Synchronization of the Travel of Hydraulic Cylinders. Modeling and Simulation

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Abstract: *In this paper, the authors present the theoretical research and simulations performed for establishing some variants of hydraulic drive for the units that require two or more cylinders. Two simple and affordable methods that do not entail special expenses are shown comparatively. The solutions can be applied for systems that do not require very precise positioning, but which must have a good repeatability.*

Keywords: *Hydraulic cylinders, synchronous travel*

1. Introduction. Need for Synchronization

Let us consider the actuation diagram in Figure 1.

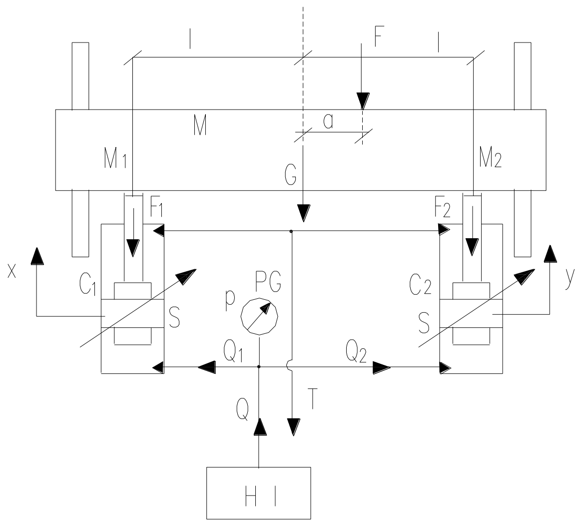


Fig. 1. Simplified hydraulic diagram of a system with two synchronized cylinders

Cylinders C_1 and C_2 – with the distance 2 *l* between them - lift a load of mass *M* and a weight *G*. The load travels on two vertical guideways against a force *F* positioned at a distance *a* related to the axis of symmetry. The cylinders are of the same type but, even in this case, there are inherent differences between them: different coefficients of friction at the rod and piston, different values of the flow losses coefficients proportional to pressure (a_1 and a_2) and of the coefficients of force loss proportional to speed (b_1 and b_2) [1, 2, 3].

Initially the cylinders are in lower position. The hydraulic unit (HI) transmits a flow *Q* to the lower surfaces *S* of the two cylinders. The pressure provided by the source has the common value *p*, visualized by means of the pressure gauge PG [4]. The specific forces F_1 and F_2 and masses M_1 and M_2 correspond to the cylinders C_1 and C_2. The positions of the cylinders C_1 and C_2 are defined by the dimension *x* and *y*, respectively [1, 3, 5, 6]. When the cylinders go upwards, it is necessary to meet at all times the condition:

$$|x - y| < \varepsilon \quad (1)$$

In the relation (1), the allowable difference of size was noted by ε. During the lifting, the oil behind the two pistons passes freely to the tank T.
The hydraulic unit is supplied by a classic pressure source consisting of a constant flow rate pump and a pressure valve [4].
Under these conditions, the mathematical model of this system is:

$$F_1 = \frac{l(F+G)-Fa}{2l} \tag{2}$$

$$F_2 = \frac{l(F+G)+Fa}{2l} \tag{3}$$

$$Q_1 + Q_2 = Q \tag{4}$$

$$Q_1 = S\frac{dx}{dt} + a_1 p_1 + \frac{V_0 + xS}{E}\frac{dp_1}{dt} \tag{5}$$

$$Q_2 = S\frac{dy}{dt} + a_2 p_2 + \frac{V_0 + yS}{E}\frac{dp_2}{dt} \tag{6}$$

$$M_1\frac{d^2x}{dt^2} + b_1\frac{dx}{dt} + F_1 + F_{F1} = p_1 S \tag{7}$$

$$M_2\frac{d^2y}{dt^2} + b_2\frac{dy}{dt} + F_{12} + F_{F2} = p_2 S \tag{8}$$

In the relations (2) - (8) it was also noted: t – time; F_{F1} and F_{F2} – the reduced total friction forces at each cylinder; V_0 - the initial volume of liquid in the circuit of each cylinder; E – the modulus of elasticity of the oil; p_1 and p_2 - instantaneous pressures on the S surfaces of the cylinders C_1 and C_2.
The synchronous travel in terms of position is ensured by the condition specified in the relation (1). As soon as both cylinders reach the maximum upper position, the lowering command can be given. In this case, the mathematical model is similar to the one shown above.
These mathematical models can be extended to more cylinders. High accuracy synchronization involves the use of expensive equipment, servo or proportional type and of position transducers (resistive, inductive, optical ones etc.) [4]. The subject of this article refers to the less accurate synchronized systems, such as the ones for auxiliary kinematic chains of the machine tools [4]. These ones use the classic equipment and do not require position transducers.
In order to study the different variants of actuation, a real case was taken into consideration: the protective guard of the working area of a vertical lathe [7]. The up and down movement of this protective guard is actuated by two cylinders. The cylinders have the working surface S = 12.56 cm^2 (diameter of 40 mm), stroke c = 900 mm, M_1 = 100 Kg, M_2 = 150Kg, F_1 = 60 daN, F_2 = 80 daN. The pressure valve is set to p = 20 bar and the pump supplies a flow of Q_P = 9 l/min. In static conditions, the pressures necessary for the two cylinders are: p_1 = 12.73 bar and p_2 = 18.31 bar. It can be noticed that these values are lower than the value set at the pressure valve. In this case, the time required to achieve the complete stroke at both cylinders is:

$$t = \frac{2Sc}{Q_P} \tag{9}$$

Making the substitutions in the relation (9) one can get t = 15 s.
In order to observe the behavior of this system in dynamic conditions, specific simulation programs were used [8].
Figure 2 shows the results of this simulation.
The lifting command was given 10 s after starting the pump. The total lifting time is about 18 s. Therefore, the lifting time resulted from the static calculation is exceeded by 3 s. In the studied case, this fact does not mean any trouble. But a real trouble and a nunacceptable fact is that the cylinder C_1 finishes its entire stroke before the cylinder C_2 starts. In the case of such a construction, it is certain that the phenomenon of blocking on the guideways appears.

Fig. 2. Results of simulating the operation of two unsynchronized cylinders

Flow dividers can be used to avoid these situations.

2. Use of Resistive Flow Dividers

Flow dividers are devices that allow a division of the input flow in a well-defined ratio for two consumers [5]. They can divide the flow into different ratios, such as: 50%/50%, 40%/60% or 30%/70%. They can operate in one direction of the flow or in both directions [5]. Figure 3 shows the construction and symbol of a flow divider that works in one direction.

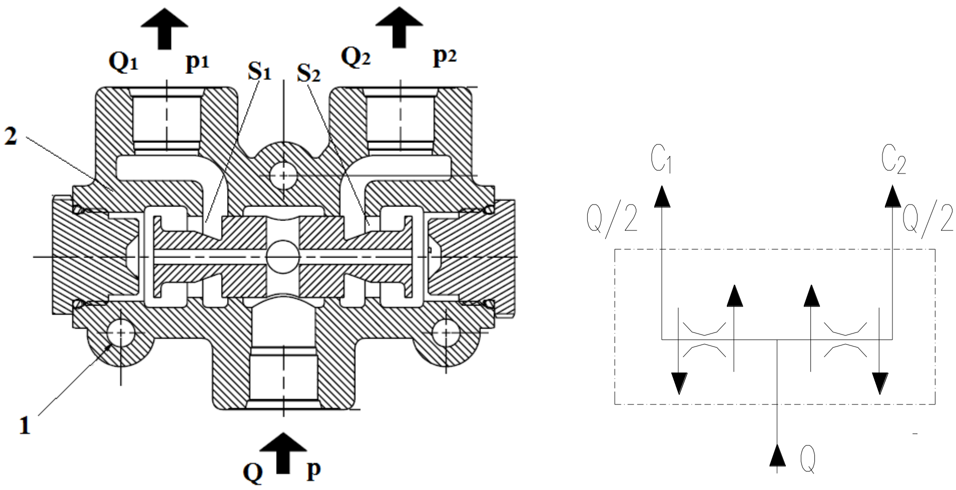


Fig. 3. Resistive flow divider

The source supplies the divider with the flow rate Q at the pressure p in the lower part of the body 1. The piston 2 works freely in this part. Depending on the values of the local pressures p_1 and p_2, the piston oscillates so that the variations of the flow surfaces S_1 and S_2 ensure the equality, or the imposed ratio, of the flows Q_1 and Q_2 sent to the cylinders C_1 and C_2.
If the diagram in Figure 1 is supplemented with a resistive flow dividerof 50%/50% type, the characteristics in Figure 4 are obtained after the simulations.
The time required to complete the stroke is ~16 s, but on this occasion it can be observed that the movement of the two cylinders is simultaneous at the pressure of p = 18.5 bar and there is no more the danger of blocking the system.
The advantage of using flow dividers compared to the use of flow regulators [2] is obvious especially in the cases where the movements of going up and going down are performed in unrepeatable conditions: change of the forces value, change in mass distribution, variations of friction forces etc. If precision flow regulators are used, the adjustment once made for certain

conditions becomes useless when changes occur. The flow dividers perform automatically the adjustmentand the imposed conditions, at anytime.

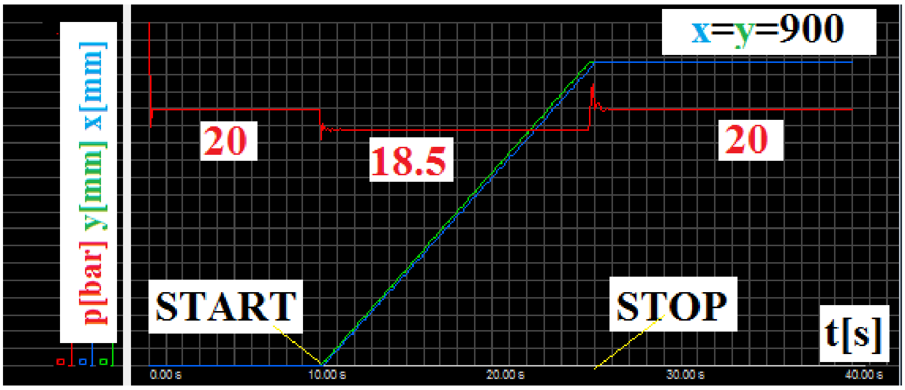


Fig. 4. The results of simulating the operation of two cylinders synchronized by means of a resistive flow divider

In some cases, it is necessary for the load moving UP-DOWN to be secured against accidental falling because of the weight or the occurrence of external forces. For these cases, it is possible to use the diagram in Figure 5 for ascent, descent and STOP phase.

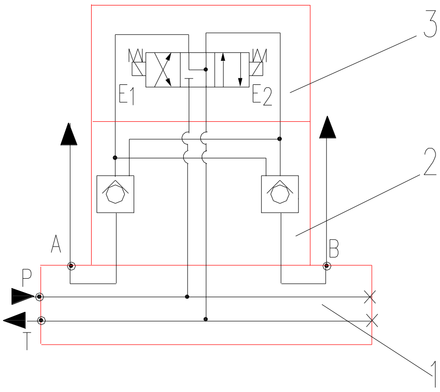


Fig. 5. Securing system against the accidental falling of the actuated load

To reduce the need for pipes, it is recommended to make a modular assembling of the plate 1, double unlockable check valve 2 and directional valve 3. When it is not actuated, the directional valve 3 has a connection of A - B - T type for an efficient locking. The ascent is performed by actuating the electromagnet E_1 and the descent is made by controlling the electromagnet E_2. In order to increase the operation safety, but also for the actuations in case of failure, hydro-pneumatic accumulators can be used [1, 2, 5, 9, 10].

3. Synchronization of the Travel of the Hydraulic Cylinders Working in “Pliers” System

The lathes intended for the simultaneous machining of the two wheels of an axle used for railroad cars and locomotives are usually specialized machine-tools and lately have become CNC machines [11].
The process of bringing the semi-finished product to the position of machining and evacuation is ensured by two identical hydraulic cylinders that raise/lower and clamp/unclamp the workpiece in the required conditions of accuracy and safety. The clamping will always be done in the same position, as the axis of the semi-finished product must be identical to the axis described by the driving system represented by the two tables (specific to this type of machine). Regardless of the weight of the semi-finished product and its clamping diameter, the two cylinders will ensure the conditions mentioned above. It is basically a pair of power “pliers” with hydraulic actuation. Figure 6 shows the actuation diagram of the two cylinders for such a case.

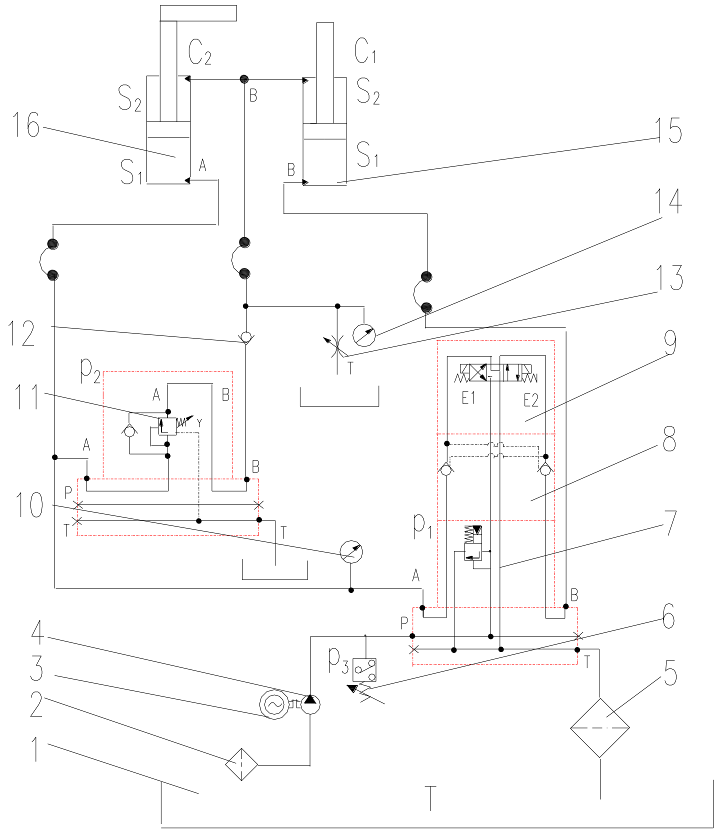


Fig. 6. Actuation diagram of a "pliers" type synchronization system

Pump 4, driven by the electric motor 3, sucks the oil from the tank 1 (T) by means of the suction filter 2. The maximum pressure in the system p_1 is adjusted by means of the pressure valve 7 and is confirmed by the pressure switch 6, adjusted to the pressure p_3 ($p_3 < p_1$). The pressure p_1 is permanently displayed on the pressure gauge 10. A pressure p_2 at least by 10 bar lower than the pressure p_1 is set at the sequence valve 11. This pressure can be read on the pressure gauge 14 during the clamping and unclamping operations. The check valve 12 ensures the compensation of the eventual losses from the upper chambers of the cylinders 15 and 16. Those ones have the surfaces S_2. The lower surfaces of the cylinders are also identical and have the value S_1. The throttle valve 13 allows the initial adjustments and the ventilation of the circuit at the initial start. The cylinder C_1 (15) is the one that supports the weight of the semi-finished product that it raises and lowers. Cylinder C_2 (16) is that part of the "pliers" that comes and clamps the semi-finished product from the top down. The electromagnets E_1 and E_2 of the directional valve 9 are powered in order to actuate the cylinders 15 and 16. The accidental pressure drops are avoided by means of the hydraulic latch 8.

In the STOP phase, the cylinders remain in the last set position thanks to the latch 8. If the electromagnet E_1 is actuated, the oil is sent through the path B of the directional valve 9 on the surface S_1 of the lifting cylinder 15. The oil on the surface S_2 of this one feeds the similar surface of cylinder 16. In the absence of flow losses, the clamping cylinder 16 descends at the same speed as the cylinder 15 raises.

If the electromagnet E_2 is actuated, the oil is sent through the path A of the directional valve 9 on the surface S_1 of the clamping cylinder 16, but also to the sequence valve 11. This one only opens if the pressure in the system reaches at least the value p_2. The flow passing through this is added to the output flow from the surface S_2 of the clamping cylinder 16 and supplies the surface S_2 of the cylinder 15 which goes down. Due to the difference in the surfaces $S_1 - S_2 > 0$, the cylinder 16 goes up and the cylinder 15 goes down. In this case too, they travel at the same speed which, in the absence of flow losses, will ensure a correct positioning related to the axis of the lathe.

To check the operation of the system, a simulation was performed in AUTOMATION STUDIO [8].

The result of this simulation is shown in Figure 7.

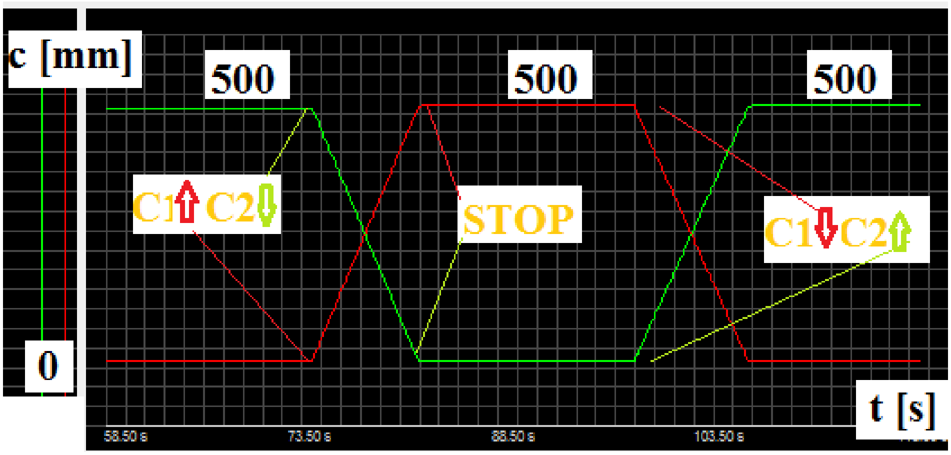
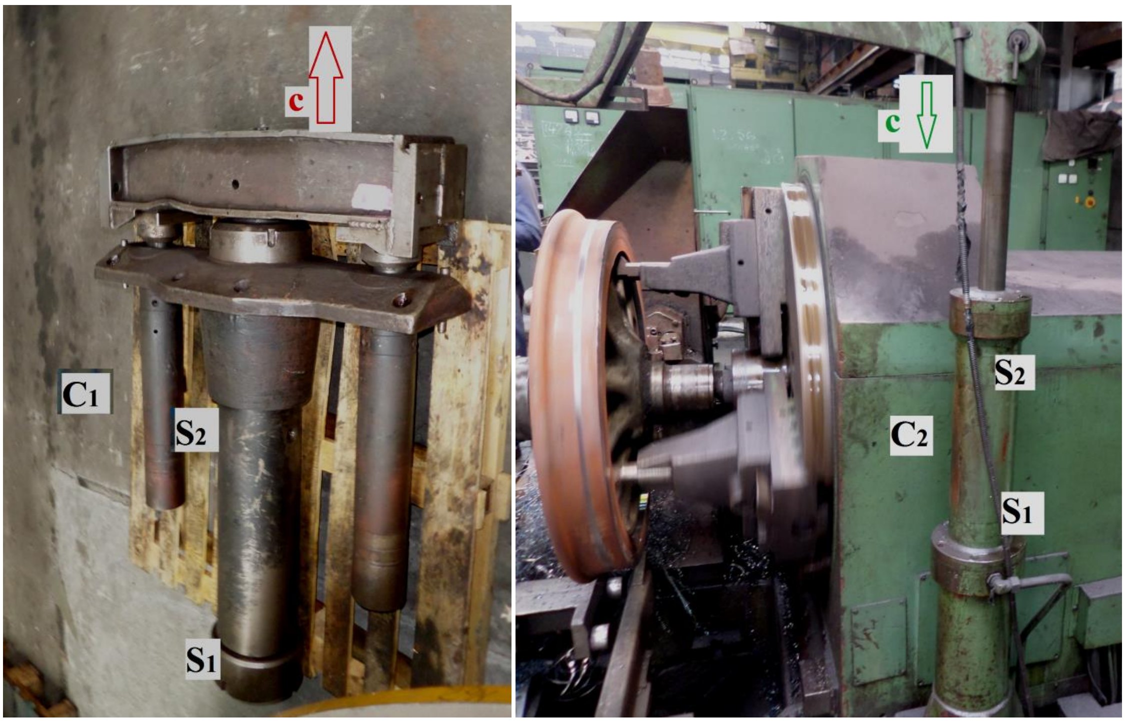


Fig. 7. Simulation of the clamping/unclamping function of cylinders working in "pliers" system

It was considered that the flow rate of the pump 4 is Q = 30 l/min, the set pressures are p_1 = 45 bar, p_2 = 35 bar and p_3 = 42 bar. The cylinders are identical and they have the stroke c = 500 mm, S_1 = 78.5 cm^2, S_2 = 59 cm^2.
It is considered that the semi-finished product has the weight G = 1000 daN.
Due to the way in which the two cylinders operate, the total stroke of clamping/unclamping is made with the value 2xc = 1000 mm. Under these conditions, the necessary time for the clamping and unclamping during a fixed stroke and in a repeatable position, regardless of the workpiece, is ~18 s. Given the overall size of these machines, but also the weight of the semi-finished products, this value of time is considered acceptable. The power of the electric drive motor will be about 4 kW.
Figure 8 shows the cylinders C_1 and C_2 before the assembling in the unit.

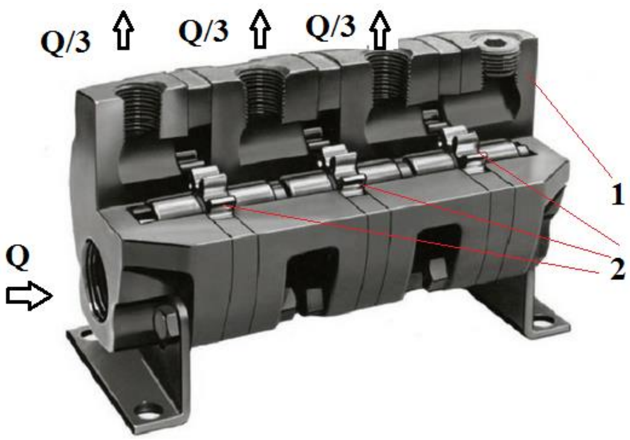


a. b.

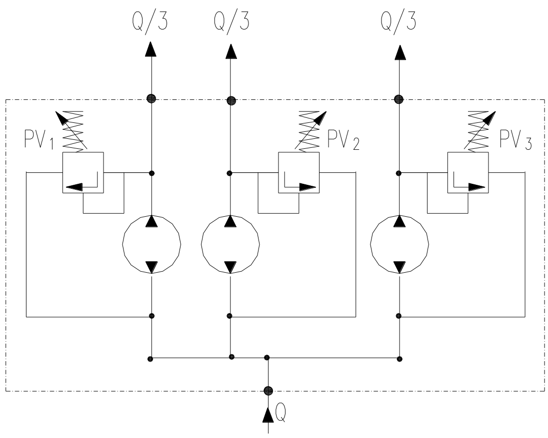
Fig. 8. Cylinders C_1 and C_2 before assembling

4. Use of Volumetric Flow Dividers

The volumetric flow dividers have a construction similar to the one of the gear pumps [1]. Figure 9 shows the construction and assembly diagram of such a divider for the supply of three consumers.



a.



b.

Fig. 9. Volumetric flow divider for three consumers

Pinions 2 rotate synchronously in housing 1. For each outlet there is a pressure valve, marked PV_1, PV_2 and PV_3.
These dividers are supplied by a pump Q_P with a flow rate higher than the required flow Q ($Q_P > Q$). For the example shown in Figure 1, a divider with two outputs (50%/50%) is chosen. If the pressure regulated at the pressure valves is not reached in each circuit, the differences that appear between the flows supplied to the two cylinders are caused by possible losses or oil compressibility.
The results of the operation simulation in this case are presented in Figure 10.

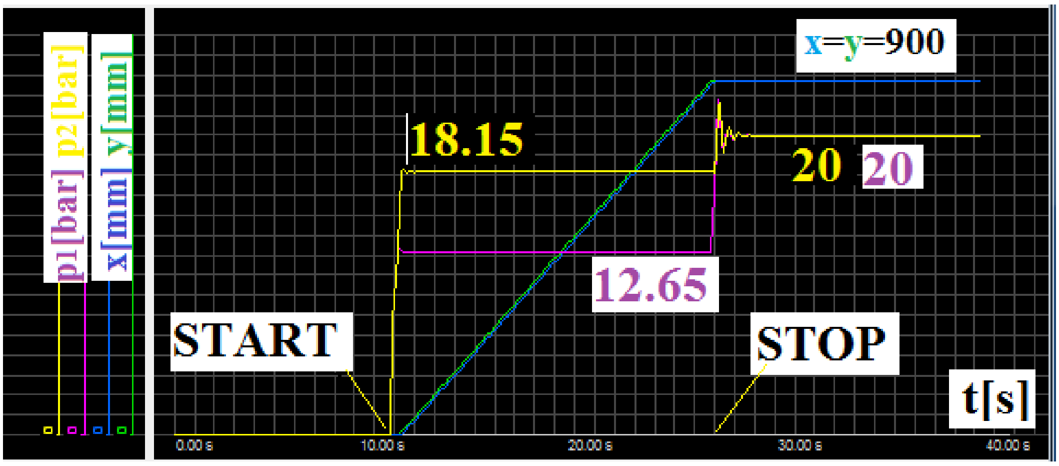


Fig. 10. Results of simulating the operation of two synchronized cylinders using a volumetric flow divider

In this case, too, the travel of the cylinders is synchronously made at different pressures: $p_1 = 12.65$ bar and $p_2 = 18.15$ bar. After the stroke of both cylinders, the pressure becomes, in both cylinders, $p_1 = p_2 = p = 20$ bar.

5. Conclusions

The synchronous movement of two or more hydraulic consumers (cylinders or rotary hydraulic motors) is difficult to achieve by using throttles or flow control valves. Even if a proper adjustment of these ones is performed, it will become inefficient in time because of the changes that occur during operation.
For the synchronous travel of two or more hydraulic systems that do not require positioning accuracy of the order of tenths of a millimeter, it is recommended to use flow dividers. If only two identical cylinders are operated, and the flows are small (in order of magnitude below 10 l/min), resistive flow dividers can be used successfully. These ones can also provide uneven flow rates to the two cylinders.
In case of higher flow rates or when several cylinders are operated, the recommended solution is to use volumetric flow dividers.
If it is intended to avoid the uncontrolled movement of the load due to weight, unforeseen forces or failures, the "hydraulic latch" type securing systems will be used.

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