosing the pump:

$$Q_P \geq \frac{\sum_1^n Q_i t_i}{\sum_1^n t_i} \quad (13)$$

4. Static calculation of the hydraulic systems that include hydro-pneumatic accumulators. Numerical example

The following values are regarded as known: n = 2, Q_1 = 16 l/min, t_1 = 5 s, Q_2 = 5 l/min, t_2 = 200 s, p_1 = 60 bar, p_2 = 80 bar, p_0 = 50 bar, γ = 1.4.
Q_P will be determined using the relation (13):

$$Q_P \geq \frac{Q_1 t_1 + Q_2 t_2}{t_1 + t_2} = 5.26[\frac{l}{min}] \quad (14)$$

A pump with Q_P = 6 l/min is selected by means of the catalogue [3].
Next, using the relation (1), the volume V_2 is determined depending on the volume V_0, still unknown:

$$V_2 = \frac{p_0 V_0}{p_2} \quad (15)$$

Considering that the discharge is adiabatically performed, it is possible to determine the volume V_2 also, as a function of V_0, with the help of the relation (3):

$$V_1 = \frac{p_0 V_0}{p_2}\left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}} \quad (16)$$

The available volume of oil represents the difference between the volumes above mentioned:

$$\Delta V = V_1 - V_2 = \frac{50 V_0}{80}\left(\left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}} - 1\right) = 0.139 V_0 [l] \quad (17)$$

The theoretical flow rate ensured by the discharge of the accumulator is:

$$\Delta Q_A = \frac{\Delta V}{t_1} = \frac{0.139 V_0}{\frac{5}{60}} = 1.66 V_0 [\frac{l}{min}] \quad (18)$$

In reality, the value of this flow rate depends also on the characteristics of the equipment used: type, DN, pressure drops etc. [7].
In order to choose the minimum volume of the accumulator, the following relation must be used:

$$Q_P + \Delta Q_A \geq Q_1 \quad (19)$$

According to the relationship above, the minimum volume of the accumulator V_0 ≥ 6 l is obtained. An accumulator with V_0 = 6.3 l is chosen from the catalogue [3]. In terms of this value, after replacement in the relations (15), (16), (17) and (18), the following values will be obtained: V_1 = 4.81 l, V_2 = 3.97 l, ΔV = 0.84 l, ΔQ_A = 10.15 l/min.
The charging throughout the normal operation of the accumulator is made with an average flow rate that has the value:

$$\Delta Q_I = \frac{\Delta V}{t_2} = \frac{0.84}{\frac{200}{60}} = 0.252[\frac{l}{min}] \quad (20)$$

During this phase, the useful flow rate will be:

$$Q_U = Q_P - \Delta Q_I = 5.7[\frac{l}{min}] \quad (21)$$

5. Simulation of the operation in dynamic mode of the hydraulic systems that contain a hydro-pneumatic accumulator by means of Matlab/Simulink programs. Numerical example [8]

To simulate the operation in dynamic mode, based on the mathematical models above (relations (1) -(9)), the diagram in Figure 4 was created by simulating in Simulink [8, 9].

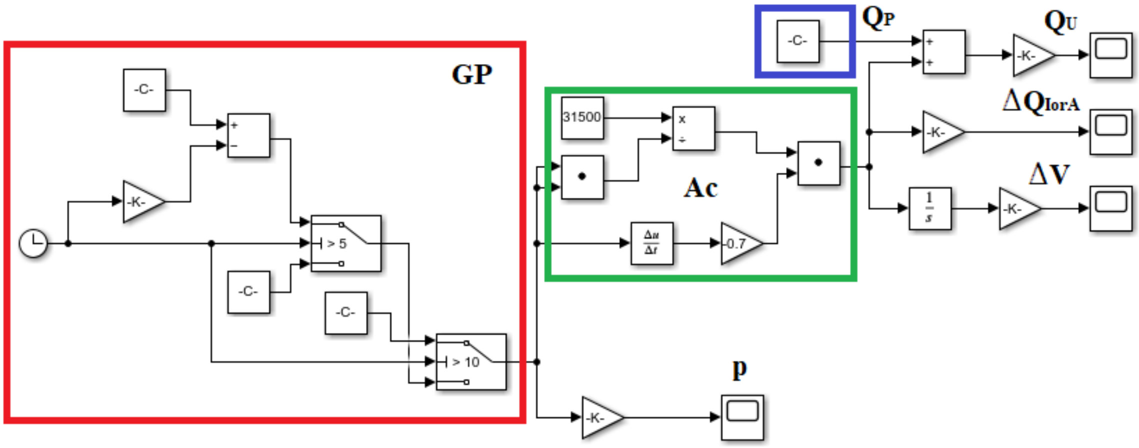

Fig. 4. Diagram of operation simulation

Figure 4 has the following supplementary notations: GP – variable pressure generator in the [60 - 80] bar range, Ac – hydro-pneumatic accumulator.
For the adiabatic discharge phase between the pressures p_2 = 80 bar and p_1 = 60 bar, the flow rate supplied by the accumulator ΔQ_A has the characteristic in Figure 5.

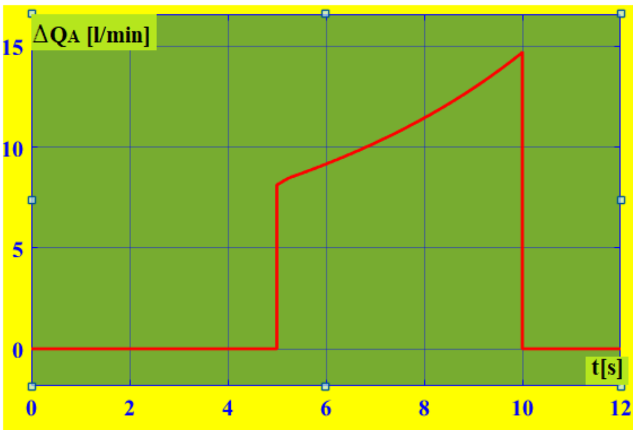

Fig. 5. Characteristic of the flow rate provided by the accumulator in the case of adiabatic discharge

In the discharge interval of 5s, the supplementary flow rate provided increases from 8 to 14 l/min. The average value is 11 l/min. The value of 10.15 l/min is obtained from static calculation.
During the isothermal charging, between p_1 = 60 bar and p_2 = 80 bar the useful flow rate evolves according to the characteristic shown in Figure 6.

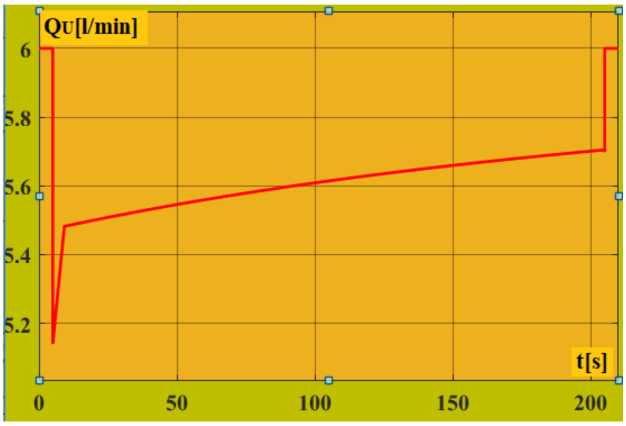

Fig. 6. Characteristic of useful flow rate in the case of isothermal charging

In the charging interval of 200 s, the usable flow rate covers the needs of the unit, even if the accumulator is charged, having an average value of 5.6 l/min.

6. Simulation of the operation in dynamic mode of the hydraulic systems that contain a hydro-pneumatic accumulator by means of Automation Studio programs [8]. Numerical example

Unlike the simulation by means of Matlab programs [8, 9], when using Automation Studio the mathematical models specific to hydraulic equipment are pre-installed; the user is able to define only the specific parameters (in the case of the accumulator - V_0, p_0, p_1, p_2, t_1, t_2 etc.), not the equations that define their operation.
Using Automation Studio, the characteristic of the adiabatic discharged flow rate between p_2 = 80 bar and p_1 = 60 bar shown in Figure 7 was obtained for the same numerical data.

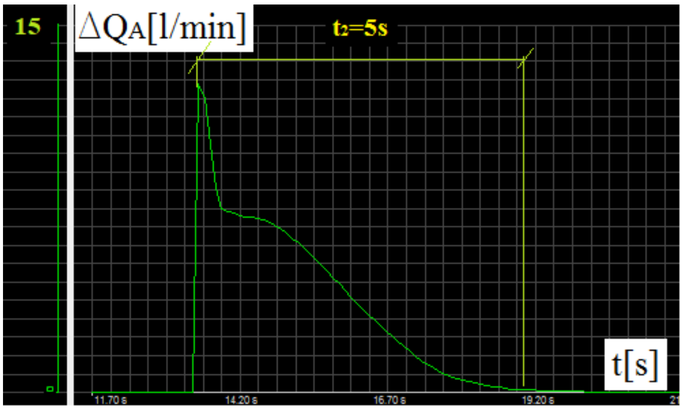

Fig. 7. Characteristic of the flow rate provided by the accumulator in the case of adiabatic discharge

During the ~5s of discharge, the provided flow rate has an approximate average value of 7 l/min.
During the simulation, it was found out that the discharge is influenced, in terms of time but also in terms of flow rate, by possible pressure drops existing in other hydraulic devices such as throttle valves, directional valves etc.
Throughout the isothermal charging of the accumulator from p_1 = 60 bar to p_2 = 80 bar, the useful flow rate develops according to the characteristic in Figure 8.
It is observed that after approximately 60 s of the available 200 s, the useful flow rate reaches a value close to the maximum of 6 l/min.
In this case too, the characteristic is influenced by the rest of the equipment.

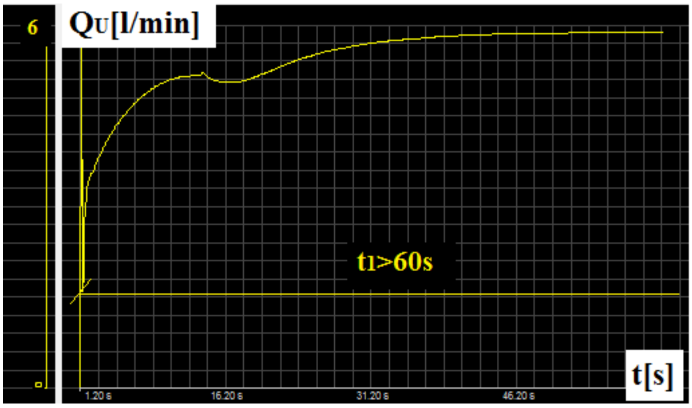

Fig. 8. Characteristic of useful flow rate in the case of isothermal charging

7. Conclusions

By using hydro-pneumatic accumulators, it is possible to obtain hydraulic units with a number of advantages such as: reducing the flow rates provided by the pumps, diminution of the power of their drive motors, reducing the tank volume and consequently the necessary oil.
The gas in the accumulators actually undergoes polytropic transformations, but in order to make the static and dynamic calculations it can be considered that in the case of short times, of the order of seconds, the transformations can be taken as adiabatic ones, while if the times are of the order of minutes the transformations can be regarded as isothermal ones.
Static models can be used for pre-dimensioning the hydraulic units. After this pre-dimensioning, mathematical models for dynamic mode can be used, but in their case, due to the multitude of factors that occur during operation, different results can be obtained.
The specific equipment of each unit, depending on the DN and the pressure drops, influences the behavior of the accumulator.
If the operation cycle of the unit allows it, the accumulator can represent a source of energy that can make possible to stop the pump for certain phases.
The simulations that use specific programs are really useful in the design phase and allow making some corrections that were usually made after the completion of the prototype.

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