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Research Article

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Development of a Multi-functional Hydraulic Test Stand

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Abstract This paper reports the details of the development of a hydraulic test stand. The hydraulic and control systems of the stand are designed to be used as a multi-functional test rig; it can be used as a teaching unit to recognize the function of the electro-hydraulic system main components, in addition to testing positive displacement pump units, directional control valves, flow control valves, check valves and hydraulic cylinders from different manufacturers. Also it can be used in research and development of hydraulic circuit and its components. Economic considerations were taken into account during the design phase of the stand. As a test rig, the stand represents an electro-hydraulic system including various hydraulic and electric components. Different measuring devices for measuring pressure, temperature, oil level and rotating speed are built in and used in the stand. A PLC based control system is used for controlling and running specific test operations. Experimental procedures for testing an external gear pump and a double solenoid-operated 4/3 directional control valve in addition to test results are presented and discussed.

Keywords Hydraulic, Test stand, Gear pump, Directional control valve, PLC

1. Introduction

Hydraulic systems are used wherever high power and high forces are required. Hydraulic drives, thanks to their high power intensity, are low in weight and occupy a small mounting space. They facilitate fast and accurate control of very high forces. The increase interest in automation makes it even more necessary for pressure, flow rate and flow direction in hydraulic systems to be controlled by means of electrical control systems. The combination of these advantages opens up a wide range of applications for hydraulics in mechanical engineering, vehicle construction, industrial product lines and aviation. So, it is necessary to study performance of hydraulic components for improved employment in practical systems.

The development of hydraulic test stands for testing hydraulic equipment attracted the attention of many researchers in different countries. For example, Salah and Kassem [1] developed and manufactured a universal hydraulic test rig for testing proportional and servo valves and cylinders. The rig can also test other types of hydraulic valves and motors. The drive and control systems of the rig are designed to match almost all the available types of valves of different sizes and cylinders of different diameters from different manufacturers. They also developed a PLC program which allows supplying the valve under test with the electric input signals required for the testing process. The pump delivery pressure and flow are remotely controlled. The electronic output signals of the flow meters and pressure transducers are displayed during valve testing and also processed to an IBA process data acquisition system for on-line graphical presentation of the measured variables and off-line analysis of the recorded results.

Markonda and Vasava [2] presented a design of hydraulic test rig to test directional control valves and to measure the pressure drop through them at different flow rates. Successful simulation of the pressure drop in a directional control valve (NG6) against flow rate has been done using FLOED module which is supported by CATIA software. The module provides a good flexibility for the simulations and also in obtaining the results in more detail. The working of the simulation starts with the creation of a new wizard in the module. The wizard contains all the basic conditions that are required to simulate like units, wall conditions, fluids, initial pressures and also the tolerance values.

Hamid [3] developed a hydraulic test bench that included various basic hydraulic components. The system facility is designed for educational purposes to demonstrate hydraulic pump, motor, cylinder performances and testing each of these components. A gear pump was tested by the developed hydraulic test bench and pump flow rate versus pump pressure, pump pressure versus temperature with and without cooling system were successfully carried out. As the test bench was manually operated Hamid [3] recommended developing computer program to simulate and operate the circuits of hydraulic trainer bench and developing programmable logic control (PLC) program to control and operate the hydraulic circuits.

Several methods to determine gear pump efficiency have been introduced in [4], [5]. Also performance of solenoid-operated directional control valves has been discussed in [6], [7] and [8].

Meng and Zhang [9] developed simulation models for hydraulic test bench's basic hydraulic circuits using AMESIM software. Simulation results were compared with the experimental data. Dual-cylinder synchronous motion circuit was simulated and experimented, in order to determine the best modeling methods and verify the modeling results. The pressure and flow rate data of the hydraulic circuit obtained by the pressure, and flow sensors, are processed through data acquisition card and LabVIEW program. Flow rate and pressure results showed lower stability compared to simulation results because the hydraulic line and components' leakage were not considered in the simulation.

Chen and Yan [10] introduced virtual instruments technology and developed a hydraulic test bench based on their technology. That test bench realizes the function of data acquisition, real-time display, output configuration, pressure adjustment, test data saving and report generation. Architecture of the test bench was introduced and its LabVIEW-based software design method was illustrated. The LabVIEW-based system has the following strength achievements: simplification of hardware design, friendly user interface and intelligent reporting. Wu and Cai [11] also proposed using LabVIEW in hydraulic monitoring systems. Using LabVIEW with PLC control for automatic hydraulic test system has been demonstrated in [12].

Using PLC in controlling hydraulic circuits has been widely used recently in different applications such as those shown in [13] and [14]. With PLC`s it became very easy to meet process requirements,
and improve greatly the system stability, reliability, security and automation level [15].

2. Hydraulic Test Stand Design

The hydraulic test stand is shown in Fig. (1). The system design is divided into 2 parts, namely the hydraulic system design and the control system design.

Figure 1: Hydraulic test stand

2.1. Hydraulic system design

Figure (2) shows the hydraulic circuit diagram of the test stand. The components are listed in table (1).

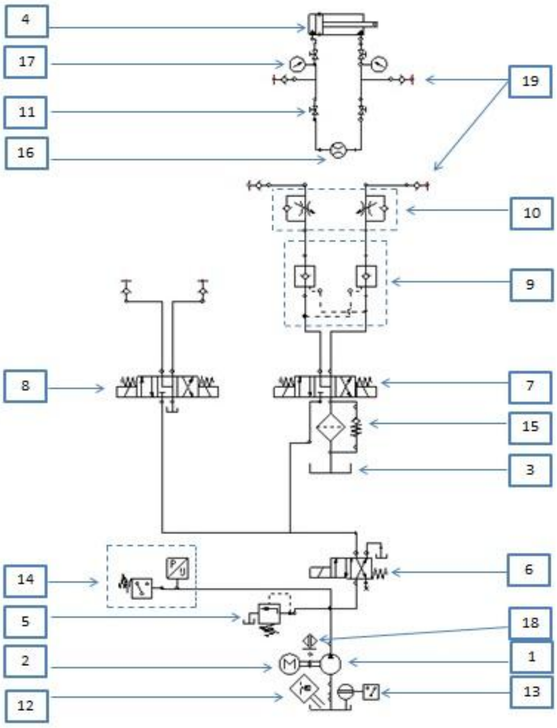

Figure 2: Hydraulic test stand circuit

Table 1: Components of the hydraulic circuit

ag	Component type	No. of Pieces
1	Pump	1
2	Electric motor	1
3	Reservoir	1
4	Cylinder	1
5	Relief valve	1
6	4/2 Directional control valve	1
7	4/3 Directional control valve (Simulation valve)	1
8	4/3 Directional control valve (Tested valve)	1
9	Double pilot operated check valve	1
10	Double flow control valve	1
11	Shut-off valve	4
12	Temperature switch	1
13	Level switch	1
14	Pressure Transmitter	1
15	Return line filter	1
16	Flow meter	1
17	Pressure gauge	2
18	Proximity sensor	1
19	Quick coupling	2

The pump (1) is a fixed displacement external gear pump of 13.33 cm3/rev geometric volume and a maximum pressure of 200 bar. It is driven by a 3-phase electric motor (2) of 7.5 kW, running at 1500 rpm. A proximity sensor (18) is used as a speedometer, as it is fixed near the coupling between the electric motor and the pump .The sensor obtains signals from 3 fixed bolts on the coupling and transfers them to the PLC.

A hydraulic reservoir (3) of 288-lit.capacity with its accessories is used to provide supply of hydraulic oil to the system. A return line filter (15) of filtrations 10 µm is mounted at the reservoir inlet, to filter return oil of the circuit. A temperature switch (12) is used to give a signal to the PLC when temperature goes beyond predetermined high limit; its sensing bulb is immersed into the oil in the reservoir and at the same time gives accurate temperature indication. A level switch (13) is used to provide a signal to the PLC when oil level decreases to a minimum value and it is mounted vertically in the reservoir.

Maximum pressure of the hydraulic circuit is controlled and regulated using an adjustable pilot operated relief valve (5). A 4/2 single solenoid-operated directional control valve (6) is used as un-loader to the relief valve. Supply pressure is measured using a pressure transmitter (14).

The pressure line feeds the system through two lines (P1 & P2). Pressure line (P1) feeds a sub-plate on which 3 valves are placed for simulation purposes including:

- A double solenoid-operated 4/3 directional control valve (7), which used to control direction of the flow,
- A pilot-operated double check valve (9) which allows free flow in one direction, and
- A double flow control valve (10), which used as meter-out device to control speed of the cylinder.

Pressure line (P2) feeds a sub-plate on which valves from different types and manufacturers can be mounted and tested.

A double-acting hydraulic cylinder (4) with dimensions (Dp = 50 mm, Dr = 28 mm, stroke = 300 mm) is used for simulation and testing purposes. A variable area flow meter (16) is used to measure the flow rate at different operating conditions. Four shut-off valves (11) are used to control the direction of flow either to pass through the flow meter (16) or to feed the hydraulic cylinder (4). Two bourdon gauges (17) are used to measure the pressure at different operating conditions.

Calibration of the measuring devices that are used in the hydraulic test stand, including (the flow meter, the pressure transmitter, and the pressure gauges), was completed before taking any measurements.

2.2. Control system design

The electric and electronic control part developed specially for the test stand includes the following major components: a PLC LOGO 6 for processing and control of the digital and analog I/O signals with additional two LOGO expandable modules 8 DI/8 DO each, a power supply module type (Telemecanique ABL7 RE2405) for input 220 VAC / output 24 VDC – 5A, a power supply module type (Telemecanique ABL7 CEM24012) for input signal 220 VAC / output 24 VDC – 1.2 A, a three-phase transformer input 380 VAC - 3phase / output 220 VAC, and a Siemens touch screen flat panel of type KTP400 as human machine interface (HMI). Fig. (3) shows the electric control cabinet including the above mentioned components.

A PLC program has been developed using LOGO! Soft comfort drawing software, to control all inputs and outputs of the system. The HMI was programmed using Siemens TIA Portal software. Operation of the test stand functions can be done using two methods, either using control panel buttons and selectors as shown in Fig. (1) or using the touch screen flat panel (HMI) as shown in Fig. (4).

Figure 3: Electric control cabinet

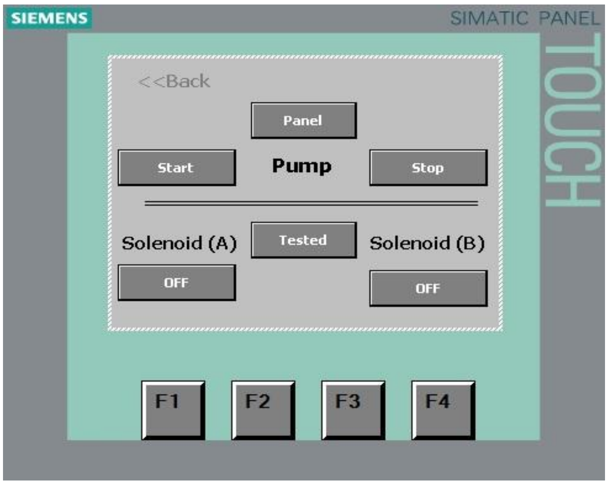

Figure 4: Touch screen flat panel (HMI) interface

3. Experimental procedures and Results

3.1 Testing the gear pump

Pump test was carried out by connecting the simulation valves set to the cylinder.

To start pump test, the following procedure is followed:

- Valves (1 and2) are opened and valves (3 and4) are closed, to insure that the flow of pump passes through the flow meter.
- Pump is then started.
- Sol (B) of the 4/3 directional control valve is activated, which automatically activate Sol (A) of the 4/2 directional control valve that loads the relief valve.
- The cracking pressure of the relief valve is adjusted to be 180 bar which will be the max. pressure at the circuit.

Figure (5) shows a simulation of pump test circuit.

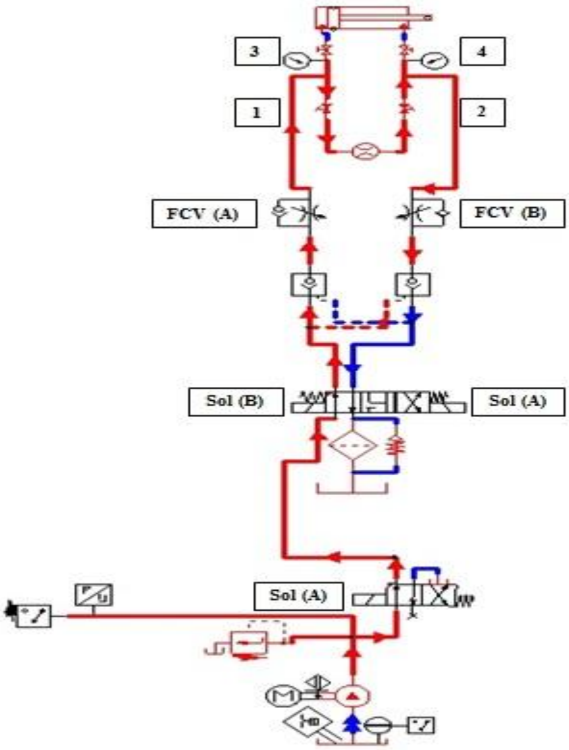

Figure 5: Pump test hydraulic circuit simulation

3.1.1. Pump performance curve (Q-P)

This test was carried out by slowly closing the meter-out flow control valve (B). The test load was applied up to 175 bar and the corresponding oil flow rate was recorded.

Figure (6) shows the pump flow rate versus system pressure. The pump test results show that the pump flow rate decreases as the system pressure increases.

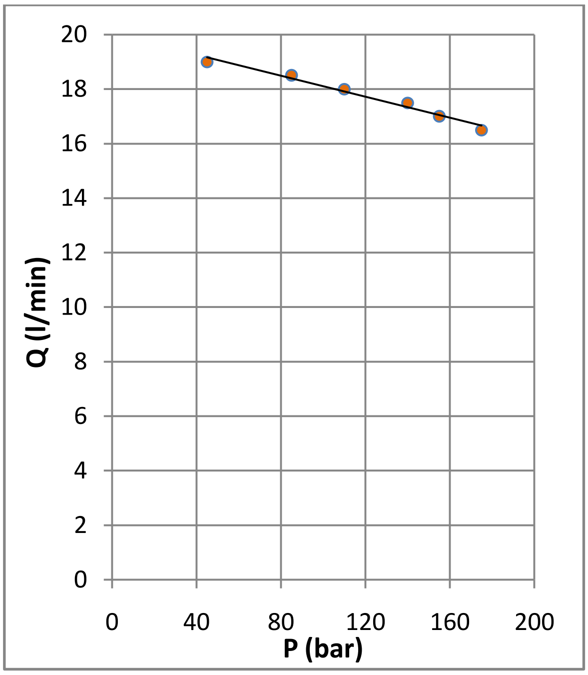

Figure 6: Pump flow rate (lit/min) versus system pressure (bar)

Based on the obtained results:

- Maximum flow rate of the pump is 19 l/min which was obtained at the lowest value of pressure of 45 bar that was obtained when flow control valve (B) was fully opened.
- Minimum flow rate of the pump is 16.5 l/min which was obtained at the highest value of pressure in the testing range which is 175 bar.

Maximum flow rate 19 l/min of the tested pump is compared to the specifications of the pump which has a maximum theoretical flow rate of 20 l/min.

3.1.2. Pump volumetric efficiency curve (η_{vol} -P)

Volumetric efficiency (η_{vol}) of the pump can be calculated using the following formula:

$$\eta_{vol} = \frac{Q_{act}}{Q_{th}}$$

Where:

Q_{act}: actual flow rate of the pump (l/min)

Q_{th}: theoretical flow rate of the pump (l/min)

Figure (7) shows the volumetric efficiency versus system pressure. From the pump test results, the volumetric efficiency decreases as the system pressure increases.

Based on the obtained results:

- Maximum volumetric efficiency of the pump 95% was obtained at the lowest value of pressure 45 bar which is obtained when flow control valve (B) was fully opened.
- Minimum volumetric efficiency of the pump 82.5% was obtained at the highest value of pressure in the testing range 175 bar.

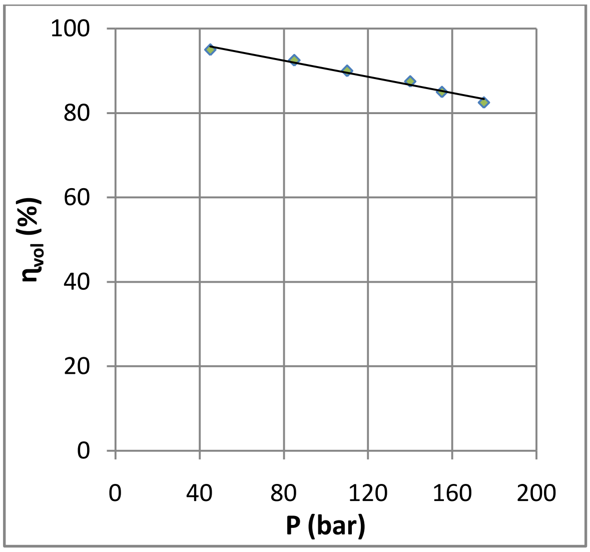

Figure 7: Volumetric efficiency (ηvol) versus system pressure (bar)

3.2. Testing the 4/3 directional control valve (size 6)

The function of directional control valves is to control different actions of the actuator by controlling the direction of the fluid flow. Some problems of slow movement, noise or low cylinder force is caused by the directional control valve. The key to fix any problem is to test the valve to identify the direct cause of its problem. Different methods of testing the directional control valve are used in this research including function test and pressure drop test.

3.2.1. Directional control valve function test

This test aims to determining whether the valve is working properly or it is malfunctioning. This is done by connecting the tested 4/3 directional control valve to the hydraulic cylinder, then activating each solenoid of the directional control valve and noticing if the hydraulic cylinder is moving or not.

- If the cylinder moves in the two directions, this indicates that the valve is doing its function.
- If the cylinder doesn't move in the two directions, this indicates that the valve has a problem.

3.2.2. Directional control valve pressure drop test

This test aims to determining the pressure drop across the directional control valve. This is done by connecting the tested 4/3 directional control valve to the hydraulic cylinder, then activating each solenoid of the directional control valve and recording the pressure readings before and after the directional control valve in different positions of it.

To measure the pressure drop across parallel arrows position (P to A) connection of the directional control valve, the following procedure, that shown in Fig. (8), is followed.

- Valves (1 and 2) are opened and valves (3 and 4) are closed.
- The pump is then started.
- The relief valve is adjusted at the maximum setting to insure that maximum flow rate of the pump 19 l/min. is reached at the flow meter.
- Sol. (B) of the 4/3 directional control valve is activated, which automatically activate Sol. (A) of the 4/2 directional control valve to load the relief valve.

This test was carried out by slowly decreasing the relief valve setting to decrease the flow rate in the circuit from 19 l/min. to 11 lit/min. and the corresponding pressure readings at ports (P and A) were recorded by closing valves (1 and 2) and opening valves (3 and 4) at each reading of flow rate.

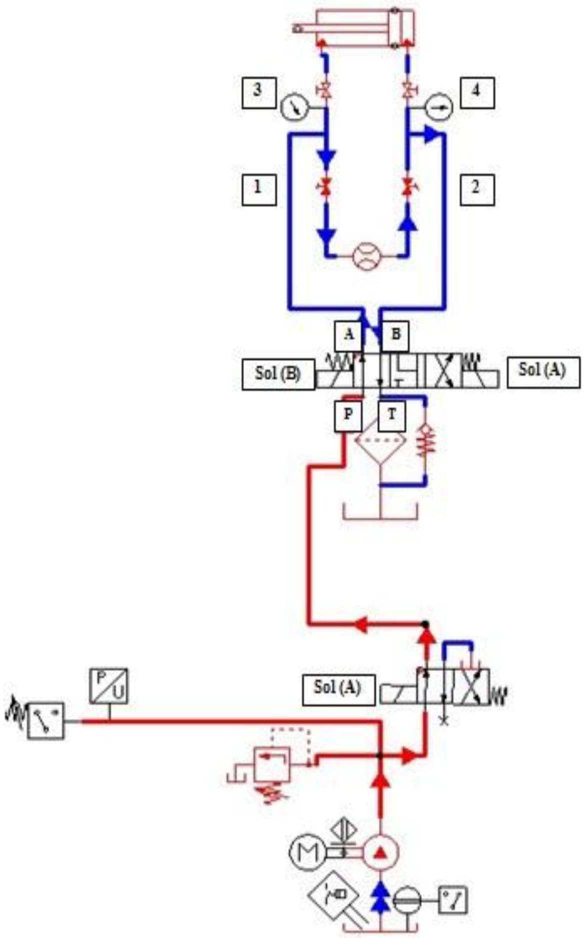

Figure 8: Pressure drop through (P to A) connection circuit simulation

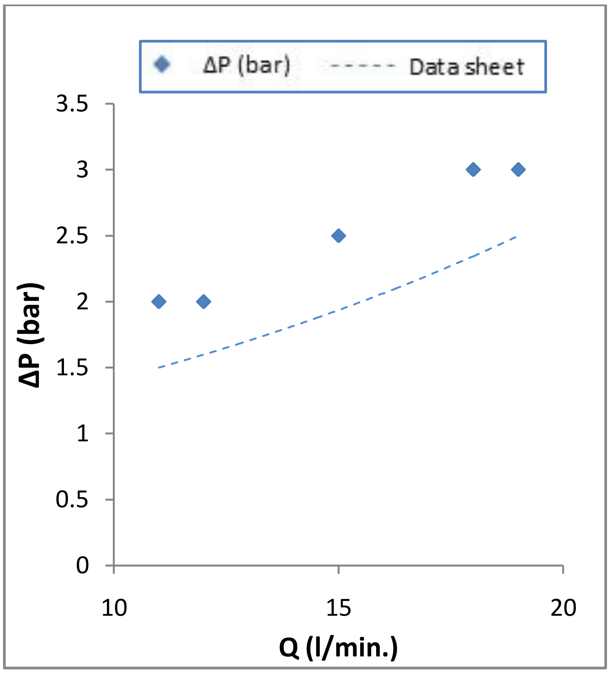

Figure 9: Pressure drop (bar) through (P to A) connection versus flow rate (l/min)

Figure (9) shows pressure drop across parallel arrows position (P to A) connection of the directional control valve versus flow rate. From the obtained results, the pressure drop across (P to A) connection increases as the system flow rate increases.

Based on the obtained results:

- A maximum ΔP of 3 bar across (P to A) connection was obtained at the highest flow rate in the testing range of 19 l/min.
- A minimum ΔP of 2 bar across (P to A) connection was obtained at the lowest flow rate in the testing range of 11 l/min.

The pressure drop across (P to A) connection of the directional control valve values obtained from data sheet are:

ΔP = 2.5 bar at flow rate 19 l/min. and ΔP = 1.5 bar at flow rate 11 l/min.

Pressure drop measurements show only about 0.5 bar difference from the data sheet values, which mean the valve is working properly at parallel arrows position and also verify the testing procedure.

The pressure drop across (P-B), (A-T) and (B-T) connections can be measured also using the same procedure.

4. Conclusion

The design and development of a hydraulic test stand, as well as a description of its electro-hydraulic control system are presented. The stand can be used as a teaching unit for engineering students, to demonstrate the operation of electro-hydraulic system main components and also it can be used in research and development of hydraulic circuit and its components.

Despite the fact that most of test stands, which manufactured globally, are used only to test specific components such as pumps or directional control valves, this stand is well thought-out to be a multi-functional test rig, as it can be used for testing positive displacement pumps, directional control valves, flow control valves, check valves and hydraulic cylinders from different manufacturers.

Results for testing an external gear pump are presented and compared with manufacturer data. These include the (Q-P) and (η_{vol}-P) performance curves. Results shows that the maximum actual flow rate of the tested pump is 19 l/min and it is compared to the specifications of the pump which has a maximum theoretical flow rate of 20 l/min that shows a maximum volumetric efficiency of 95 %.

Test results for double solenoid- operated 4/3 directional control valve (size 6) are presented and discussed. These cover function test and pressure drop (ΔP) test for the valve against flow rate (Q). Results shows that a maximum ΔP of 3 bar across (P to A) connection was obtained at the highest flow rate in the testing range of 19 l/min which is compared to the valve’s data sheet ΔP of 2.5 bar at the same flow rate value.

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