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Effect of upstream throttle valve on static and dynamic characteristics of counterbalance valve

By

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Abstract:

For negative loads, the counterbalance valve is responsible for building up the necessary back pressure to carry the load, in addition to the braking action to prevent the load from being freely fall. Here, we argue that the introducing of a throttle valve connected upstream to the counterbalance valve has an effect on its dynamic characteristics (response) and braking characteristics, leading to enhancement in the circuit performance.

Theoretical and experimental investigations have been carried out for different setting of throttle valve and for different cracking pressures of the counterbalance valve. The results showed that the introduction of the throttle valve connected upstream has an effect on the static characteristics of the counterbalance valve. While the dynamic characteristics (response time) of the counterbalance valve is enhanced by introducing the throttle valve and is mainly controlled by the throttle valve setting as well as the cracking pressure. The response time of the counterbalance valve could be increased by decreasing the throttle valve setting which is suitable for light loads and vice versa. This enhancement reduces the load shocks at starting as well as improves the braking effect of the freely falls load.

Keywords:

Counterbalance valve, throttle valve, static and dynamic characteristics, braking action, negative loads.

* Egyptian Armed Forces

1. Introduction:

For actuators under action of negative loads, it is necessary to create the necessary back pressure to carry this load and to produce the necessary braking action. The counterbalance valve positioned in a meter out connection provides that function to prevent the load from being freely fall under its load. The circuit under investigation consists of a gear pump, relief valve, hydraulic cylinder, throttle valve, check valve, counterbalance valve and pilot check valve as shown in Fig. 1.

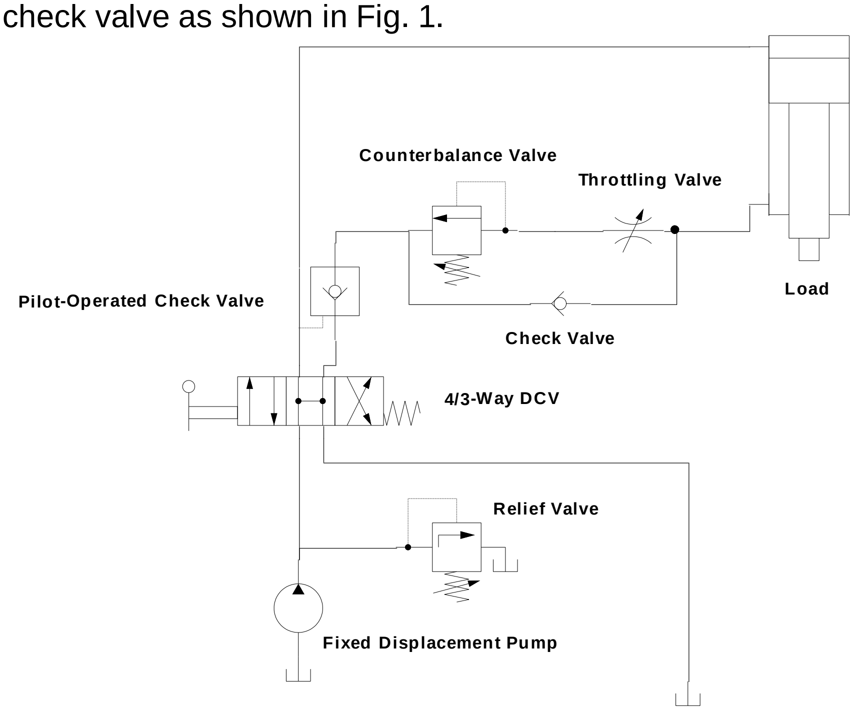

Figure (1): *Hydraulic circuit under investigation*

There are three main modes during the descending motion of a negative load;

1. At the starting of the motion where there is no flow through the throttle valve, the pilot operated check valve carries out the main share of the back pressure required to carry the load.

2. Secondly, as the load moves, flow increased through the throttle and counterbalance valves producing the necessary back pressure to carry out the load.
3. In the third mode as the load falls freely, the braking mode, the counterbalance valve is closed gradually as a result of decreasing its inlet pressure and produces less shock wave and vibration to the working system.

In this paper, the effect of introducing a throttle valve positioned upstream the counterbalance valve for free falling loads on the static and dynamic characteristics of the counterbalance valve is investigated experimentally and validated by modeling the dynamical equations of motion of different components using SIMULINK. The main goal is that to highlight the idea of combining a throttle valve (as a meter-out) with a small size counterbalance valve to produce better dynamic performance.

2. Experimental Study:

The experimental test rig has been set up in the Hydraulic laboratory at the Mechanical Power and Energy Department in Military Technical College. The test rig has been established on hydraulic bench equipped with all accessories and hydraulic components needed to build the required circuits. The conducted experiment is shown in Fig. 2.

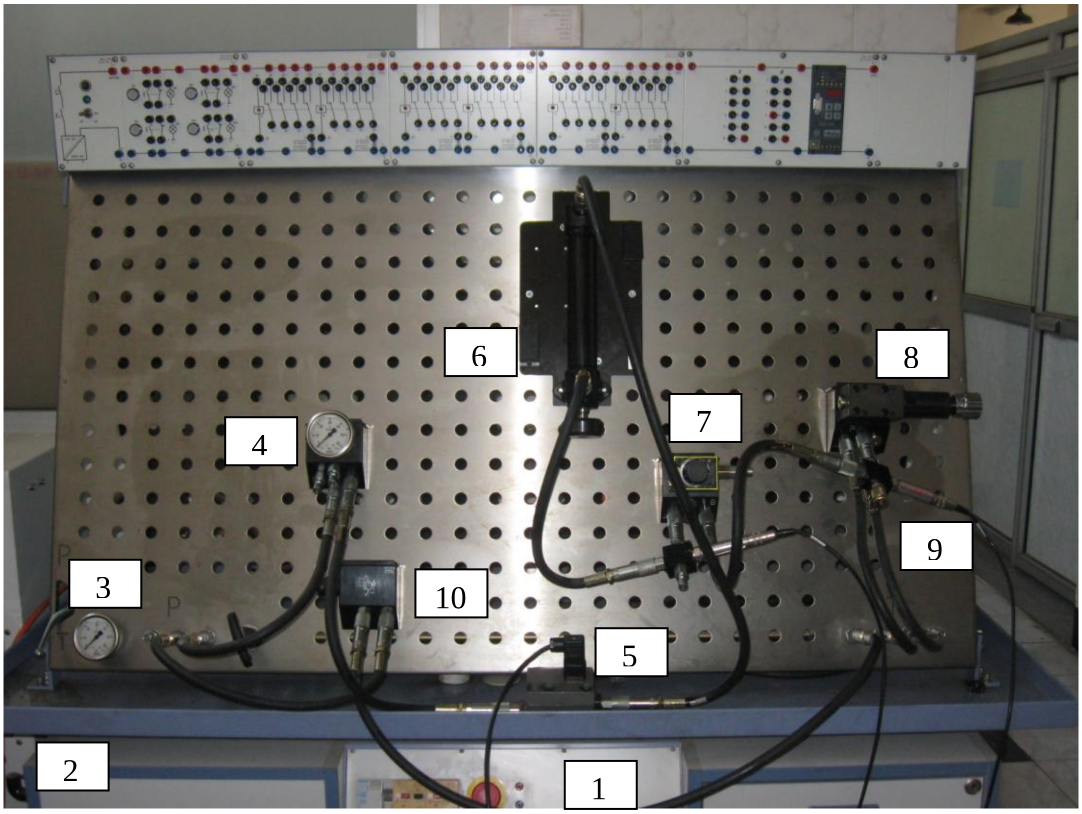

Figure (2): *Experimental set up; (1) power pack unit, (2) hydraulic bench, (3) inlet control valve, (4) pressure gauge, (9) digital flow meter, (6) double acting cylinder, (7) adjustable throttle valve, (8) adjustable counterbalance valve, (9) pressure transducer, (10) pressure relief valve.*

The hydraulic circuit under investigation, shown in Fig. 2, consists of a power pack (1); a hydraulic reservoir, fixed displacement gear pump and relief valve, connected to the hydraulic bench (2). The components under investigation are the throttle valve (7) and the counterbalance valve (8) which are connected in meter-out position to double acting cylinder. The throttle valve is adjustable and has 10 adjustable setting positions (percent of valve closing) to provide the needed variable throttling effect. The counterbalance valve is adjustable too with different initial spring loading to produce the necessary different cracking pressure. All the investigated components have been attached to the bench with quick plug hoses to allow easy connections with the bench. The instrumentations used are pressure transducers (9) of the range 100 bar. The transducers have been calibrated to find out the scale of the volt corresponding to pressure. The transducer has been also connected to a readout unit which is connected to a data acquisition USB unit to store the measuring data over the sampling time.

3. Experimental Study:

The circuit diagram of the investigated hydraulic circuit is shown in Fig. 3. Each element of the hydraulic circuit, as shown in Fig. 4 for the counterbalance valve, has been studied individually in order to obtain the mathematical model. Then, all the elements are integrated in one mathematical model using the SIMULINK program to find out the static and dynamic characteristics of the hydraulic circuit.

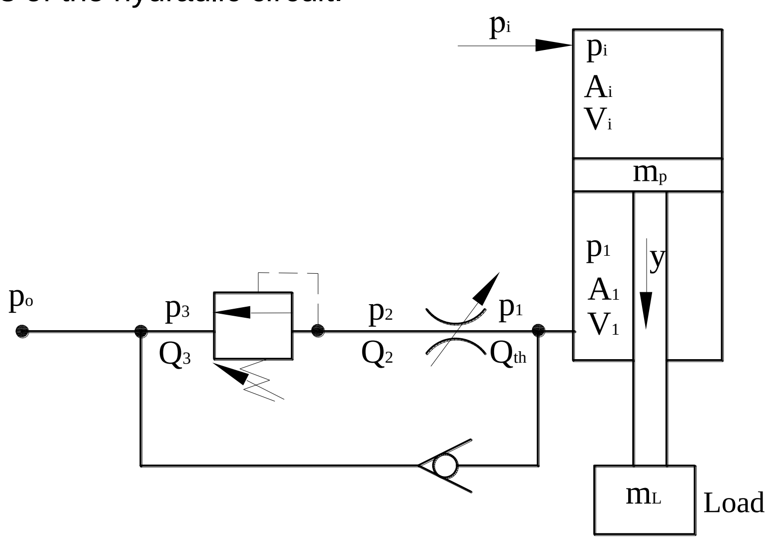

Figure (3): *Schematic representation of the free fall actuator connected with throttle / counterbalance valve in meter-out position.*

The hydraulic system under investigation is shown in Fig. 3. The analysis has been described by system of equations, throttle valve characteristics and the throttle/ counterbalance valve characteristics in the following sections:

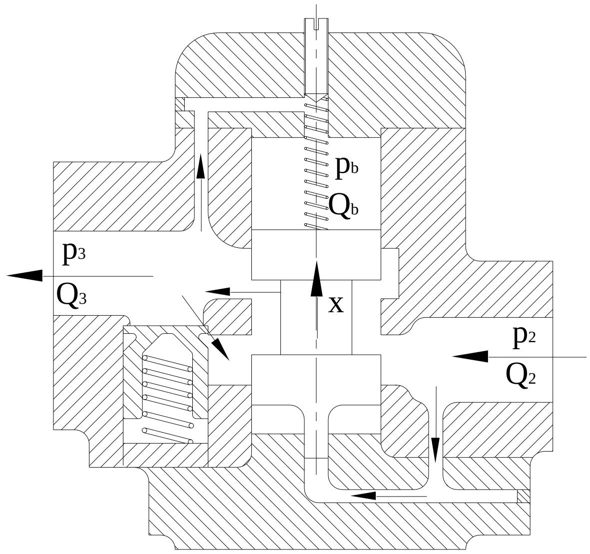

Figure (4): *Schematic drawing of the counterbalance check valve*

3.1. Piston load dynamics:

The following equations describe the displacement of the linear hydraulic actuator against the free fall force and the back pressure generated from the hydraulic brake system (throttle or throttle / counterbalance valves).

$$(m_L + m_p)\ddot{y} + f\,\dot{y} + F_f = p_1 A_1 - p_i\,A_i \tag{1}$$

The right hand side of Eq. (1) represents the actuator generated pressure force produced by load mass free fall. Some actuators with running-away (or overrunning) loads will let the load free fall when the directional valve that controls the actuator shifts to lower the load. Cylinders with large platens and tooling or hydraulic motors on winch drives are two examples of such actuators. When the directional control valve shifts, an overrunning load forces the actuator to move faster than pump flow can fill it.

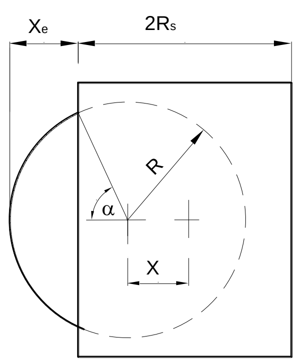

Figure (5): *Valve ports area variation with spool displacement*

3.2. Mathematical model for the throttle valve:

The throttle valve when placed at the return port of the actuator is worked as a speed control

valve (meter-out). Reducing the flow area through the throttle restriction leads to a higher back pressure in the actuator and thus to reduce velocity.
Neglecting the local losses through transmission line, the equations that describe the flow rate through the throttle valve and the back pressure accordingly could be deduced by applying the flow equation:
The flow rate though the throttle valve:

$$Q_{th} = C_d\, A_{th} \sqrt{\frac{2(p_1 - p_2)}{\rho}} \tag{2}$$

$$A_{th} = \pi\, d_{th}\, x_{th} \tag{3}$$

From the continuity equation, the hydraulic actuator back pressure, p_1, could be deduced from the continuity equation of the flow through the throttle valve.

$$Q_{th} - Q_2 - \frac{V_{th}}{B}\frac{dp_1}{dt} = 0 \tag{4}$$

3.3. Mathematical model for the Counterbalance valve

The counterbalance valve is located in meter-out to the cylinder. The flow rate though the counterbalance valve, as shown in Fig. 5, could be calculated as follows:

$$Q_2 = C_d\, A_2 \sqrt{\frac{2(p_2 - p_3)}{\rho}} \tag{5}$$

$$A_s = \begin{cases} 0 & x \le R_s - R_2 \\ \left[2R_2^2 \arctan\left(\sqrt{\frac{R_2 - R_s + x}{R_2 + R_s - x}}\right) - (R_s - x)\sqrt{R_2^2 - (R_s - x)^2} \right] & R_s - R_2 < x < R_s + R_2 \\ \pi R_2^2 & x \ge R_s + R_2 \end{cases} \tag{6}$$

$$Q_3 = C_d\, A_3 \sqrt{\frac{2(p_3 - p_o)}{\rho}} \tag{7}$$

$$A_3 = \begin{cases} 0 & x \le R_s - R_3 \\ \left[2R_3^2 \arctan\left(\sqrt{\frac{R_3 - R_s + x}{R_3 + R_s - x}}\right) - (R_s - x)\sqrt{R_3^2 - (R_s - x)^2} \right] & R_s - R_3 < x < R_s + R_3 \\ \pi R_3^2 & x \ge R_s + R_3 \end{cases} \tag{8}$$

$$Q_b = C_d\, A_b \sqrt{\frac{2(p_3 - p_b)}{\rho}} \tag{9}$$

The pressure, p_2, which effects to the great extend on the cylinder back pressure p_1 and the counterbalance valve spool back pressure p_b could be deduced from the continuity equation of the flow through the counterbalance valve.

$$Q_2 - Q_3 + A_{sr}\, \dot{x} - \frac{V_{os} - A_{sr}\, x}{B} \frac{dp_2}{dt} = 0 \tag{10}$$

$$Q_b - Q_3 + A_{sc}\, \dot{x} - \frac{V_{ob} - A_{sc}\, x}{B} \frac{dp_b}{dt} = 0 \tag{11}$$

The dynamic response of the counterbalance valve spool under the effect spool inertia and the back pressure provided by the flow restriction effect could be produced by the following equation.

$$m_s\, \ddot{x} + f_s\, \dot{x} + k(x + x_o) + F_{seat} = p_2\, A_{sc1} - p_b\, A_{sc} \tag{12}$$

$$A_{sc1} = \begin{cases} \pi D_{sc1}^2 / 4 & x \le 0.002 \\ \pi D_{sc}^2 / 4 & x > 0.002 \end{cases} \tag{13}$$

4. Results

The measured data has been analyzed to find out the static and dynamic characteristics of the throttle valve alone and that when the throttle valve is combined with the counterbalance valve. Different cracking pressures have been applied to the counterbalance valve and different throttle valve setting have been applied to the throttle valve as well. Also, the simulation results have compared with the experimental measurement to verify the model at a fixed load then a new set of results have been obtained for different falling loads.

4.1 Steady State Results:

The static characteristics for the throttle valve and throttle / counterbalance valve has been introduced for different throttling and different cracking pressure for the counterbalance valve.

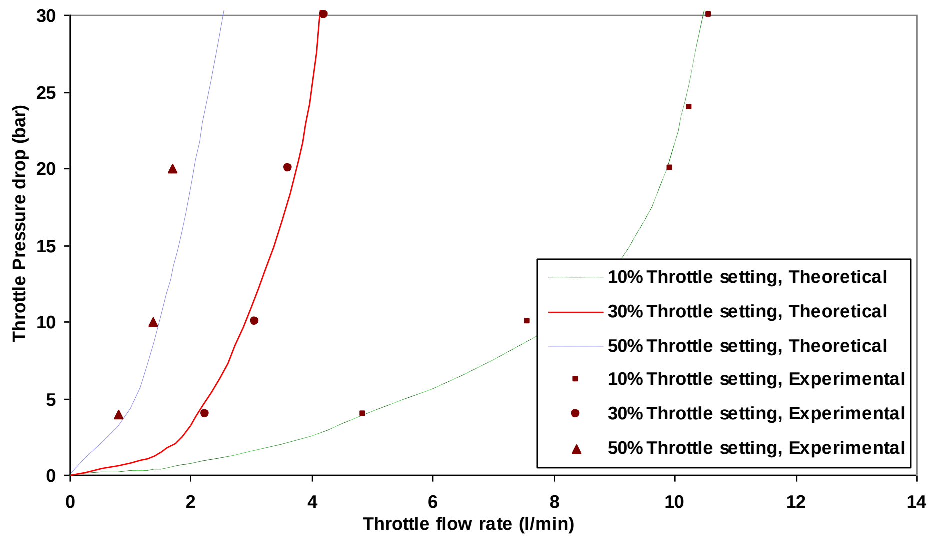

Figure (6): *Experimental and theoretical steady state characteristics of the throttle valve. (Counterbalance valve cracking pressure 17.3 bar)*

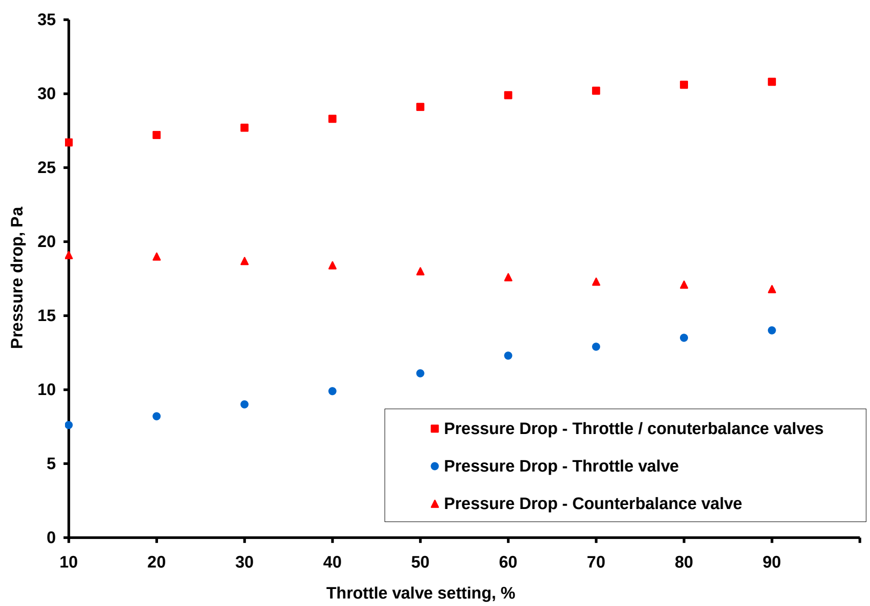

Figure (7): *Experimental results for the pressure drop across the throttle valve and the counterbalance valve (Counterbalance valve cracking pressure 17.3 bar).*

It has been shown in Fig. 6 that the introduction of the counterbalance valve connected in meter out position to the cylinder at a fixed load has no effect on the throttle valve steady state characteristics. In Fig. 7, the experimental results for the pressure drop across the throttle valve and that across the counterbalance valve have been plotted as a function of the throttling percent for cracking pressure 17.3 bar. It has been shown that the static characteristics of the counterbalance valve are affected by the introduction of throttle valve. The total pressure drop across the two valves has been increased over that of each one alone which produces the necessary braking action and absorbs the shock from the falling loads.

4.2 Transient Results:

Fig. 8 to Fig. 11 show that the experimental dynamic response of the throttle valve and that for the counterbalance valve in a throttle / counterbalance valve meter-out connection. The start time of the dynamic characteristics has been shifted right to illustrate each dynamic characteristic curve individually. In Fig. 8, the experimental dynamic response of the throttle valve for different throttle setting and for a counterbalance valve cracking pressure of 17.3 bar has been plotted. In Fig. 9, the experimental dynamic response of the throttle valve for different counterbalance valve cracking pressure and throttle setting of 70% has been plotted.

It could be noticed that the same trend has been obtained for all results. The introduction of the counterbalance valve connected in meter out position to the cylinder at a fixed load has no effect on the throttle valve dynamic characteristics.

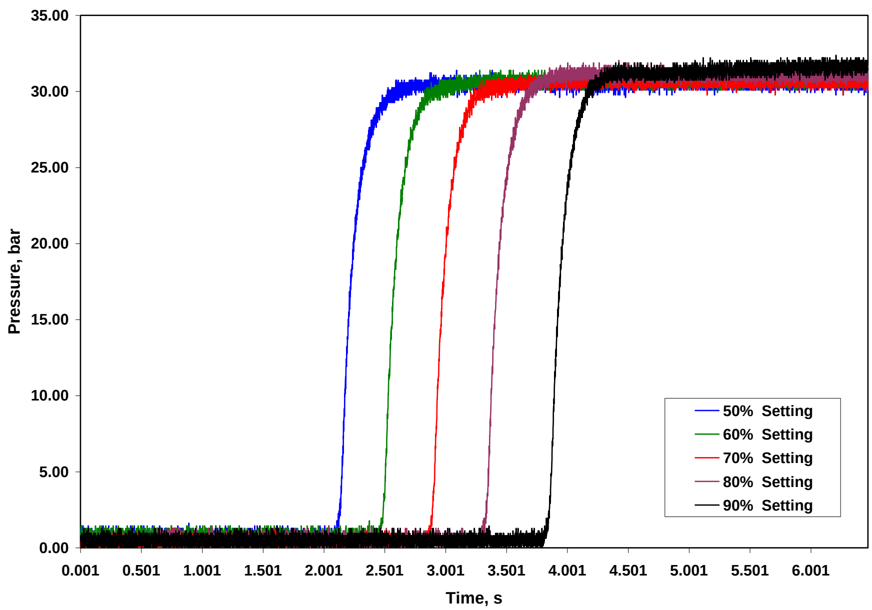

Fig. 8: Experimental dynamic response of throttle valve.
(Counterbalance valve cracking pressure 17.3 bar)

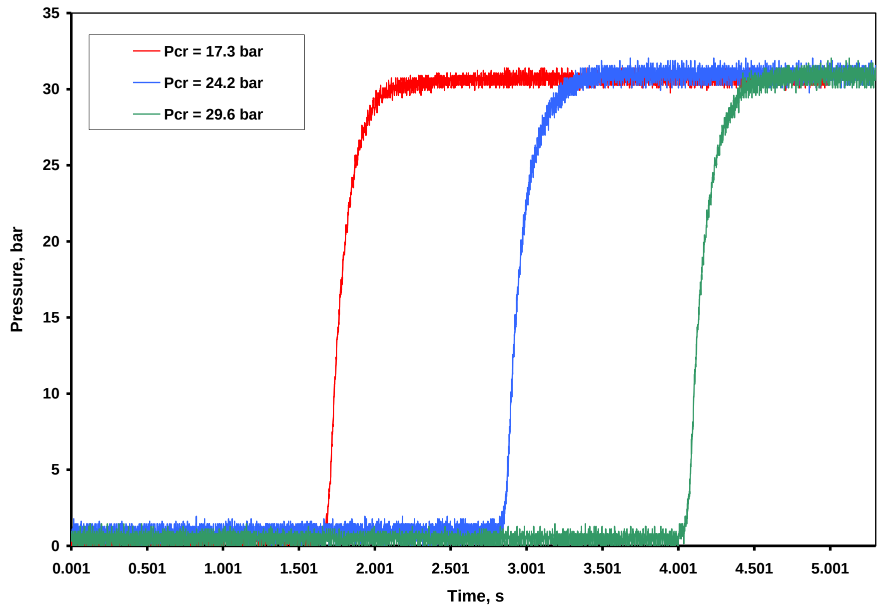

Fig. 9: Experimental dynamic response results of throttle valve, (Throttle setting 70%).

In Fig. 10, the experimental dynamic response of the counterbalance valve for different throttle setting and that for the counterbalance alone has been plotted for a counterbalance valve cracking pressure of 17.3 bar. It could be noticed that the slope of the dynamic characteristics have been changed with the throttle valve setting. The time response of the counterbalance valve has been plotted for different throttle valve setting in Fig. 11.

The response time has been calculated for the time duration that has been taken to reach the steady state characteristics. It has been shown that the introduction of the throttle valve has an effect on the counterbalance valve dynamic characteristics. The response time of the counterbalance valve could be increased by decreasing the throttle valve setting which is suitable for light loads and vice versa.

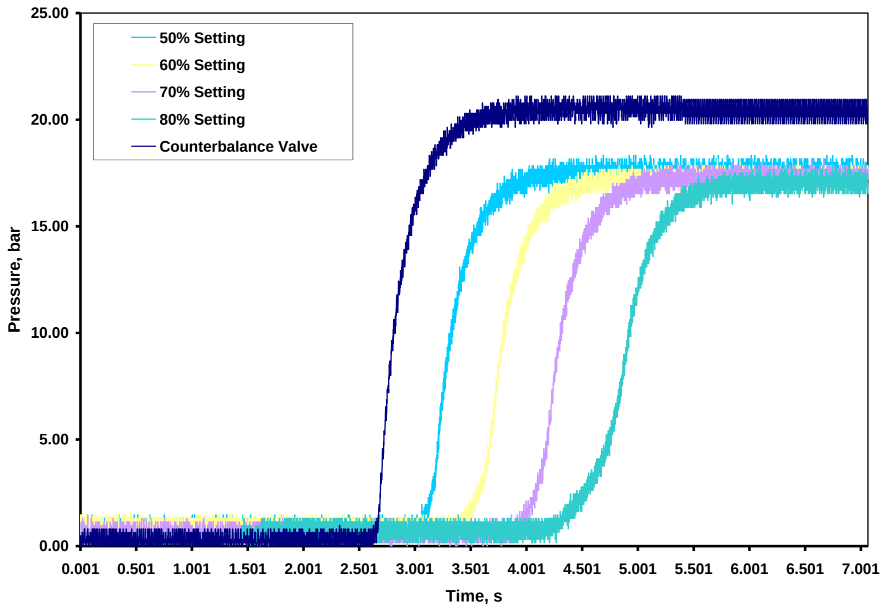

Figure (10): *Experimental dynamic response of counterbalance valve and that of the counterbalance valve alone (Counterbalance valve cracking pressure 17.3 bar).*

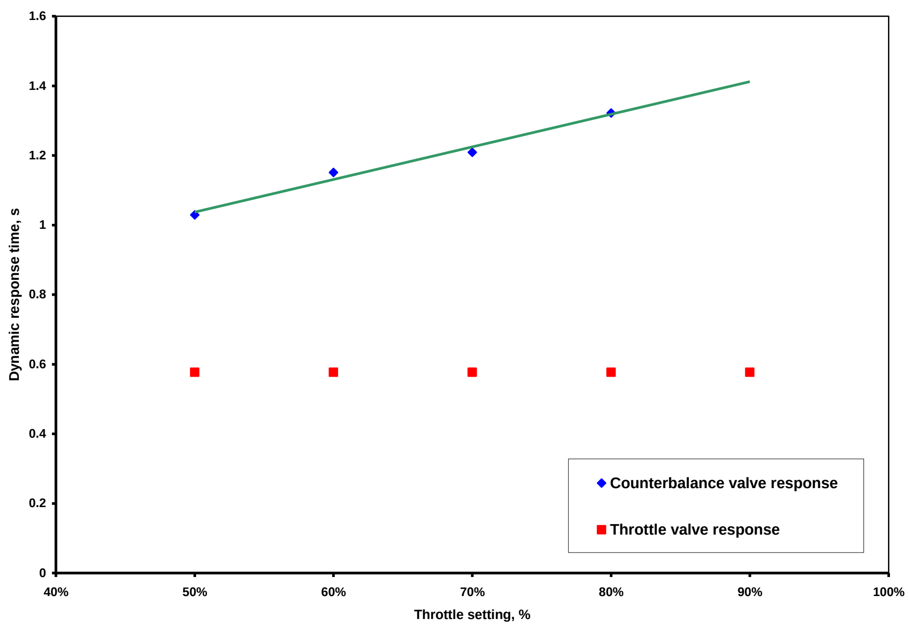

Figure (11): *Experimental dynamic response time for throttle valve and counterbalance valve (Counterbalance valve cracking pressure 17.3).*

In Fig. 12, a comparison has been established for the experimental and theoretical dynamic response of the counterbalance valve. It could be noticed that the same trend has been obtained for both results. In Fig. 13, the dynamic response of the counterbalance valve has been plotted for different throttling.

In Fig. 14, the experimental dynamic response results of counterbalance valve in the throttle valve/ counterbalance valve connection for different cracking pressure and for 70% throttling have been plotted.

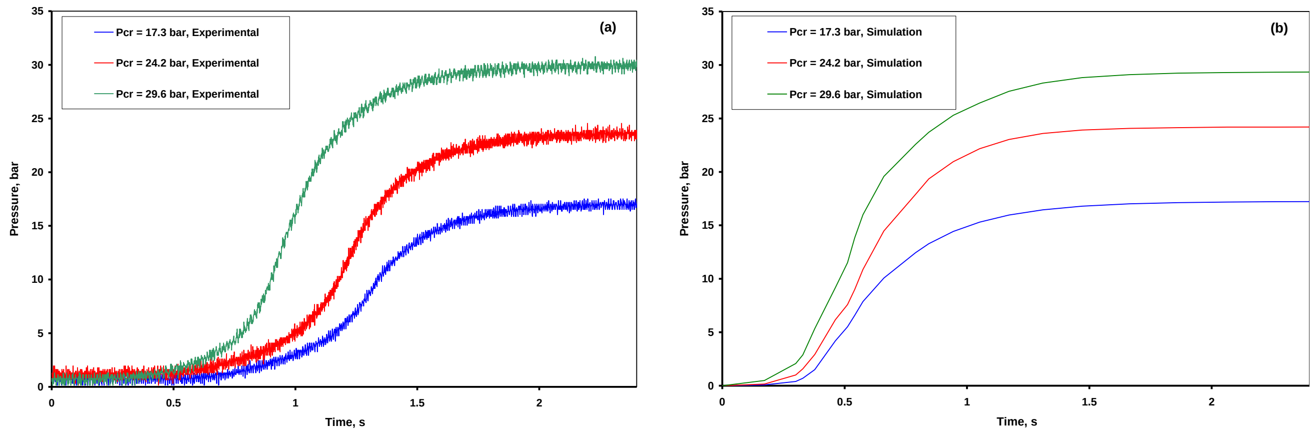

Figure (12): *Experimental and theoretical dynamic response of the counterbalance valve (a) Experimental results, (b) Theoretical results, (Throttle valve setting 70%).*

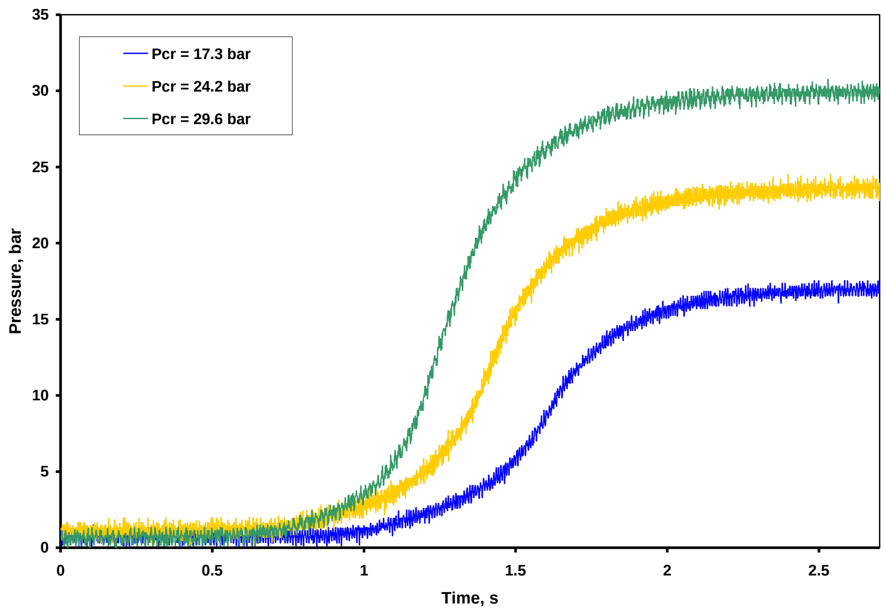

Figure (13): *Experimental dynamic response of the counterbalance valve, (Throttle valve setting 80%).*

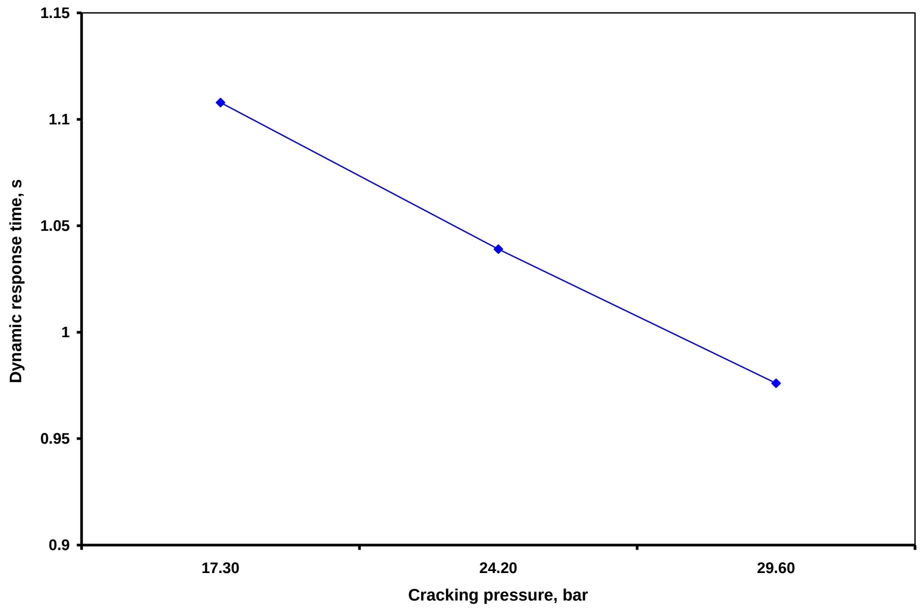

Fig. 14: Experimental dynamic response time of the counterbalance valve. (Throttle valve setting 80%).

As a sensitivity analysis, the dynamic response of the cylinder displacement (piston displacement) could be plotted for the throttle valve and that for the throttle valve/ counterbalance valve for the same cylinder load, as shown in Fig. 15. It could be noticed that the piston displacement reached its steady state position in throttle valve/ counterbalance valve combination faster that that for throttle valve only.

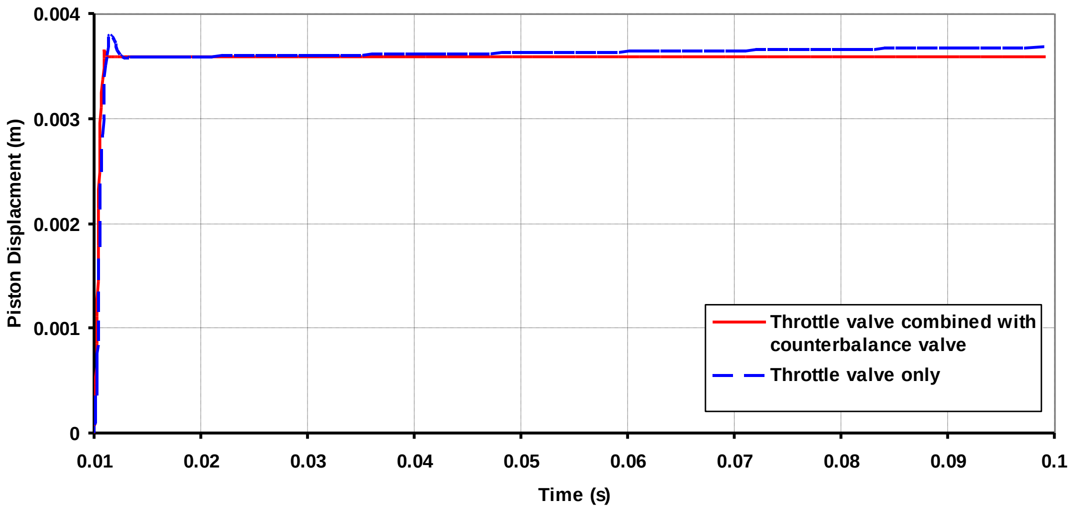

Figure (15): *Comparison between the piston displacement for the throttle valve and that for the throttle valve / counterbalance valve for the same cylinder load.*

5 Effect of cylinder load:

The effect of the different cylinder loads on the dynamic response of the throttle valve is shown in Fig. 16. A comparison between the drafting of the actuator falling under the effect of throttle valve and throttle/counterbalance valve is shown in Fig. 17. It could be noticed that the piston displacement reached its steady state position in throttle valve/ counterbalance valve combination faster that that for throttle valve only especially for heavy cylinder loads.

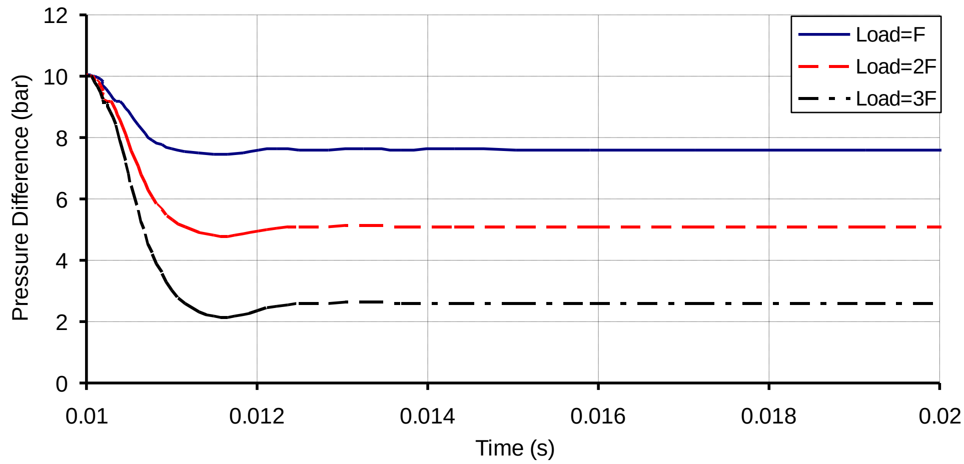

Figure (16): *Theoretical dynamic response results of the throttle valve for different cylinder loads.*

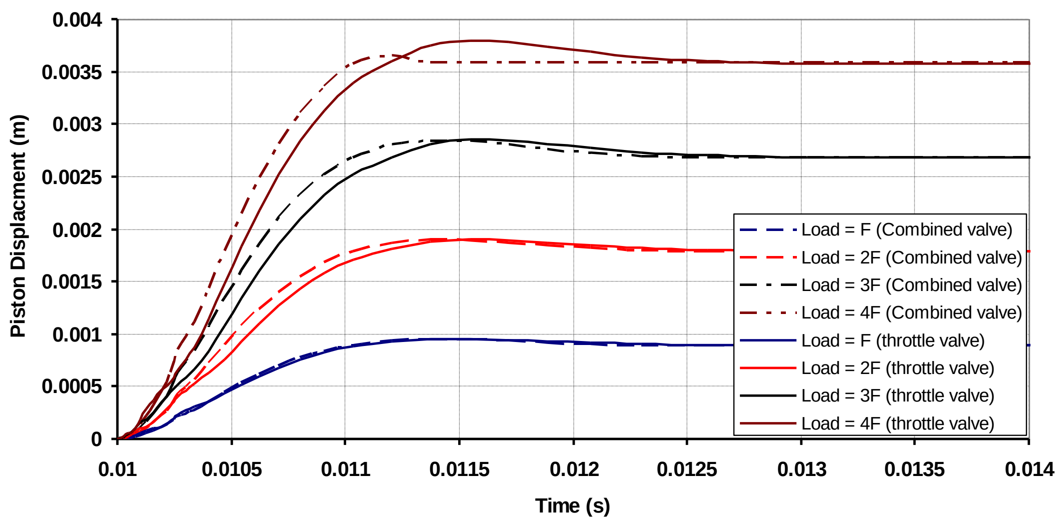

Figure (17): *A comparison of the piston displacement for the throttle valve only and that for the throttle valve / counterbalance valve for different cylinder loads.*

6. Results and Discussion:

At the start of motion of negative loads, the pressure is built up in the cylinder until it reaches the cracking pressure of the counterbalance valve. With the increase of the pressure the counterbalance valve is opened allowing for the flow rate to increase, acceleration mode. When a free fall is detected, the flow rate from the cylinder is increased while the pressure is constant. The increase of the flow rate across the throttle valve leads to a reduction in downstream pressure of the throttle valve. As a result, the inlet pressure of the counterbalance is reduced. Then, the counterbalance is partially closed leading to increase of the back pressure of the throttle / counterbalance valve.
Increasing the throttling for the same counterbalance characteristics will increase the response time as the back pressure will decrease and the counterbalance valve will close faster. This result leads to a smoothing braking action.
The dynamic response time of counterbalance valve has been decreased with the decrease of the throttle valve setting for the same cracking pressure producing a high response for braking action of the negative load. For the same throttle valve setting, the dynamic response time of counterbalance valve has been decreased with the increase of the cracking pressure.

7. Conclusions

The static and dynamic characteristics of a hydraulic circuit have been investigated theoretically and experimentally for different throttling positions, different cracking pressure of the counterbalance valve and for different cylinder loads, to show the effect of introducing the throttle valve upstream the counterbalance valve. Different cracking pressures of the counterbalance valve have found to have minor effect on the throttle valve steady state characteristics.

Introduction of a throttle valve, upstream the counterbalance valve, found to affect the dynamic characteristics of the counterbalance valve. It reduces the shock loads at both starting and braking of the free fall loads.

The results showed that the throttle valve, upstream the counterbalance valve, enhances the dynamic characteristics of the counterbalance valve. The response time of the counterbalance valve could be controlled by using a suitable setting of the throttle valve. For heavy loads, increasing the throttle valve setting will increase the response time as the back pressure will increase and the counterbalance valve will close slower. This result leads to a smoothing braking action.

Nomenclature

A_1 , A_i… Actuator piston effective areas (m^2)
A_{sc}, A_{sr}... Counterbalance valve spool areas (m^2)
A_{sc1}……. Counterbalance valve effective spool areas (m^2)
A_{th}…….. Throttle area (m^2)
B………. Bulk's modulus (Pa)
C_d…….. Discharge coefficient.

d_s……… Counterbalance valve spool diameter (m)
d_{th}…….. Throttle valve diameter (m)
F………. Viscous damping coefficient (Ns/m)
F_f…….... Coulomb friction force. (N)
f_s………. Counterbalance valve viscous damping coefficient (Ns/m)
k............ Spring stiffness (N/m)
m_L…….. Mass of the actuator load (kg)
m_p…….. Mass of the actuator piston (kg)
m_s…….. Counterbalance valve spool mass (kg)
p_1…….... Actuator outlet pressure (Pa)
p_2, p_3……. Counterbalance valve inlet and outlet pressure (pa)
p_2…….... Throttle valve outlet pressure (Pa)
p_b……… Counterbalance valve back pressure (Pa)
p_o……… Return pressure (Pa)
p_i…….... Actuator inlet pressure (Pa)
Q_2…….. Counterbalance valve inlet flow rate (m^3/s)
Q_b…….... Counterbalance valve back flow rate (m^3/s)
Q_{th}……. Throttle inlet mass flow rate (m^3/s)
t……….. Time (s)
V_{os}, V_{ob}.. Counterbalance valve initial volumes (m^3)
V_{th}…….. Throttle valve internal volume (m^3)
x………. Counterbalance valve spool displacement (m)
x_s……… Counterbalance valve spring precompression distance (m)
x_{th} ……. Adjustable throttle vent (m)
y……… Actuator displacement (m)
$\tilde{\rho}$ Density (kg/m^3)

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