Mathematical Modeling and Simulation of the Operation of Hydraulic Systems with Resistive Adjustment

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Abstract: *In this paper, the author presents, based on mathematical models in static and dynamic conditions and with the help of simulation programs, how to achieve the resistive adjustment of the operating speed of the hydraulic cylinders. The described models take into account the characteristics of the cylinders and throttles, but also those of the pressure valve. In all cases it is considered that the drive pump has constant capacity and is actuated by an electric motor whose rotational speed is also constant.*

Keywords: *Resistive adjustment of speed, direct, return, derivation*

1. Introduction. Defining the Elementary Source [1, 2]

The elementary source is formed of the pump P and the pressure valve PV, as shown in Figure 1. The pressure in the hydraulic unit HI is visualized at any moment by means of the pressure gauge M.

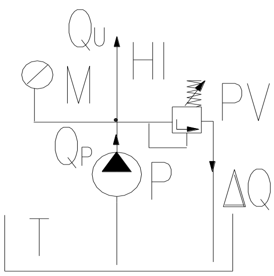

Fig. 1. Hydraulic diagram of the elementary source

The flow rate supplied by the pump is Q_P and is considered constant. The hydraulic unit HI is supplied by the elementary source with useful flow Q_U; the flow ΔQ [1, 3] is discharged through the pressure valve PV.
These flow rates have the following relation:

$$Q_U = Q_P - \Delta Q \tag{1}$$

The discharge of the flow ΔQ is made according to the characteristic shown in Figure 2.

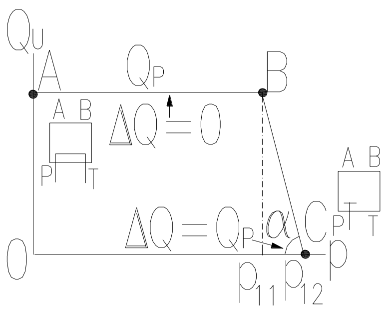

Fig. 2. Operating characteristic of the elementary source

The pressure valve is adjusted so that the first drop of oil passes through it at pressure p_{11}; when the pressure p_{12} is reached, the entire flow of the pump Q_P passes through it. It is considered a linearized characteristic on the segment BC having its angle α very close to 90°. The useful flow can be expressed as follows:

$$Q_U = \begin{cases} Q_P, p \le p_{11} \\ Q_P \frac{p_{12}-p}{p_{12}-p_{11}}, p_{11} < p \le p_{12} \\ 0, p_{12} < p \end{cases} \quad (2)$$

As it can be seen in Figure 2, the flow sent by the elementary source to the hydraulic unit depends also on the type of directional control valve used. If this one has a P→T connection, during the “at rest” position, the supplied flow depends on the pressure on the ABC path. If the directional control valve has its P path closed in the “at rest” position [1, 4], the useful flow follows the CBA path when the opening control is actuated. As it will be shown below, depending on the involved cylinder and its load, the operating point will be identified on the characteristic in Figure 2. If the unit is provided with throttling, this one can be used, with real effects, only on the BC segment.

2. Direct Throttling. Stationary Mathematical Models

Let consider the diagram with direct throttling shown in Figure 3.

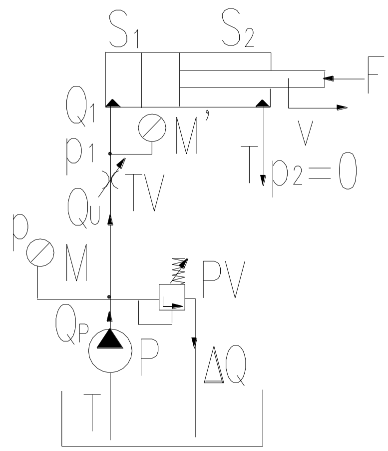

Fig. 3. Flow direct adjustment

The elementary source supplies the cylinder with the active surfaces S_1 and S_2 through the TV throttle. The pressure p_1 is measured by means of the pressure gauge M’. The cylinder rod moves with speed v against force F. It is considered that the entire flow supplied by the elementary source (Q_U) is sent by the throttle (Q_1) to the active surface S_1 and that the return pressure (on surface S_2) is negligible. The coefficient of the surfaces is $k = S_2/S_1$. This one keeps within the range [0, 1] and most often is ~0.5 [5]. If the throttling surface is S_{TV}, the oil density is ρ and the throttling constant is denoted by C_{TV} [5, 6, 7], the following expression is obtained for speed v:

$$v = \frac{C_{TV} S_{TV}}{S_1} \sqrt{\frac{2}{\rho}\left(p - \frac{F}{S_1}\right)} \quad (3)$$

Starting from the characteristic of the elementary source in Figure 2 and from the relation (3), the Figure 4 shows the way to determine the operating point of the unit (X) and the way to determine the speed for a series of parameters of the unit: Q_P, p_{11}, p_{12} and S_{TV}.

The working pressure must be higher than F/S_1 and the operating point X is obtained by opening (+) or closing the throttle (-) TV, at the intersection of the characteristic of the elementary source with the parabolic characteristic. A certain speed and the pressure p_X correspond to this operating point. If point X belongs to segment AB, the throttle adjustment is inefficient. If point X belongs to BC segment, the adjustment depends on: Q_P, p_{11}, p_{12} and S_{TV}.

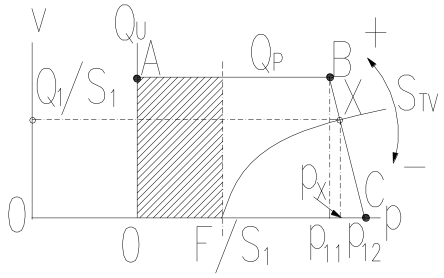

Fig. 4. Determination of the operating point in case of direct throttling

3. Return Throttling. Stationary Mathematical Models

Consider the diagram with return throttling in Figure 5. The TV throttle adjusts the flow rate Q_2 pushed out by the surface S_2 of the cylinder. The pressure p_2 measured by the pressure gauge M' is developed on this surface.

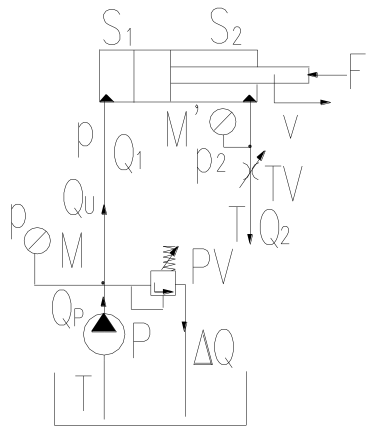

Fig. 5. Adjustment of flow on cylinder return

The pressure of the elementary source acts on the surface S_1 of the cylinder and the useful flow is the flow supplied by the elementary source. The speed obtained in the same conditions as above is:

$$v = \frac{C_{TV} S_{TV}}{k\sqrt{k} S_1} \sqrt{\frac{2}{\rho}(p - \frac{F}{S_1})} \tag{4}$$

It can be noticed that a higher speed is obtained for a same adjustment. Thus, for k = 0.5, the speed obtained by relation (4) is almost three times higher than the one obtained with the help of the relation (3).
The determination of the operating point and speed can be done according to the characteristic in Figure 6.
The operating point X moved to the left related to the position occupied by the characteristic of direct throttling, presented by means of a dotted line. The pressure p_X too moves to the left, approaching the pressure p_{11}.
Therefore, in case of return throttling, the travel can be adjusted more precisely, with higher accuracy.
The presence of the pressures p and p_2 on the surface S_1 and respectively S_2 guarantees a greater stability.

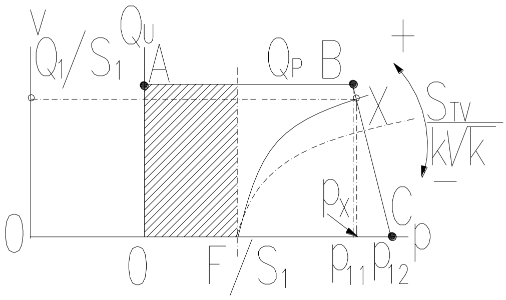

Fig. 6. Determination of the operating point in case of return throttling

4. Derivation Throttling. Stationary Mathematical Models

In this case, the throttle is assembled in front of the consumer, so that the excess flow is discharged directly to the tank, as shown in Figure 7.

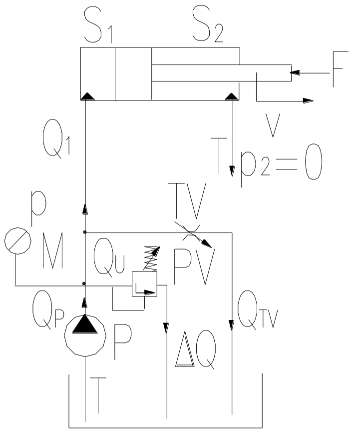

Fig. 7. Flow adjustment by derivation throttling

In such case, the flow rate Q_1 for surface S_1 supply is (keeping the same notations as above):

$$Q_1 = Q_U - Q_{TV} \tag{5}$$

The flow discharged through the TV throttle has the expression below and the characteristic in Figure 8.

$$Q_{TV} = C_{TV} S_{TV} \sqrt{\frac{2}{\rho} p} \tag{6}$$

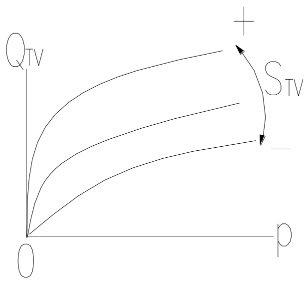

Fig. 8. Characteristic of the throttle assembled in derivation

One can observe that the Q_{TV} flow rate depends parabolic on the pressure. According to the parabola opening, the operating point and implicitly the cylinder speed can be determined by means of the relations (5) and (6) and with the help of the characteristics in Figures 2 and 8.
If the characteristic of Q_{TV} flow has a large opening (large S_{TV}), its intersection with the characteristic of the elementary sources made in the AB segment of this one, thus obtaining the characteristic in Figure 9.

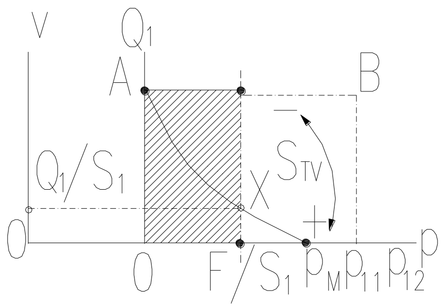

Fig. 9. Determination of the operating point in case of derivation throttling at large opening of the throttle

One can notice that the maximum pressure p_M in the unit is lower than the value p_{11}; the set speed is much reduced.
If the Q_{TV} flow characteristic has a smaller opening (S_{TV} small), its intersection with the characteristic of the elementary source is made on the BC segment of this one, obtaining the characteristic in Figure 10.

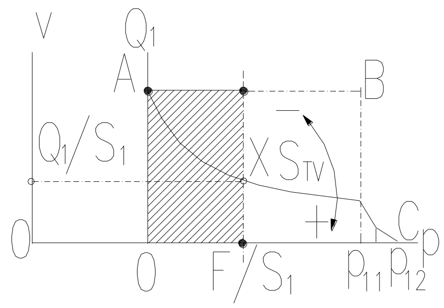

Fig. 10. Determination of the operating point in case of derivation throttling at small opening of the throttle

In this case, it is observed that the pressure can even reach the value p_{12}. In this situation too, the set speed is much reduced.

5. Simulation of Resistive Speed Adjustment Systems for the Hydraulic Cylinders

In order to study the behavior of cylinders in dynamic mode, several methods can be used:

- elaboration of differential equations and their solution by classic methods [8];
- elaboration of differential equations and their solution by specialized programs [6, 9];
- direct use of specialized programs, without the need for specific differential equations [10].

The results of the simulations performed using the AUTOMATION STUDIO programs package are presented below.
The data of the studied elements are: the pump has a flow rate Q_P = 9 l/min, the pressure adjusted at the pump $p_{11} = p_{12}$ = 60 bar, all the equipment is DN6. The TV throttle can be adjusted so that its surface $S_{TV} \in [0, 0.28]$ cm^2; it has an opening of 5% of this value. The hydraulic cylinder has the useful surfaces in the relation $k = S_2/S_1 = 0.7$.
In the direct throttling, if at the moment of the command the pump discharges freely to the tank (P→T), the time necessary for reaching the maximum speed (0.85 m/min) is about 2.7 s according to the characteristic in Figure 11.

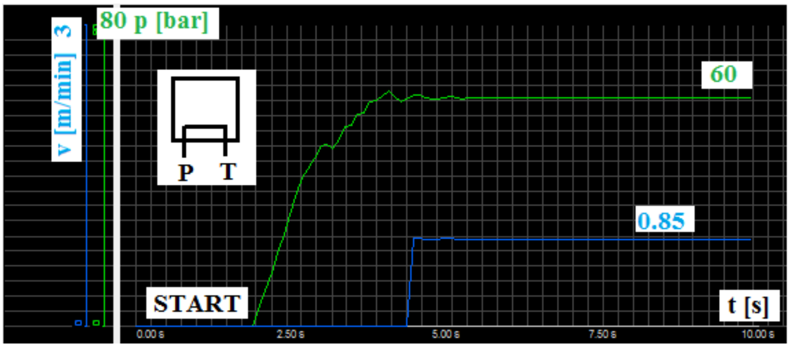

Fig. 11. Characteristic of direct throttling with zero initial pressure

The pressure reaches the maximum value set at the pressure valve PV, namely 60 bar.
If the pressure has its maximum value at the moment of the command, the maximum speed of 0.85 m/min is reached in less than one second. The pressure decreases at the start and then reaches the initial value, as in Figure 12.

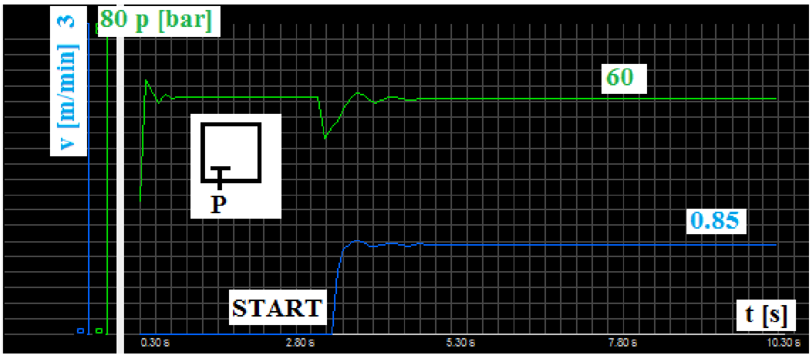

Fig. 12. Characteristic of direct throttling with maximum initial pressure

In this case, the system responds faster to commands, but in the stop phase, a larger amount of electric power is consumed. The unit may heat up for this reason.
By placing the throttle on the return, as it results from the relations (3) and (4), the same parameters make possible a higher speed. Thus, the maximum speed, reached as per the characteristic in Figure 13, is 1.35 m/min.

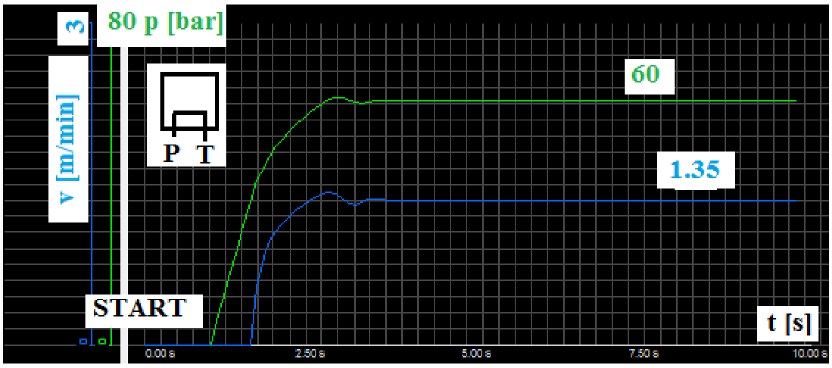

Fig. 13. Characteristic of return throttling with zero initial pressure

Since the initial pressure is zero, the speed stabilization time is approximately 3 s. The pressure is the one set at the pressure valve.
If one chooses a directional control valve that ensures a maximum value of the pressure at the time of the command, the characteristic in Figure 14 is obtained.

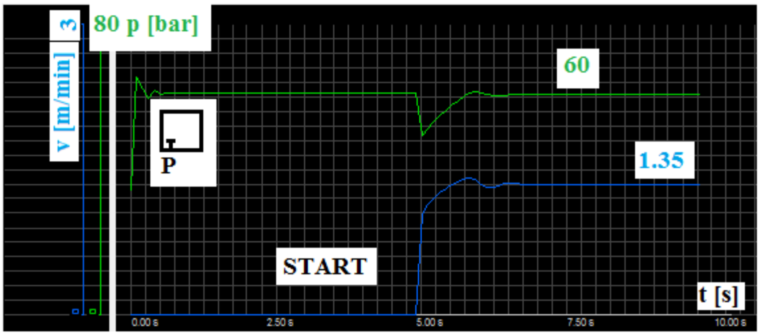

Fig. 14. Characteristic of return throttling with maximum initial pressure

The system is much faster given that the maximum speed is reached in ~0.5 s. The pressure decreases at the moment of the command, which can be explained by the need to compress the column. The major disadvantage of this variant is maintaining the pressure permanently, which can lead to the heating of the system and to an increase in energy consumption.
If the throttling is made in derivation and the pump discharges freely, the characteristic in Figure 15 will be obtained at the moment of the start command.

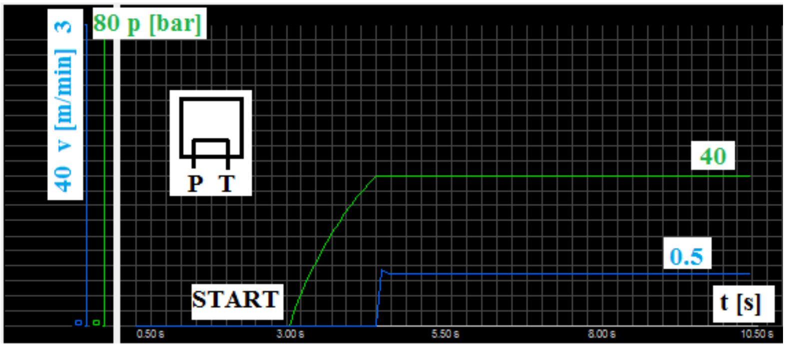

Fig. 15. Characteristic of derivation throttling with zero initial pressure

One can notice that the maximum value of the pressure, adjusted by means of PV valve, is no longer reached. The maximum speed is much reduced, reaching the value of 0.5 m/min. It is the variant with the lowest risk of heating and is also the lowest energy consumer.
If the throttling is made in derivation, but with the maximum pressure at the start-up moment, the characteristic in Figure 16 will be obtained.

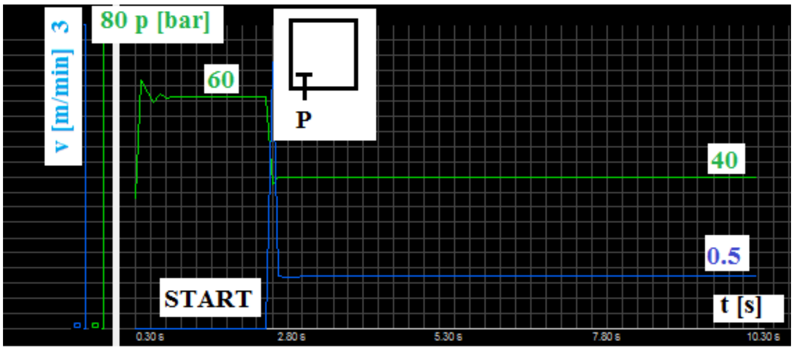

Fig. 16. Characteristic of derivation throttling with maximum initial pressure

One can observe that, even if the start is made with maximum pressure, this one will decrease and get stable when the speed reaches the value of 0.5 m/min. The start-up time is considerably reduced, with a visible pressure drop of ~ 20bar.

6. Conclusions

The resistive adjustment of the speed (flow rate) is usually performed by means of throttles. These ones can be assembled directly (between the pump and the cylinder), on the return (at the outlet from the cylinder towards the tank) or in derivation (after the pump, before the cylinder, but directly connected to the tank). Each of these three variants has its advantages and disadvantages. The return adjustment ensures a higher speed at the same throttle adjustment than the direct adjustment. The ratio of the obtained speeds depends on the ratio of the cylinder surfaces (k) proportional to $k^{3/2}$. The presence of pressures on both sides of the cylinder leads to a much more stable movement.
In the case of derivation throttling, the maximum pressure during operation may be lower than the pressure adjusted at the pressure valve. The speeds in this situation are lower than those in the direct or return adjustment. The energy consumed is lower and the heating level decreases. In some cases, the throttled oil can be used to lubricate some mechanisms.
The characteristics of the throttling are also influenced by the type of directional valve used to drive the cylinders. If the directional valve, in the “at rest” phase, ensures the direct connection P→T, then, after the command, the pressure increases and the cylinder starts only after overcoming the resistance forces.
If the directional valve ensures the maximum pressure at the command moment, the start is much faster, making possible a greater promptness.
Depending on the specifics of each unit, after a thorough analysis and possibly after a simulation with real data, the optimal variant can be determined.

References

[1] Prodan, Dan. *Machine-Tools Hydraulics/Hidraulica Masinilor-Unelte*. Bucharest, Printech Publishing House, 2004.
[2] Prodan, Dan, Emilia Balan, and Sanda Gandila. "The Calculation Method of the Point of Functioning of the Hydraulic System." *Romanian Journal of Technical Sciences Applied Mechanics,* Tome 49 (November 2004): 207-213.
[3] Portelli, Michel. *Industrial Hydraulic Technology/Technologie d’hydraulique industrielle*. Paris, Editions Casteilla, 1995.
[4] Totten, George E., and Victor J. De Negri. *Handbook of Hydraulic Fluid Technology*. Boca Raton, CRC Press Taylor & Francis Group, 2012.
[5] ***. ATOS, PARKER, and BOSCH REXROTH Catalogues and leaflets.
[6] Prodan, Dan. *Machine Tools. Modeling and Simulation of Hydrostatic Elements and Systems/Maşini-Unelte. Modelarea şi Simularea Elementelor şi Sistemelor Hidrostatice*. Bucharest, Printech Publishing House, 2006.
[7] Guibert, Philippe. *Applied Industrial Hydraulics/Hydraulique industrielle appliquée*. Paul Verlaine Université de Metz, 2008.
[8] Mazilu, Ion, and Virgil Marin. *Automatic Hydraulic Systems/Sisteme Hidraulice Automate*. Bucharest, Romanian Academy Publishing House, 1982.
[9] Oprean, Aurel, Constantin Ispas, Emil Ciobanu, Sergiu Medar, Adrian Olaru, and Dan Prodan. *Hydraulic Drives and Automation/Acţionări şi Automatizări Hidraulice.* Bucharest, Technical Publishing House, 1989.
[10] ***. AUTOMATION STUDIO Software package.