Proportional Hydraulic Control System of Overrunning Variable Load Actuator

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Abstract - *Most variable hydraulic loading machines uses traditional counter balance valve to create the opposing hydraulic force. The valve would be either fixed or manually adjusted. The manual regulatory process can causes time or changing some of the hydraulic component so the system would be combatable with the needs of application. The process would be lacking in control especially when the load is changing continuously.*

A smart system has been proposed that work with proportional pressure control valve, industrial load cell, and also electronic pressure sensor through Arduino controller, which is programmed with Labview program to control a variable load actuator in four cases of hydraulic pump pressure supplying in a way that keeps the variable load actuator hold still in position no matter how much or how long the applied load changes. The system was simulated by using simulation program (Automation Studio) to make sure the function of it is work. Fluid analysis was calculated to see the limitation of components and the suitable cases. A laboratory device was also built that simulates the system's work to ensure the performance and design of the system and as a result, a proportional relationship between load sensor at the load actuator and the holding pressure has been obtained in all the four cases which produced a successful variable load actuator. It has been concluded that when the supplying pressure value increases, the hydraulic actuator variable loading ability decreases where the limitation of the proportional pressure decreases.

Key Words: load sensing, control of variable loading, proportional pressure relief valve, and data acquisition through Labview.

1. INTRODUCTION

The requirement to reduce machine maintenance costs and to increase reliability and safety make electro-hydraulic solutions for open circuit application in load control, attractive and cost effective.

Most variable hydraulic loading machines uses traditional counter balance valve to create the opposing hydraulic force. The valve would be either fixed or manually adjusted that requires intervention of staff and continues monitoring for the valve which is located far away from the areas of the control system.

In this research, the control system will be modified such that the loading pressure is controlled automatically by adding load sensor and pressure sensors that are auto-sensitized without intervention of staff. The signals of load and pressure measurement are transferred electronically to the proportional pressure control valve to set the required holding pressure for the actuator. The block diagram of the system is shown below in figure (1).

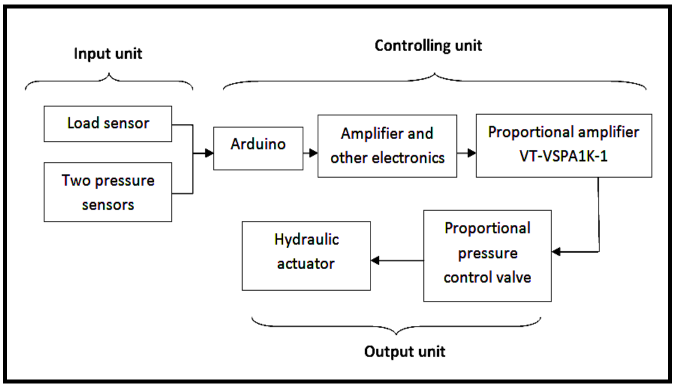

Fig -1: block diagram of proportional control system for overrunning load actuator

Several points used from the researches. [1] Presented a method to derive an optimal pressure curve for sheet hydro-forming process which has been characterized by three factors. Firstly, initial pressure which derived from no lifting condition. Then, final pressure is obtained from result of FE (finite element) analysis. Finally, pressure path is assumed to be proportional to the punch penetration volume. The predicted pressure curve has been verified optimal pressure curve for successful forming since no defect has been observed. [2] Used the proportional pressure relief valve as a loading unit which is known as energy saving system for supplying hydraulic actuators with highest efficiency. [3] Presented experimental study through adaptive PID, two pressure sensor, variable displacement axial piston pump, and a 2 ways proportional valve that has been used for controlling variable load sensing. [4] Analyses the relationship between counterbalance valve and stability of the lifting system. [5] Studied load-sensing concept in hydraulic systems when a stable and comfortable control of the actuators is needed at high frequency load variations. [6] Used a load cell, pressure sensors and self-tuning grey predictor – fuzzy PID controller to study force control problem solving by a hydraulic hybrid actuator. [7] Used counter-balancing principle for heavy-loading in a robotic arm.

2. LOAD SENSING

Load sensing is a mature and robust technology that is widely applied in process control to measure the weight of goods, to monitor the strain on structure and to gauge filling levels on containers [8]. A most popular way is to use a load cell which is, in a simple manner, a system that outputs an electric signal by a physical force applied to it. The load cell is based on strain gages. The structure is composed of specially selected and formed metal chassis called as spring component, and Wheatstone bridge, which is formed with strain gages. Physical force applied to spring component causes a deformation. The deformation that occurs in spring component is outputted as electric signal over Wheatstone bridge [9]. The load cell S-type is highly accurate strain gage based sensors which has been used. Loading range (0-50) Kg, equipped with a braided shield 4-wire round cable for electrical interface. The load cell is used with the loading table in a tension manner as shown in figure (2).

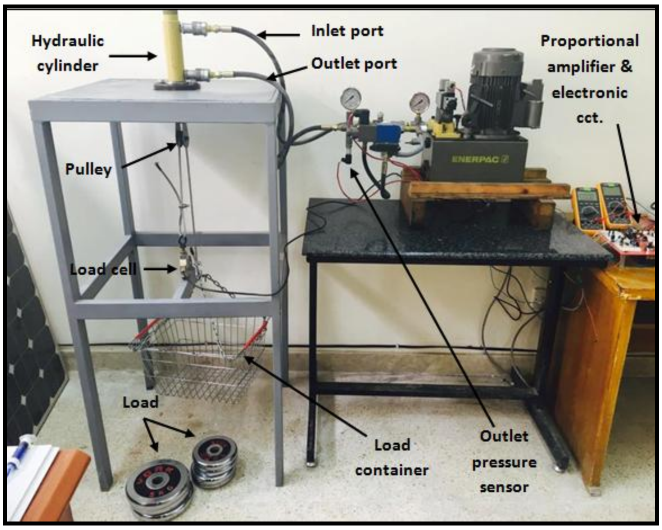

Fig -2: the electro-hydraulic system for proportional control of overrunning variable load actuator

3. HYDRAULIC SYSTEM

First of all the hydraulic actuation system works mainly in three stages. It begins with mechanical energy input that will be converted to fluid energy with hydraulic pumps. Then, this fluid with its energy goes through conduits and necessary hydraulic control devices such as hydraulic control valves. Finally the fluid energy converted into mechanical energy with output devices such as cylinders [10]. The hydraulic system is shown in figure (3). It is consisting of:

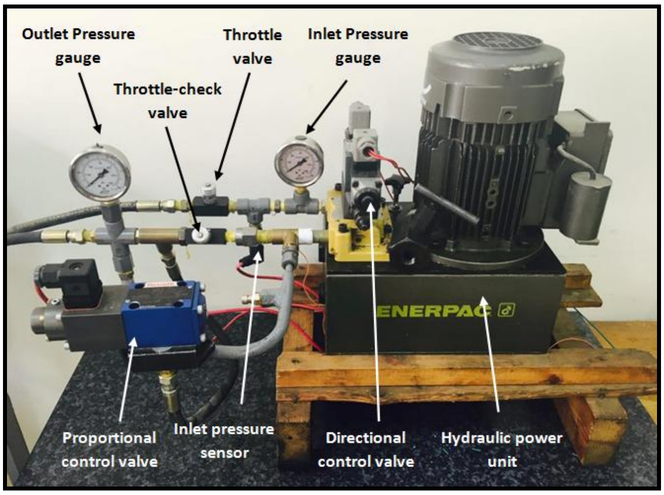

Fig -3: The Electro-hydraulic system

3.1 Hydraulic Power Unit

Hydraulic power unit is a complete system with two ports; one for supplying flow to the hydraulic system (hydraulic pump piston type driven by an electric motor) which converts mechanical energy to fluid pressure and flow. The other port for return flow from the hydraulic system is hydraulic tank [11].

3.2 Directional Control Valve

Directional control valve (DCV) used in the test rig has four ways and three positions for controlling the direction of motion of hydraulic cylinders. A 4/3 DCVs are used to start, stops, or change the direction of fluid flow [12].

3.3 Throttle Valve

The throttle valve is used to restrict the fluid flow in both directions. For setting the pump supplying pressure [12].

3.4 Check Valve

The check valve is generally used to allow for free flow in one direction, and obstruct the fluid flow in the opposite direction. It allows the fluid flow in the lifting case [12].

3.5 Proportional Pressure Control Valve

The proportional pressure relief valves are directly operated by means of proportional solenoids. They are used for converting electrical input signals into a proportional pressure output signal. These valves are used for limiting the pressure in a system [13]. The type of proportional pressure control valve (PPCV) used was DBEP6A06-13/45AG24K4M. A proportional amplifier type VT-VSPA1K-1[14] used to control the circuit of the proportional pressure relief valves.

3.6 Hydraulic Actuator

The hydraulic cylinders convert the hydraulic power into mechanical power, performing rectilinear motion. The pressure of input oil is converted into force acting on the piston [12]. The hydraulic cylinder used in the test rig is Enerpac double acting universal cylinders. It can lift the load up, down, or hold it into the required position. A mathematical model of a double-acting hydraulic cylinder is analysis by Heinze. Basically, the resulting force of a double-acting cylinder is determined by the difference of the chamber's product of pressure and cross-sectional area:

$$p_2A_2 - p_1A_1 = F_1 - F_2 + F_g - F_{fr} \quad ...(1)$$

Where p_1 is the pump supplying pressure in bar, p_2 is the opposing holding pressure by the PPCV in bar, A_1 is the piston side area (5.1) cm2, A_2 is the rod side area (2.19) cm2, , F_1 is the applied load in kg, F_2 is the force applied to the piston side, F_g is the gravitational force, and F_{fr} is the friction force. The last three ones are neglected. The resulting equation would be:

$$p_{holding} = (5.1 * p_{supplying} + F_{load})/2.19 \quad ...(2)$$

This holding pressure will change as the load changes to make the actuator hold still in position.

4. SIMULATION ANALYSIS WITH AUTOMATION STUDIO

Automation Studio (AS) package was developed in (2003) by (FAMIC Technologies Inc/Canada) to contain comprehensive libraries of hydraulic, pneumatic, ladder logic, and digital electronic symbols. This package is completely integrated software package that allows the user to design, simulate and animate circuits consisting of various automation technologies [15]. Proportional hydraulic control system of overrunning variable load actuator was built and simulated with this program. All components and parameters of the system have been selected and connected as in the actual system in the project work sheet as shown in figure (4).

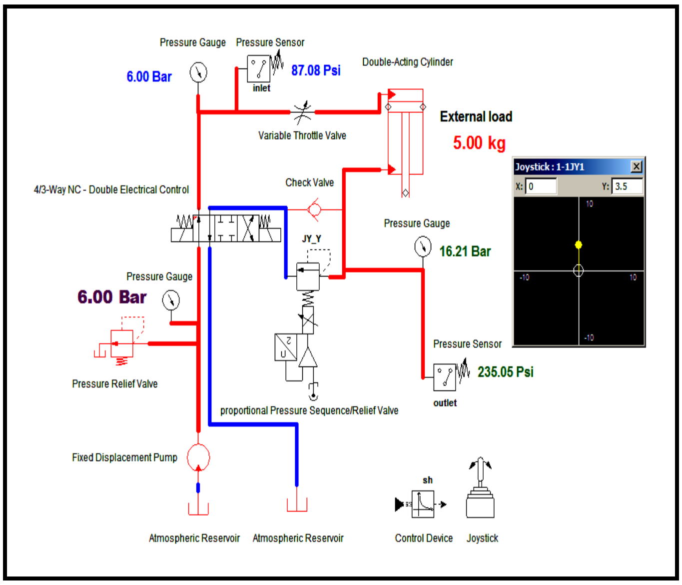

Fig -4: the simulation process of the system

5. ELECTRONIC CIRCUIT WITH ARDUINO UNO BOARD

The circuit are designed and built experimentally by the researcher from simple electronic components. The block diagram of this circuit is shown in figure (5). The circuit connection of Arduino UNO connected with load cell, two pressure sensor and VT-VSPA1K-1 card are shown in figure (6) using Fritzing software.

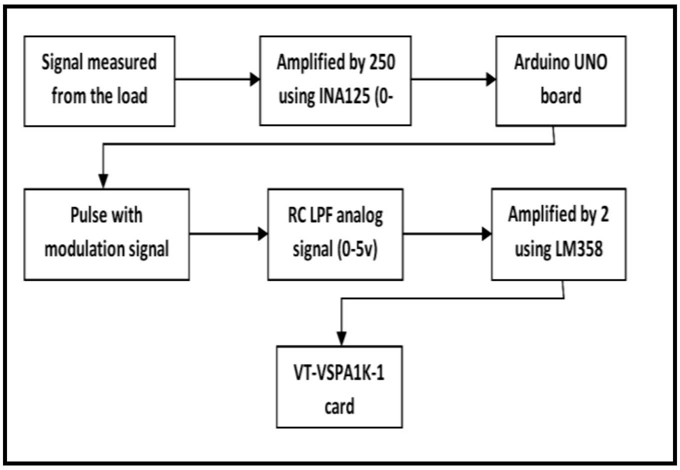

Fig -5: Block diagram of electronic circuit

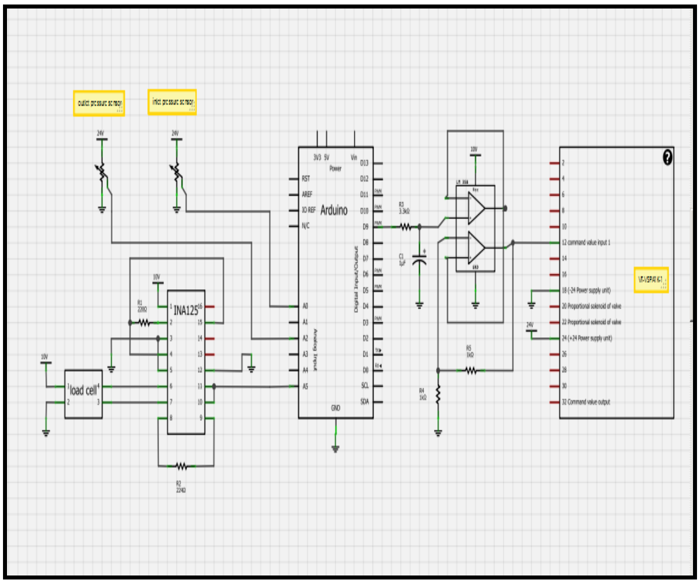

Fig -6: electronic circuit connections

6. PROCEDURE OF THE THEORETICAL AND EXPERIMENTAL WORK

1- Find calibration of load cell, the range of load is (0-30 kg), in order to get relationship between load and voltage by using digital voltmeter. From the calibration found another relationship between the load and the amplified voltage that will feeds into the Arduino board. This relationship curve is shown in figure. (7).

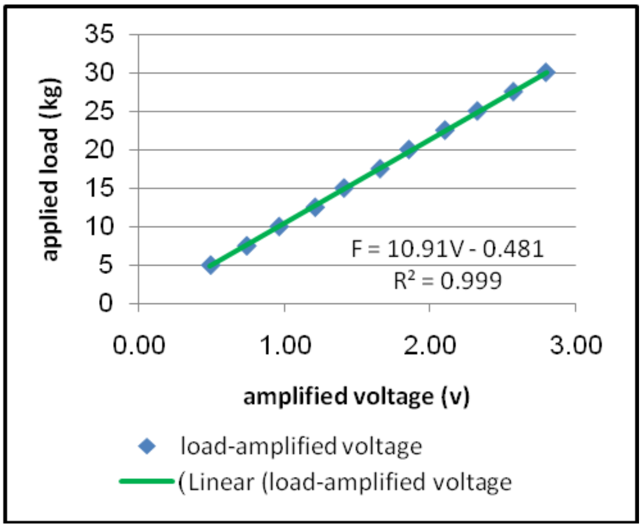

Fig -7: amplified voltage and the applied load relationship

2- Find calibration of two pressure sensor in order to get relationship between pressure and voltage.

3- Find calibration of proportional pressure control valve (PPCV) by connecting it to a hydraulic pump which supplies a constant pressure with a pressure gauge and pressure sensor. The range of PPCV is (0-45 bar). The calibration diagram and curve is shown in figure. (8) and (9) respectively.

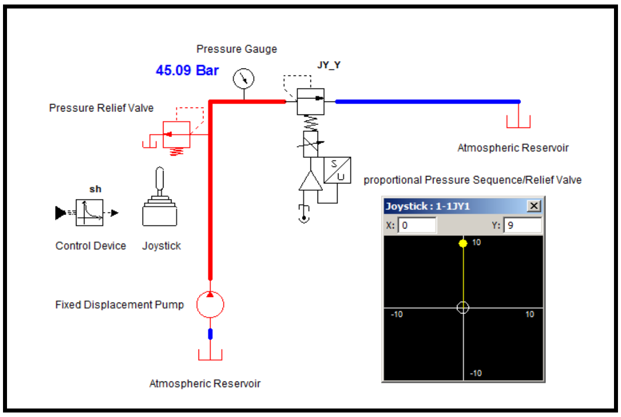

Fig -8: diagram of proportional pressure control valve calibration

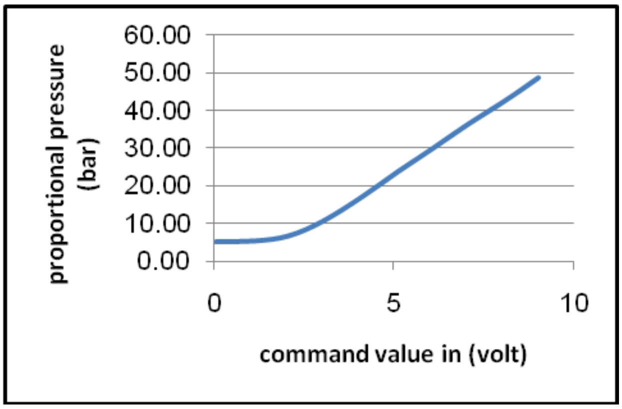

Fig -9: curve of proportional pressure control valve calibration

4- Find the fluid analysis for the hydraulic system with the influence of variable load according to equation (2) in order to see the limitation of components and the suitable cases.

5- Find the controlling mathematical equation of PPCV at different hydraulic pump pressure supplying. Where the input is a variable load (F) at the hydraulic actuator cause variable pressure at the outlet port, and the output is voltage (V) to PPCV card that provide the holding pressure. This operation has been done by selecting a specific weight each time and from the mathematical result of fluid analysis knowing the required holding pressure for it. Then from the calibration of PPCV knowing the command input value 1 for the proportional card that provide the required holding pressure. The operation has been repeated in four cases in load range of (2.5-70) kilograms. The controlling equations provide the necessary holding pressure for the actuator is:

$$V = a1 * F + a2 \quad \text{... (3)}$$

Where a1 and a2 values changes as the pump supplying changes, a1 and a2 values are shown in table (1).

Table -1: factors of controlling equations

Pump supplying (bar)	a1 value	a2 value
6	0.028	1.418
10	0.026	2.321
15	0.021	3.315
No supplying	0.052	1.28

6- Interfacing the Arduino board with the graphical programming environment Lab VIEW by using (LIFA) toolkit through a VI package manager that allows users to control sensors and acquire data through an Arduino microcontroller through the previous controlling equations. This step allows the users to focus on high level application rather than low level platform configuration.

7- Creating a GUI lab view program in order to get the behavior of the sensors and to perform the required action upon it.

7. DATA ACQUISITION THROUGH LABVIEW SOFTWARE

The LabVIEW Interface for Arduino (LIFA) Toolkit is a free download. LIFA allows users to control sensors and acquire data through an Arduino microcontroller using the graphical programming environment LabVIEW. The GUI made to read the voltage signal from the three sensors. these voltages convert by the sensor calibration equations that is listed in table (2) into the real measured value (load, inlet pressure, and outlet pressure) by Kalman Filter. Kalman Filter most important applications include control, supervision, modeling and noise reduction.

Table -2: Equations of sensors

Sensors	Equation
Loading Sensor	$V = 0.369F - 0.0018$
Inlet Pressure Sensor	$V = 0.0958P + 0.0019$
Outlet pressure Sensor	$V = 0.0833P + 0.052$

This action can be done by adding a formula node to the GUI LabVIEW. Then using these real measured values to decide which hydraulic pump supplying case and accordingly use the specified controlling equation to set the command value input 1 for proportional amplifier card that can be done by using case structure in the GUI LabVIEW. The final GUI LabVIEW front panel is shown in Fig. (10) and the block diagram is shown in Fig. (11). Table (3) shows explanation for the block diagram.

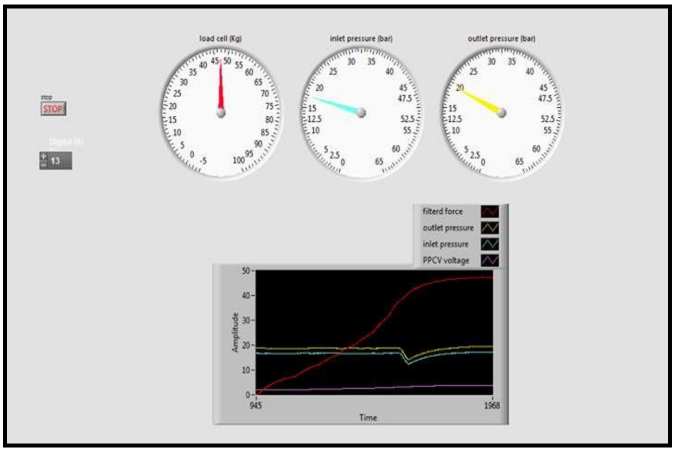

Fig -10: LabVIEW front panel for the system

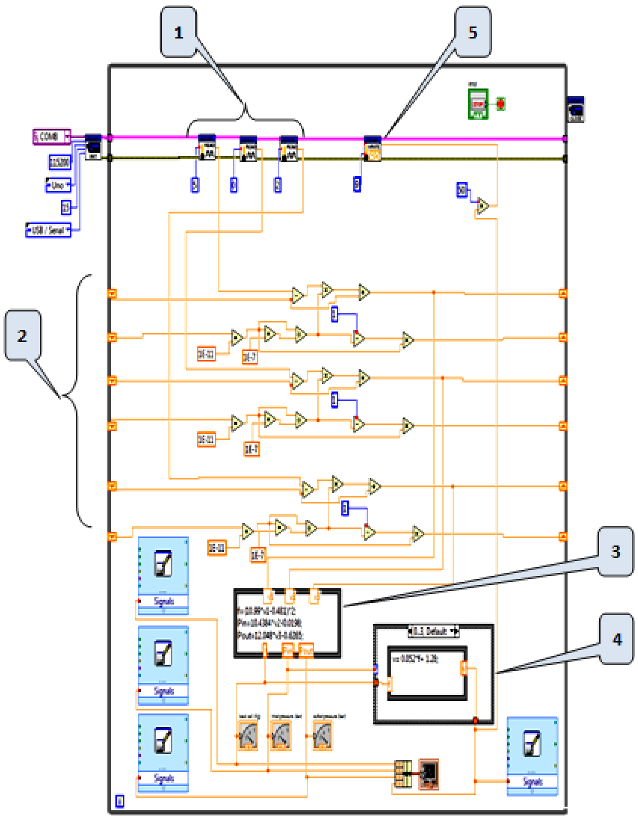

Fig -11: LabVIEW block diagram for the system

Table -3: LabVIEW block diagram description for the system

Item	Description
1	Read analog pin A5 for load sensor, pin A0 for inlet pressure sensor, and pin A2 for outlet pressure sensor.
2	Three Kalman Filter, one for each sensor signal.
3	Formula node for writing the mathematical equation of calibration for each sensor.
4	Case structure to determine the on going case which could be no pump supplying, 6 bar, 10 bar, and 15 bar pump supplying. Each case has a controlling equation.
5	PWM write pin09 for the proportional amplifier card.

Now, the GUI program converts the input sensors voltages into their compatible values by the formula node. Then the case structure decide the current supplying case and through it send the required value to the proportional card that provide the required holding pressure at that specific load. The program is checking the variable changing continuously and takes an action upon it with out human intervention.

8. RESULTS AND DISCUSSION

8.1 Simulation Results

Electro hydraulic system has been built with automation studio package V5.2 this result was represented the function of its work. The linear speed of double-acting cylinder at different loads using a traditional counter balance valve and a proportional pressure relief valve has been shown in figure (12) and (13) respectively. In case of the counter balance valve it can be observed strong oscillations and the velocity peak changes continuously in function of the applied load at the cylinder. But when the PPCV is used, the necessary setting pressure is provided to control the variable load system. A major oscillation is avoided and this leads to an improvement of the dynamic behavior of the cylinder. Figure (14), (15), and (16) shows measured data of input controlling voltage of proportional pressure control valve with the required pressure at different loads when the hydraulic pump supplying pressure at 6 bar,10 bar, and 15 bar respectively.

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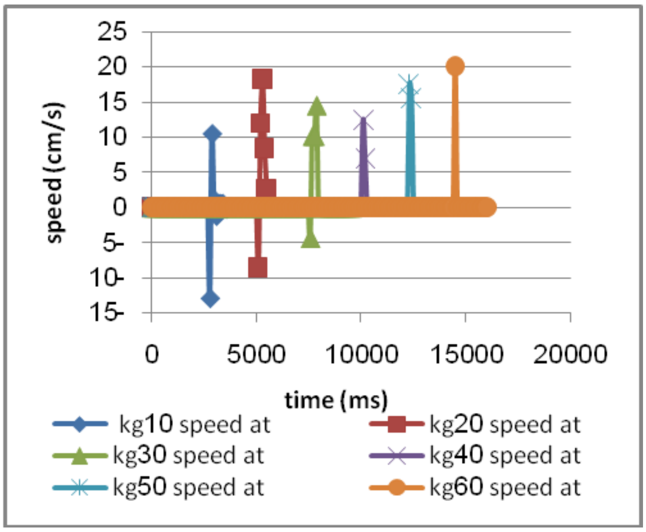

Fig -12: linear speed of a double-acting cylinder using traditional counter balance valve

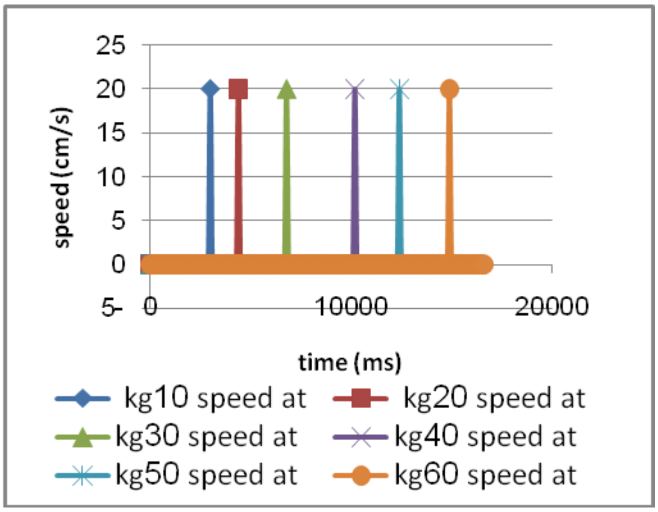

Fig -13: linear speed of a double-acting cylinder using proportional pressure control valve

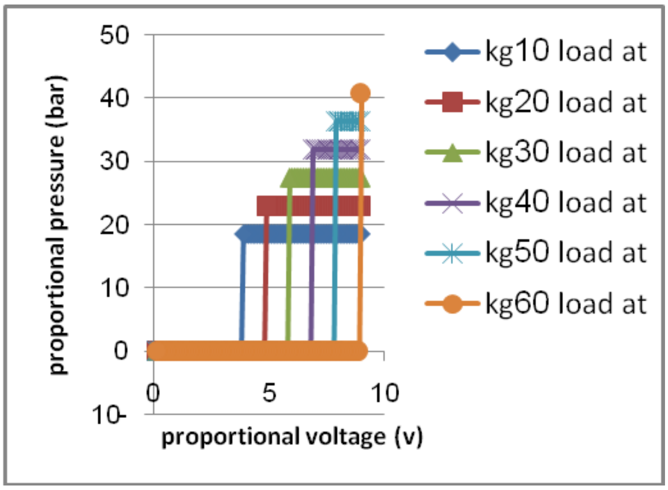

Fig -14: Measured data of proportional pressure control valve at different loads with pump supplying pressure at 6 bar

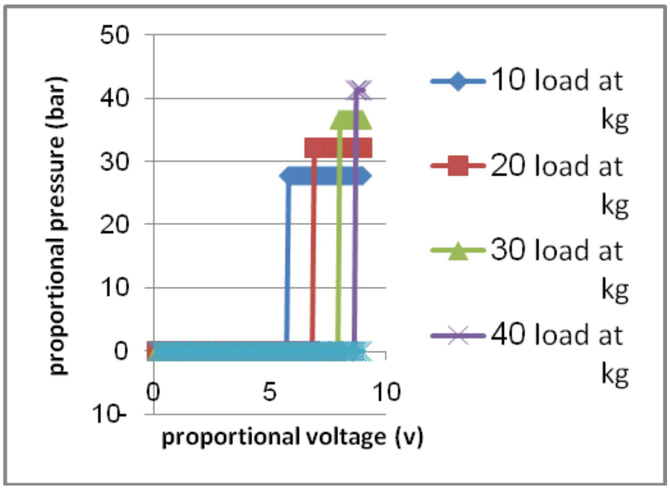

Fig -15: Measured data of proportional pressure control valve at different loads with pump supplying pressure at 10 bar

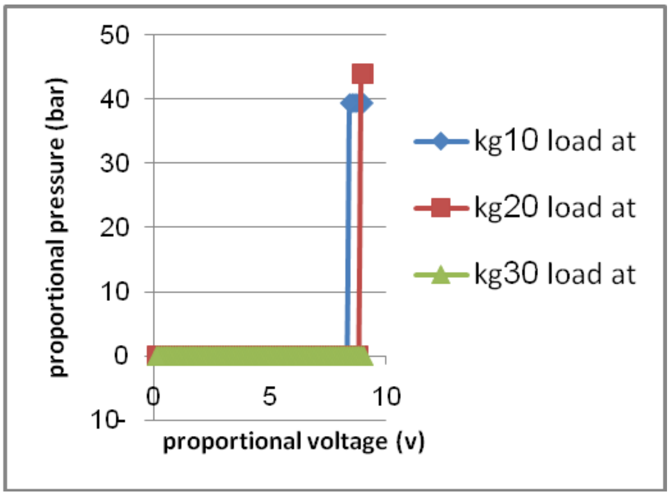

Fig -16: Measured data of proportional pressure control valve at different loads with pump supplying pressure at 15 bar

From the previous three figures, the simulation results showed that when the supplying pressure value increases, the hydraulic actuator variable loading ability decreases where the limitation of the proportional pressure decreases.

8.2 Mathematical Results

A theoretical study of the load variation with the holding setting pressure for the PPCV at different supplying pressure from the hydraulic pump has been calculated as it explained in equation (2). The holding setting pressure has to be in the pressure working area of PPCV and don't exceeded it which is 45 bar or the actuator will fail to hold the load. The result will also be presented later in the compression.

8.3 Experimental Results

The experimental results were obtained from the test rig by using a load sensor and two pressure sensors for monitoring, four cases which is shown below when there was no pressure drop in the hydraulic system and pressure drop took a place when the actuator fail to hold the variable loading. The actuator failure occurred when the loading exceeded the PPCV holding limit at a specific pump supplying. These results obtained from Labview software connected with Arduino board.

Figure (17) shows behavior of the load sensor and two pressure sensors at 6 bar with time. It shows that as time passes, the system pressure settles down no matter how much the load changes. The two pressure sensor was used to find out the behavior of the pressure in pipeline and notice that the two sensors have the same response, with a difference due to the cylinder area ratio, and this is good. Notice that when the failure happens at (69 kg) the pressure drops immediately until the actuator stroke is finished then the pressure rises again and settles due to the pump continues supplying. Both sensors have very high response.

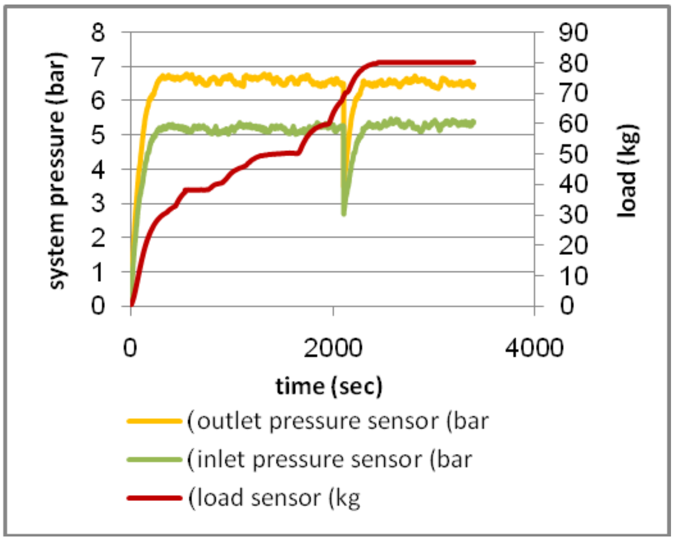

Fig -17: Behavior of the system at 6 bar

The behavior of the load sensor and two pressure sensors, at 10 bar, 15 bar, and on pump supplying as shown in Fig. (18), (19), and (20) respectively.

Notice that in Fig. (19) the failure accrues before the system settling because the loading process is hard to repeat it but that didn't affect the system performance.

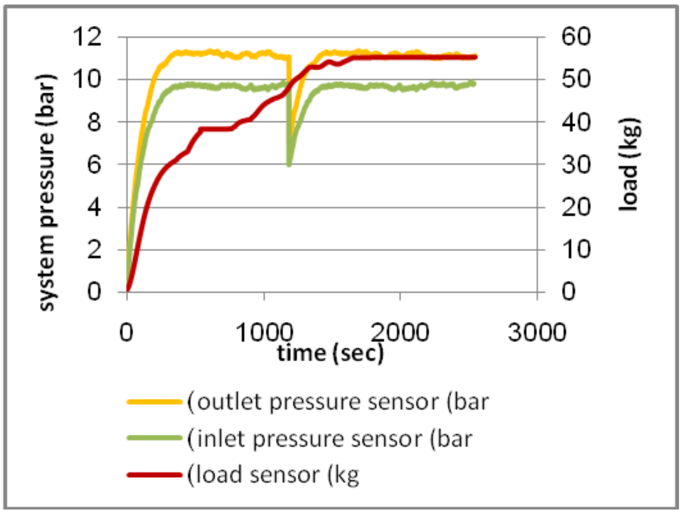

Fig -18: Behavior of the system at 10 bar

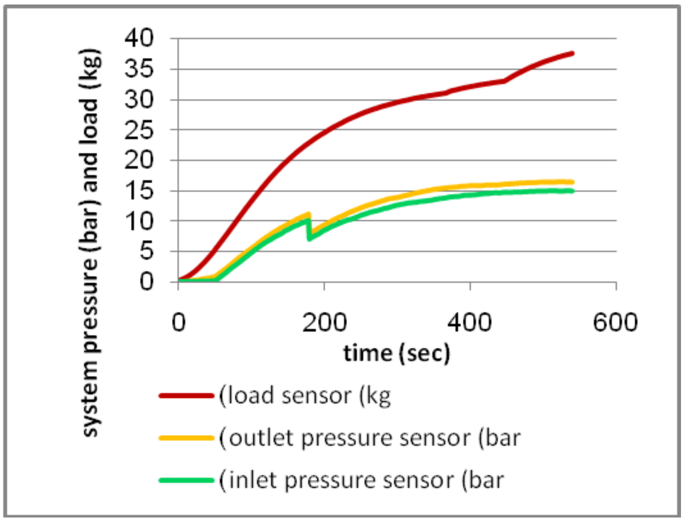

Fig -19: Behavior of the system at 15 bar

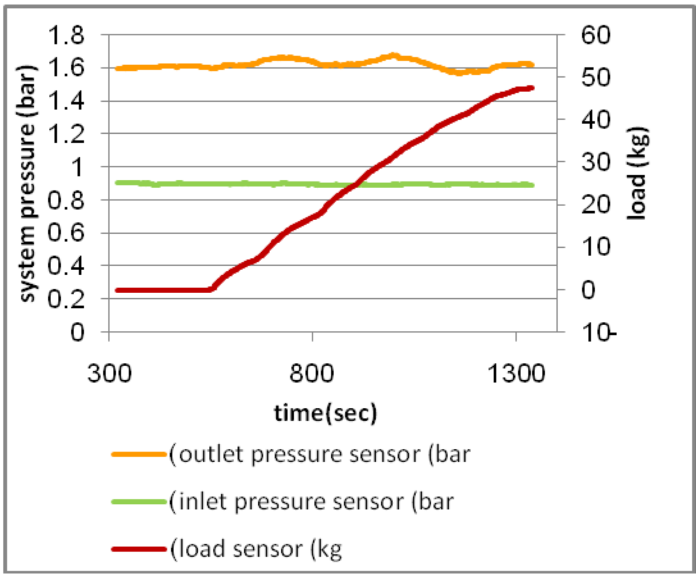

Fig -20: Behavior of the system at no pump supplying

A comparative study between theoretical, experimental, and simulation results of the load variation with pressure setting for the PPCV at different supplying pressure from the hydraulic pump. Four cases were taken at 6bar, 10 bar, 15 bar, and on pump supplying as shown in Fig. (21), (22), (23), and (24) respectively. The comparison shows that the theoretical and simulation holding pressure path is considerably compatible to each other which means the simulated system is working correct on the bases of the theoretical.

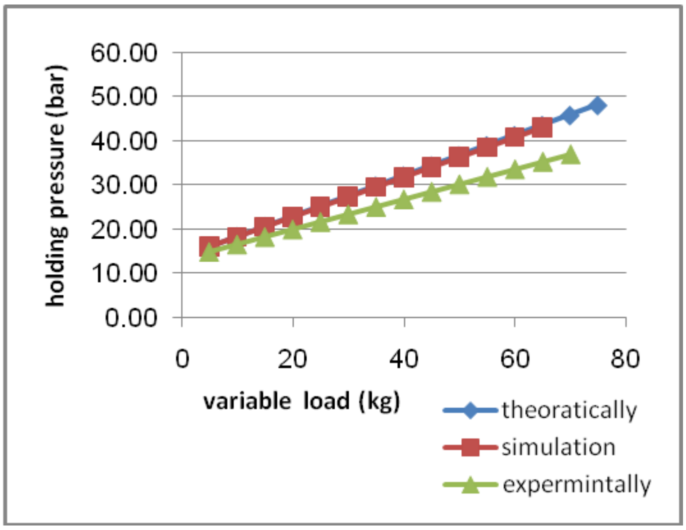

Fig -21: Variation of holding pressure with variable load at 6 bar hydraulic pump supplying

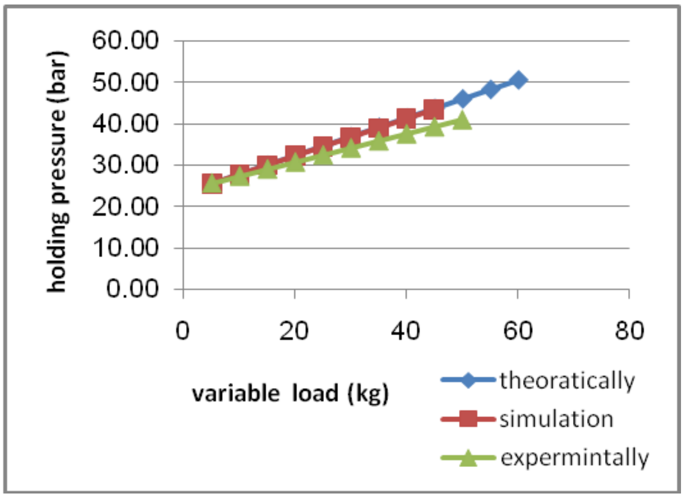

Fig -22: Variation of holding pressure with variable load at 10 bar hydraulic pump supplying

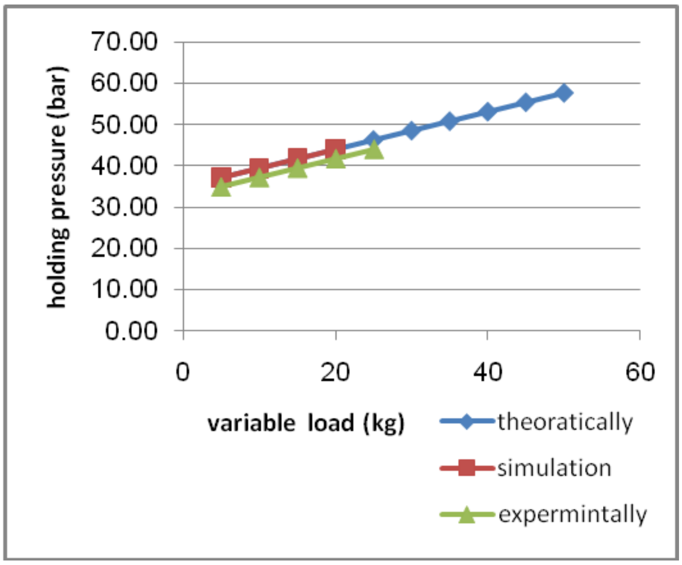

Fig -23: Variation of holding pressure with variable load at 15 bar hydraulic pump supplying

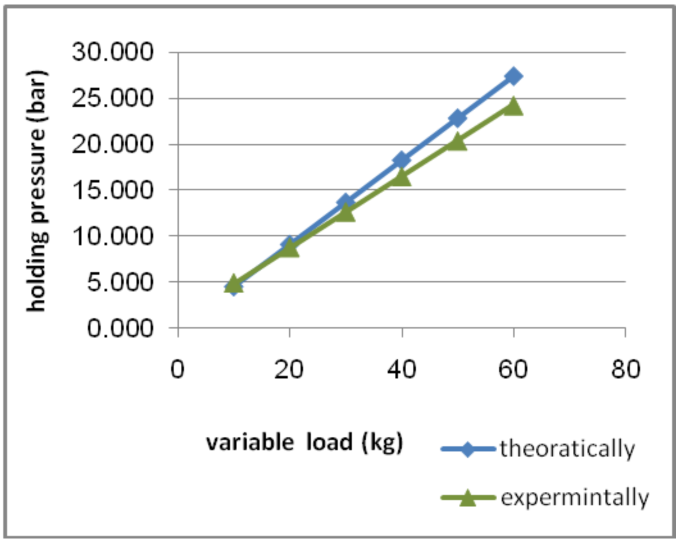

Fig -24: Variation of holding pressure with variable load at no pump supplying

When the experimental holding pressure path at each supplying case is compared to the theoretical and simulated holding pressure path it shows that as the load increases the experimental holding pressure path increases in divergent from the theoretical and simulation holding pressure path. That can results from various things which could be mechanical losses, pressure drops in pipe line, or the hoses and pipes flow resistance, ect. In spit of all the decreasing factors, the important part is to find a correction value so that the real system would be matched to the ideal theoretically system. The correction value is found from the holding pressure paths above.

Ideal holding pressure = Experimental holding pressure + Correction value

Correction value = a * Applied load + b

Where (a) and (b) values, changes as the pump supplying changes, (a) and (b) values are shown in table (4).

Table -4: Factors of correction value equation

Pump supplying case (bar)	a value	b value
No supplying	0.068	-1.017
6	0.118	0.622
10	0.116	-0.682
15	-0.002	2.321

9. CONCLUSIONS

As a result of this study, the following conclusions are made:

1- A simple method to derive an optimal pressure curve has been proposed. Pressure controlling equations have been obtained experimentally for open-loop hydraulic system in four pump supplying cases. The pressure path is proportional to the variable loading. The load sensor will sense the new load and the pressure sensor will sense the pump supplying case. With the determined pressure curve, the corresponding electronic circuit and sensor signals and through the LabVIEW software the new holding pressure for the hydraulic actuator sets automatically to the proportional pressure control valve.

2- The research results showed that when the supplying pressure value increases, the hydraulic actuator variable loading ability decreases where the limitation of the proportional pressure decreases.

3- Through the comparison of experiment and analysis, the predicted pressure curve has been verified optimal pressure curve for controlling variable loading actuator since no vacuum cavity has been formed.

ACKNOWLEDGEMENT

Thanks due to Mechatronics Engineering Department, Al-Khwarizmiy College of Engineering, University of Baghdad for support this project.

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