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DEVELOPMENT OF A TEST BENCH FOR ANALYSIS OF THE SUPPLY PRESSURE VARIATION IN HYDRAULIC SYSTEMS

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Abstract: *Hydraulic systems have gained widespread use and applicability to the industrial manufacturing process. Although the hydraulic technology is old, there are many modern applications such as presses, mechanical excavators, backhoes, loaders, forklifts and cranes. However, studies show that the stability of the supply pressure is a determinant for gain efficient of any hydraulic equipment. This study aimed to analyze the characteristics of the variation in supply pressure in a hydraulic system under different conditions of operation, through a test bench. Were first showed constructive and operating characteristics of the major components analyzed, these being the proportional directional valve, pressure relief valve direct operated (relief valve) and the accumulator. Subsequently, addressed the relationship between the operation of the relief valve and the behavior of the supply pressure. In the experiments, the proportional directional valve is subjected to different conditions of pressure difference and aperture alternating also, the use of an accumulator in the circuit. The results show the relation between the operating conditions of the hydraulic circuit and the change in supply pressure.*

Keywords: *Hydraulic System, Pressure Supply, Relief Valve, Tests Bench.*

1. Introduction

Hydraulic systems can be defined as the combination of physical elements conveniently mounted using the fluid as energy transfer and control of forces and movements. Currently great efforts have been made to the development of this technology, due to huge application in all fields of activities, from mining to industrial space. Because of this, highlights that the recent growing interest and need for more industry adequate to meet the market demanding hydraulic systems. These are factors that favor the funding of academic research dedicated to increasing of hydraulics systems knowledge [1], [8].

Most hydraulic systems are equipped with a pressure relief valve (relief valve) that keeps the working pressure of the system (supply pressure) to a predetermined level. This component protects both the hydraulic pump and the electric motor of an excessive increase in system pressure through the partial or total diverting flow provided by the pump [2].

However, due to the static response of the relief valve, supply pressure fluctuations arising from the amendment present the flow passing through it. This change in the working condition of the relief valve is caused, for example, after activate the directional control valve. Depending on the application this behavior should be avoided [3].

In this case, due to the absence of an accumulator, is necessary to work at low speeds so that the variations in flow and therefore the pressure gonna be slower and the pressure control valves are able to maintain the supply pressure constant. The drop in supply pressure directly influences the hydraulic subsystem, hurting following the required hydraulic force, which consequently affects the mechanical subsystem, increasing the trajectory errors of the actuators.

This work will be analyzed the characteristics of fluctuations in supply pressure, checking the relationship between the operating conditions of the hydraulic system, ie opening of the proportional directional valve and loading the cylinder, and the behavior of the relief valve in a hydraulic system, in addition to analyze the influence of the energy accumulator in the behavior of this phenomenon. In order to get the results, one test bench was developed as will be shown later in the experimental procedure.

2. Literature Review

A hydraulic circuit can be divided into two parts: the circuit of action that encompasses the parts that promote action on the load, and the unit responsible power circuit for supplying hydraulic power for the circuits of activity. The components of a circuit may vary according to the needs of the project in order to adjust them several applications [5].

The valves control and direct the fluid from the pump outlet when returning to the reservoir. The relief valve is almost always the first valve located after the fluid leaves the pump. In a simple circuit probably the second valve used is a directional control valve [6]. The type of pressure control valve is used more relief valve (VA), since that is found on virtually all hydraulic systems. It is a normally closed valve, whose function is to limit the pressure there is a maximum value specified by the partial or total bypass flow from the pump to the reservoir. There are many types of this kind of relief valve, but the concepts discussed in this paper about the VA refer to the pressure relief valve direct operated, Fig.1(a), [7].

The relief valve is basically composed of a shutter which is held in its seat by the effect of the spring force pre-set by a screw. The supply pressure, (P_s) acting on the area of the shutter produces a force (pressing force) that directly opposes the preload force of the compression spring, so that the minimum opening pressure of the valve, (P) is determined the ratio between the strength of pre-compression, (F_m) and (A_p) area subject to the action of supply pressure, (A_p) [1]. The minimum opening pressure (F_m) and strength of pre-spring compression adjustment Fm are given as follows [8], Equation (1) and (2):

$$P_r = \frac{F_m}{A_p} \tag{1}$$

$$F_m = k.x_0 \tag{2}$$

Where:
A_p = Area Shutter subject to the action of pressure P_s
k = Elastic spring constant
x_0 = Course precompression spring

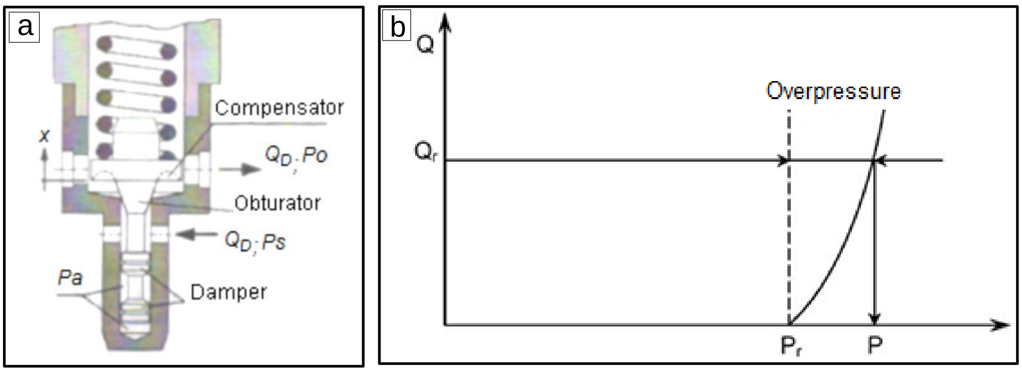


Fig. 1. Principle of operation of the pressure relief valve, direct operated.
(a) the constructive-way [1] and (b) static feature [10]

Any pressure increase above the minimum opening pressure (P_r) causes the shutter to move allowing the adjustment of pressure by diverting flow from the pump to the reservoir. The pressure difference (P_s – P_r) sets the aperture and shutter flow is described following the Bernoulli Equation 3 [9]. The flow through the VA is given by [10]:

$$Q_d = C_d.\omega\frac{A_p}{k}\left(P_s - P_r\right)\sqrt{\frac{2P_s}{\rho}} \tag{3}$$

Where:
Q_d = Flow diverted through the VA
P_s = Supply pressure
P_r = Minimum opening pressure of VA
A_p = Area the shutter subject to supply pressure
k = Spring stiffness
C_d = Discharge coefficient
ω = Proportionality coefficient of orifice area control
ρ = Specific mass of the fluid

According to the behavior described in Figure 1 (b), states that after the opening of the VA, the spring force varies with displacement of the shutter, x. The pressure difference (P – P_r) is called pressure, and the greater the displacement of the shutter against the spring (and the greater stiffness of the spring), the larger the effect of the pressure produced by the additional spring force. Thus, it can be stated that the higher the diverted flow overpressure. This shows that the maximum pressure (P), corresponds to the total flow diverted by the VA, (Q_r). When (P = P_r), pressure and preload force compression spring are in balance, and with it, the VA remains closed. On business papers the static characteristics of the VA are provided assuming that the flow through this is the independent variable. In Fig.2 where a typical curve of a pressure relief valve provided by manufacturers of this type of valve is shown, it is observed that by modifying the working condition of 1 to 2 due to the change in flow, pressure is affected [10].

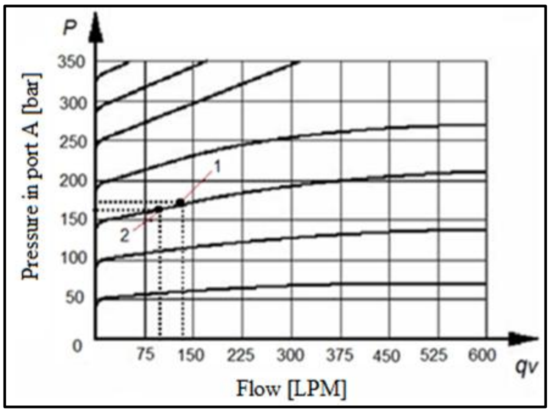


Fig. 2. Typical curve of steady state of a relief valve [4]

3. Experimental Procedure

The hydraulic circuit used in the experiments was assembled in order to simulate the performance of a hydraulic system subjected to an external load. The circuit performance is composed of the following components: Symmetrical through-rod double action, RAGI manufacturer, model RHI01SLBR-TBD200AEXX, the piston diameter of 25 mm, rod diameter 18 mm, 200 mm stroke cylinder; Symmetrical proportional directional valve, direct operated, with pressure balance, without electrical position feedback 4/3, Vickers manufacturer, maximum flow of 1.5 LPM, maximum operating pressure of 120 bar, input signal ± 10 V;

A unit of power used to generate hydropower has the following components: Gear pump with capacity of 3.5 GPM maximum flow rate, operating pressure of 0-60 bar, maximum pressure of 100 bar; Electric motor drive with power of 0.5 HP; Bourdon type pressure gauge to check the pressure setting; Pressure relief valve direct operated; Energy storage diaphragm, FCH manufacturer, model 108498-01125, gas volume of 0.75 L and a maximum pressure of 210 bar.

3.1 Charging System and Data Acquisition System

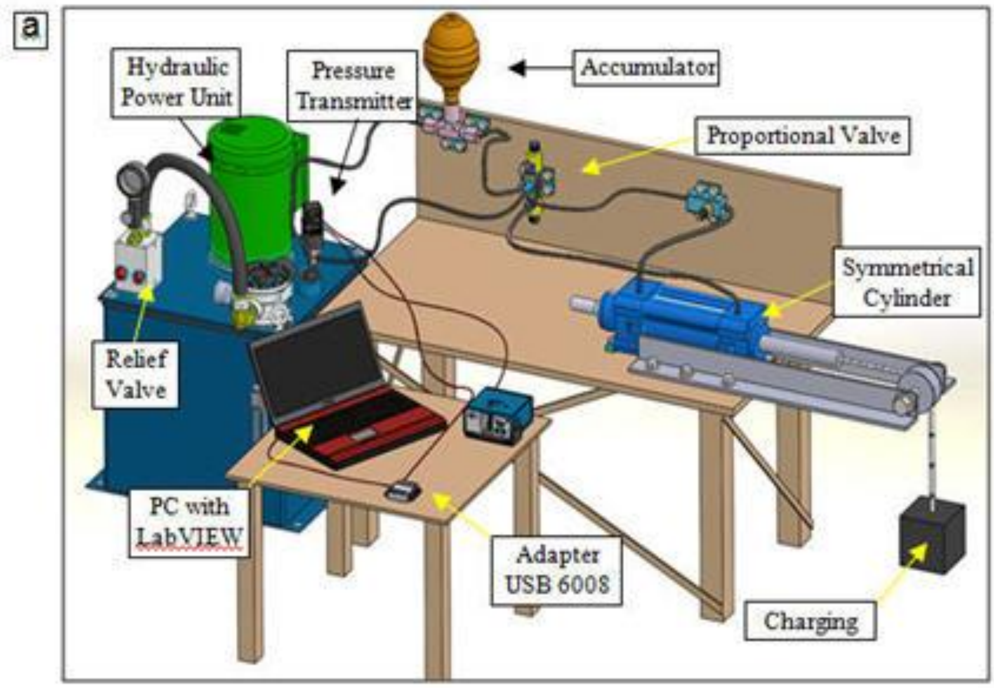
For loading of the hydraulic cylinder used a system with steel blocks with a mass of about 20 kg each hydraulic cylinder attached to a cable, moving vertically through a pulley. Through this system the cylinder was fired with three loading conditions, 20, 40 and 60 kg, thus generating three different values of load pressure Pc and knowing that the pressure difference in pressure differential VDP is obtained from the subtraction between the pressure (P_s) supply and pressure load (P_c), modifying the loading caused three conditions of pressure difference pressure differential on the VDP. The pressure in the supply line was measured by a pressure transmitter, GEFRAN manufacturer, model TKN1EB01CMV, measuring range 0-100 bar, and uncertainty ± 0.5 bar, input signal 0-10 V.

The signals measured by the transmitter were sent to a device data acquisition, USB 6008 board. Using LabView (Laboratory Virtual Instrument Engineering Workbench) software, software was developed that allowed the visualization of the signal measured by the pressure transmitter and the generation of graphics necessary to interpret the data acquired by USB 6008 board. The sampling period of the data acquisition system was 1ms.

3.2 Experiments on Bench Study

The experiments performed in the hydraulic circuit based on the displacement of the cylinder by pushing VDP, alternating operating conditions of the circuit performance in each test. For each test run are triggered VDP with different values of control signal (valve opening) and the loading hydraulic cylinder. Values of the step-like command set on the electronic chart to drive the voltage VDP were 4, 6, 8 and 10V (ie, command signals openings or equal to 40, 60, 80, 100%) and loading conditions of the cylinder 20, 40 and 60kg. All tests performed with the conditions described were made with and without the presence of the accumulator in the hydraulic circuit, this control being done through a record of opening and closing of the accumulator system found in the same block safety.

According to Fig. 3, the flow delivered by the pump (Q_b) equals the sum of the flow diverted by the VA (Q_d) and available flow in the hydraulic circuit (Q_c). Therefore, disregarding the compressibility of the fluid, the change in flow (Q_c) controlled by VDP causes the change in flow diverted by the VA.



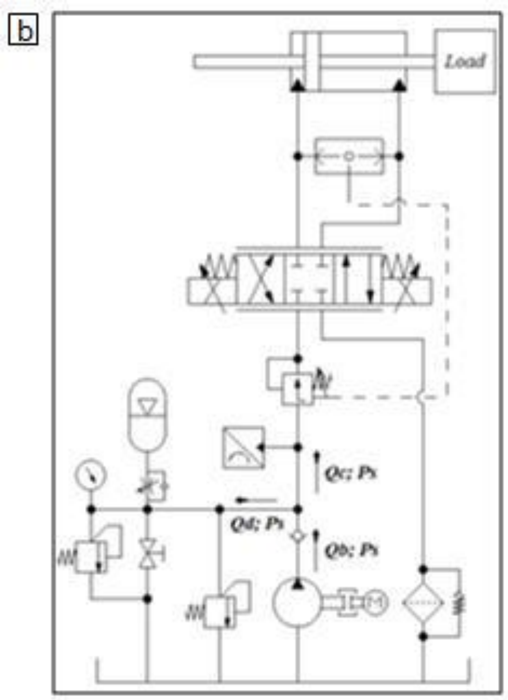


Fig.3 - Bench study: (a) principal components and (b) hydraulic circuit

The minimum opening VDP 40% (command) was determined assuming the internal leakage this happens to be greater for less than this amount opening. The internal leakage in this case could, in the case of this work, compromising the results of the variation of (P_s) because during the performance of a portion of VPD (Q_c) would go directly to the reservoir rather than being diverted by the VA.

The flow rate passing through the VDP used in the experiments has a similar graph to that described in Fig.4 behavior. According to the chart the flow through the VDP is dependent on both the opening signal as the difference in pressure acting on the same, this relation is observed through the characteristic curves for each operating condition. Thus, it was considered that the flow through the VPD was different for each test.

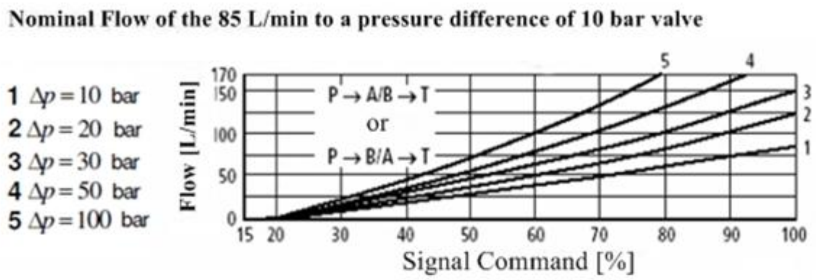


Fig. 4. Graph command signal versus of a flow proportional valve [4].

The supply pressure was initially set at 55 bar ± 1 bar (*P_A)* because this value is enough to overcome the loading cylinder, where it has been measured by the pressure transmitter for the return of the cylinder, ie in the direction opposite the weight force of the blocks. The cylinder moved in each test approximately 180 mm, avoiding that way, that it reached the end of its stroke and impairs the measurement of supply pressure.

The following are some considerations made regarding the parameters adopted for the experiments: the line pressure of the reservoir was considered zero, pressure loss in piping and circuit components have been disregarded, dynamic Drive VDP was disregarded and force of this friction in the loading system was disregarded.

4. Analysis of Results

According to the relationship between Q_c, Q_b, Q_d (Fig. 3) the opening of the VDP caused the change of flow diverted by the VA, the VA pushing the shutter to move between intermediate positions between its maximum aperture and its closure as the conditions of each test.

The results obtained have demonstrated both the dynamic behavior such as pressure drop P_S based on changes in the working conditions of the control valves used in hydraulic circuit. In the analysis of the results also compared the influence of the action of the accumulator in this phenomenon when this component was used in the circuit.

4.1 Analysis of the Dynamic Behavior of Supply Pressure

For analysis of the dynamic behavior of (P_s) used the results obtained with and without using the accumulator in circuit with a load of 20 kg in the cylinder and openings VDP 40 and 100%. The results were compared in order to be able to examine the relationship between the operation of the circuit components in the behavior of (P_s).

4.1.1 Results without the use of accumulator in the circuit

The Fig. 5 (a) and (b) show the behavior of the roller (P_s) loaded with a mass of 20 kg, and the opening of the VDP 100% and 40%, respectively, without the presence of the accumulator in the circuit.

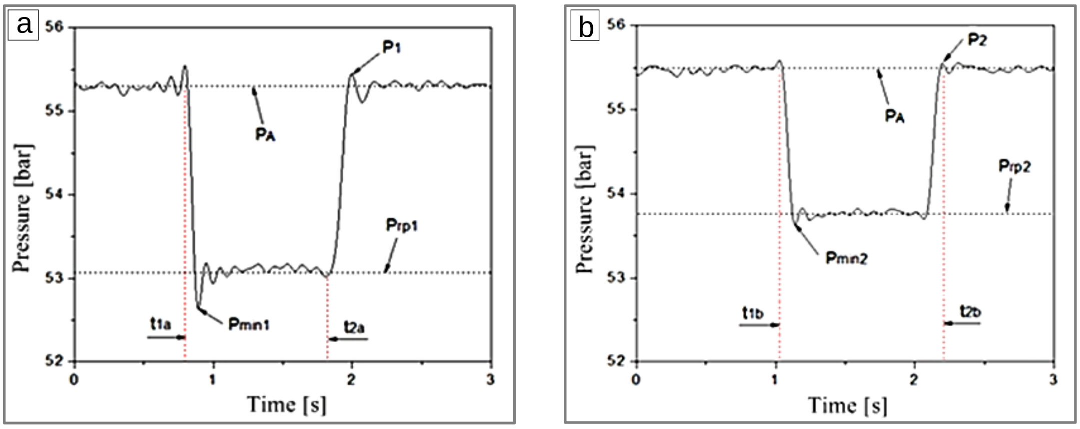


Fig. 5 - Dynamic behavior of supply pressure without the use of the accumulator: (a) - opening of 100% in the VDP, (b) - opening of 40% in the VDP.

Initially, before the opening of the VDP (P_s) pressure is permanently at the value set at the VA, (P_A), displaying only pulsations arising from the operation of the hydraulic pump. After the activation of the VDP moments (t_{1a}) and (t_{1b}), part of the pump (Q_b) was directed to the circuit by the VDP, the diminishing with this (Q_d) flow diverted by the VA. As noted in both cases, Fig. 5 (a) and (b), after the change in working conditions in the control valves observed pressure drop in supply, where it hovered until it reaches the steady state value and (P_{rp1}) and (P_{rp2}). The oscillation P_S occurred due to the operation of the mechanical device of VA.

The mechanical device that controls the flow through the VA composed of the shutter, the spring and damper tuning, has modeled as a damped spring-mass system behavior [11]. After reduction of the flow VA shutter moves in the direction to decrease the valve opening and due to the delay in the mechanical response of this device, the shutter continued to move causing minimum peaks occur (P_s), and (P_{min1} P_{min2}), Fig.5 (a) and (b), respectively. The effect of damping of this oscillation arises in reaction to movement of the shutter, the restriction to flow through the radial clearance existing between the piston (damper) and the jacket of the damping system [1].

It is observed that in the first case, Fig.5 (a), with the valve fully open (opening = 100%) directed into the flow circuit is greater than in the second case (b) (opening = 40%); causing a further decrease in the flow diverted through the VA. These oscillations in the displacement of the shutter and system pressure, (P_s), result from the disruption of flow and pressure, caused by the sudden increase of pressure in the hydraulic system. Leaving it is concluded that the amplitude of oscillation (P_{min1}, P_s) was higher in the case described in Fig.5 (a) for having generated a disturbance of higher flow in the flow control device VA [1].

The closing moments of the VDP (t_{2a}) and (t_{2b}), caused flow in the circuit passed again being diverted by the VA. Due to the operation of the VA, the rapid increase in flow through this caused the sudden increase in supply pressure, where again it can be seen in both cases the effect of the delay in the response of the device of VA, causing pressure spikes (P_1) and (P_2), as Fig.5 (a) and (b), respectively. After this fact was damped oscillation until the value of the steady pressure initially (P_A) adjusted.

It was noted that in both cases the values (P_1) and (P_2) were very close and relatively low. However, it is known that in cases where the flow and pressure are higher than the values used in the experiments these pressure peaks, as seen in Fig.5 can decrease the pump life.

4.1.2 Results Using the Accumulator in the Circuit

Initially the supply pressure (P_s) is permanently at (P_A) value set in VA, with pulsations again due to the pump. However, as Fig. 6 (a) and 6 (b), the use of the accumulator circuit has caused a change in the dynamic behavior of the supply pressure during the opening of the VDP in relation to the results without the use of the accumulator.

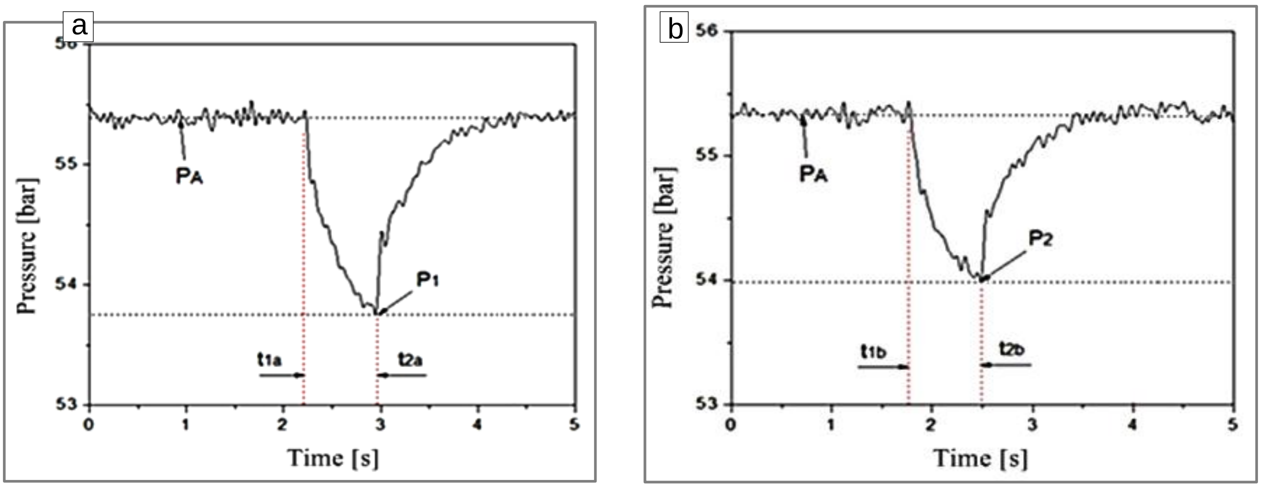


Fig. 6 - Dynamic behavior of supply pressure using the accumulator: (a) - opening of 100% in the VDP, (b) - opening of 40% in the VDP.

In the cases analyzed the supply pressure (P_s) did not show the behavior in steady state during the opening of the VDP may be noted that the fall of (P_s) soon after the opening of the valve occurred gradually until the closing moments of the VDP.

Analyzing the two cases, it was found that after initially opening the VDP in moments t_{1a} and (t_{1b}), part of the flow delivered by the pump (Q_c) was directed to the circuit causing the drop in supply pressure due to operation of VA. From this moment the pressure inside the accumulator became higher than the value of (P_s), allowing the discharge of the pressurized fluid within the accumulator circuit. As part of flow (Q_c) *w*as provided by the accumulator drive, analyzing the (Q_c, Q_b, Q_d) it is concluded that there was less variation in the flow diverted by the VA and, consequently, smaller drops (P_s, P_1 and P_2).

Analyzing the behavior of (P_s), it was noted that his fall was more marked after opening the VDP due to dynamic operation of the accumulator. From the onset of action the accumulator in the circuit, the rate of change of (P_s) decreased characterizing the damping effect generated by the accumulator. In this way, use of the accumulator prevented sudden drop in (P_s, P_{min1} *and* P_{min2}) oscillations observed in the results was not used in this component, as Fig. 5 (a) and 5 (b).

After the closing of VDP in moments (t_{2a} and t_{2b}), we noticed again the damping effect generated by the accumulator. It was concluded that with the closing of the VDP, part of the pump was absorbed by the battery (energy storage process) rather than being quickly diverted by the VA and thereby avoided the sharp increase in supply pressure. Moreover, it was found that due to the dynamics of operation of the energy accumulation process performed by the accumulator occurred late in restoring the steady state in the set value (P_A). As can be seen, the pulse pump accompanies every curve oscillation (P_A).

4.2 Analysis Fall P_S depending on the operating conditions of the circuit

According to the analysis on the dynamic behavior of (P_s), it was found that the variation of the pressure, ie the pressure drop (P_s) value is related to the decrease in the flow deflected by (Q_d) VA. Decreased flow (Q_d) depends on the increase of the flow (Q_c), resulting from activation of the VDP, so this variation is related to the flow behavior through the VDP. Therefore, the analysis is based on the relationship of the operating conditions of the circuit, the VDP opening and loading of the cylinder, and falling (P_s). Comparing the results, we also analyzed the effect of using the accumulator drop (P_s).

4.2.1 Results P_s drop without using the accumulator circuit

For calculations of the fall of (P_s) each test, we considered the difference between the pressure set on VA (P_A) in continuous and steady state values that occurs during the opening of the VDP, as noted in the analysis of the dynamic behavior (P_s). Each VDP open condition and charging the drum was repeated four times, after this we calculated the average pressure drop between these four values and the standard deviation of these results. The results are shown in Table I.

Tab.I – Results (P_s) drop as a function of the loading cylinder and the control signal VDP without using the accumulator in the circuit

	Loading - 20 kg		**Loading - 40 kg**		**Loading - 60 kg**	
Opening VDP [%]	**Falling P_s [%]**	**Standard Deviation (%)**	**Falling P_s [%]**	**Standard Deviation (%)**	**Falling P_s [%]**	**Standard Deviation (%)**
4	3,34	0,196	3,09	0,102	2,35	0,128
6	3,78	0,147	3,58	0,179	2,74	0,145
8	3,80	0,135	3,61	0,229	2,76	0,121
10	3,83	0,185	3,63	0,204	2,79	0,192

According to Fig.7, the relationship between the increasing opening of the VDP and (P_s) variation for the three load conditions is approximately the same as can be observed in the linear behavior of each condition. This demonstrated that the relationship between the gap and increase the flow through the VDP was approximately the same in all three conditions of the cylinder, as this valve flow behavior observed in Fig.6.

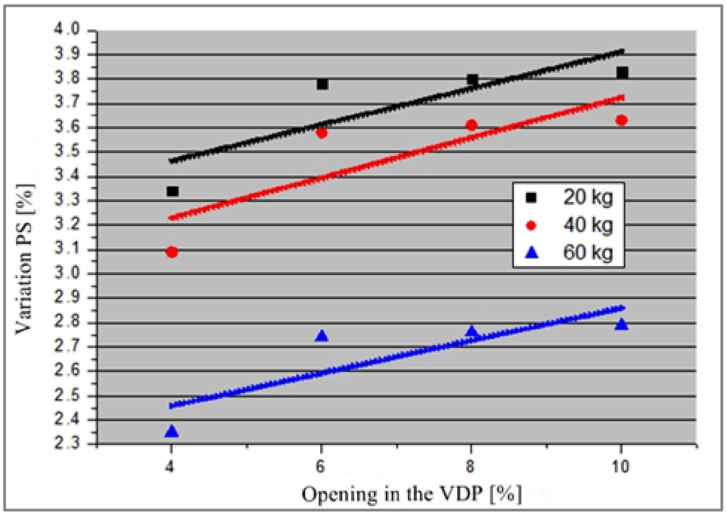


Fig.7 - Variation of (P_s) x aperture VDP (not using the accumulator in the circuit)

Relating to the graph described in Fig.4, the rise of the load pressure decreases the flow through the VDP. The increased load on the cylinder, that is, the load pressure, decreased flow through the VDP generating a smaller change in the flow diverted by VA, and consequently, the less variation in the supply pressure. The decrease in flow by VDP due to increased loading pressure was higher with the loading condition of 60 kg assuming drop (P_s) relatively low compared to other loading conditions.

4.2.2 Analysis of the drop P_s using the battery in the circuit

The variation of (P_s) using the battery in the circuit is calculated based on the values of (P_A) steady state peak and minimum pressure (as Fig. 8). Again, each of the VDP open condition and charging the drum was repeated four times, after that calculated the mean pressure drop from these four values and the standard deviation of these results. The results are shown in Table II.

Tab.II - Results of (P_s) drop as a function of the loading cylinder and the control signal VDP, using the battery in the circuit.

	Loading - 20 kg		Loading - 40 kg		Loading - 60 kg	
Opening VDP [%]	**Falling P_s [%]**	**Standard Deviation (%)**	**Falling P_s [%]**	**Standard Deviation (%)**	**Falling P_s [%]**	**Standard Deviation (%)**
4	2,39	0,187	2,33	0,114	2,09	0,113
6	2,79	0,191	2,74	0,147	2,42	0,156
8	2,81	0,162	2,75	0,149	2,43	0,132
10	2,84	0,148	2,78	0,163	2,51	0,109

As discussed in section 4.1.2, the use of accumulator caused a lower minimum peak pressure in the supply. Figure 8 shows the values were lower drops (P_s) using the battery in the circuit. Comparing the linear behavior with the results without using the battery, it is noticed that in this case the relationship between openness and the fall of the VDP (P_s) was higher.

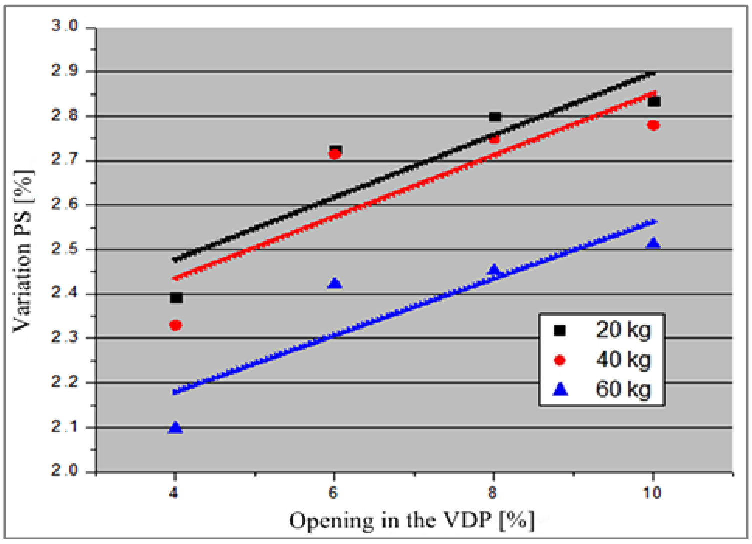


Fig.8 - Variation of (P_s) x opening VDP (using the accumulator in the circuit).

The Fig.9 shows that the reduction in drop (P_s) taken by accumulator was higher in conditions with mass loading of 20 and 40 kg. This fact means that the function of accumulator in the fall of compensation (P_s) was more effective under conditions in which there was greater variation in pressure (P_s), ie, the loadings of 20 and 40 kg in the cylinder, as seen in the results shown in Fig.7.

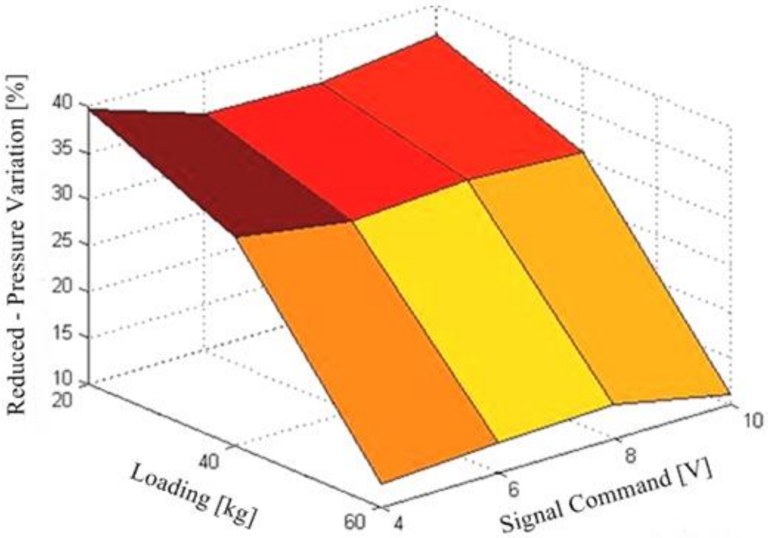


Fig.9 - Reduction of variation ie, the loadings (P_s) from use of the accumulator

5. Final Considerations

With the development of this work can reach the following considerations:

- The behavior of the hydraulic power circuit, that is, flow and pressure depend directly on the operation of mechanical devices of the valves responsible for its control. Therefore, the operating characteristics of hydraulic components must be considered during the design of a hydraulic system;
- The delay in the response of the relief valve checked the result without the accumulator was greater with increasing flow variation through this. In a system that operates at high flows this phenomenon could be enlarged due shutter operation of the relief valve, which could bring damage to circuit components;

- The results showed that the accumulator pressure variations become smoother supply acting as a buffer and avoiding too much pressure peaks. It was also found that the variation reduction of supply made by the accumulator was greater in the most critical, ie, at times of high flow variation promoted by VDP cases;
- The results for the variation of pressure do not correspond to those found in real applications because it used components with low flow capacity;
- For future work is suggested to conduct similar experiments done in this work, however using control valves and power unit with capabilities similar to the values commonly used in industrial applications.

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