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# EXPERIMENTAL STUDY OF LEAKAGE COMPENSATION ON DYNAMIC CHARACTERISTICS OF HYDRAULIC POWER SYSTEMS

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## ABSTRACT

Leakage compensation in constant load speed hydraulic systems is highly required to have a precise control of the job target. To achieve this two options are available, either pump control or flow control. In the present work, experimental investigation of a constant load speed system test rig equipped with proportional electro-hydraulic valve and variable pump is studied. The leakage compensation has been achieved by controlling the proportional electro-hydraulic valve input volt or controlling the pump speed through frequency modulator. The study aims to highlight the difference between these two control options on the dynamic and steady state response of the system. The supply and return cylinder pressures, cylinder displacement and flow rate are recorded. Different external leakages have been intentionally introduced in the connections to the flow control valve to simulate the external system leakage.

Results showed that the dynamic and steady state system performance have been affected by the system leakage. The volt control signal for proportional DCV and frequency control for pump control could be used for leakage compensation through controller with a precise control algorithm to compensate leakage in electro-hydraulic proportional systems.

## KEY WORDS

External system leakage, leakage compensation, proportional directional control valve, constant load speed hydraulic system.

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## INTRODUCTION

Hydraulic actuators are widely used on mobile equipment and robots, due to their good capability in positioning especially in servo system, fast and smooth response, high power density, environment tolerance, and compact size. Using actuators for constant speed operation hydraulic systems is highly required in many applications such as steel sheet rolling, pressing operations, production assembly lines, robotics, aircrafts equipment and submarine systems. However, accepted positioning in these applications requires an accurate electro-hydraulic actuator due to leakage problems.

System leakage includes internal and external leakage. Internal leakage is essentially affected by the flow geometry, working pressure in addition to the fluid properties such as oil viscosity while the external leakage is affected by the seal type and the connections. There are many methods could be used in achieving the leakage compensation to develop an effective actuator velocity control such as using a proportional electro-hydraulic control valves with either open loop or closed loop, another method is using a variable speed pump control.

One of the fundamental tasks in designing hydraulic actuating systems is the development of effective velocity control of the actuator using a control valve as explained in Burrows (1994). The adoption of electro-hydraulic proportional valves, which are usually 4-way infinite position directional control valves, increased the efficiency and performance of hydraulic actuating systems as in Caputo (1994). The existence of friction and internal leakage might reduce the robustness and tracking accuracy of the system. However, it always exists in mechanical systems such as the electro-hydraulic actuator system presented to control constant speed load as described in Cadunas et al. (1995) and Olssen et al. (1998).

Amirante et al. (2008) presented an innovative open loop control technique for direct single stage hydraulic proportional valves whose response rate is significantly higher than that obtained by standard open loop control techniques, even comparable to more costly commercial closed loop systems. Different from standard open loop techniques, which provide the coil with a constant current proportional to the target position widely used in Diesel engine modern supply systems. Different valve opening procedures with step response have been compared to demonstrate the merits of the proposed boosted PWM technique. No overshoots have been registered. Moreover, the proposed method is characterized by a significantly higher response rate with respect to a standard open loop control.

Werlefors and Medvedev (2008) Nonlinear observers with static feedback are considered for leakage detection in hydraulic servo systems. Two issues, namely fast dynamics reduction and elimination of multiple stationary points in the estimation error dynamics, are treated. It is shown that leakage detection performance is not degraded by the use of a reduced plant model.

Menshawy et al. (2009) investigated theoretically and experimentally the dynamic performance of an electro-hydraulic system, containing a proportional directional valve, which is used to control a hydraulic cylinder velocity under constant load.

Experimental works have been carried out to measure the pump-relief valve characteristics and the pressure losses in the connecting hoses. A verified theoretical model of the directional proportional valve has been validated with previously presented and published in Menshawy at al. (2008). The simulation model of the electro-hydraulic proportional system has been validated experimentally and has been used to investigate the performance of the system when works under different operating conditions.

Here, experimental study has been carried out to show the effect of external system leakage on the hydraulic system steady state and dynamic performance neglecting the speed variation due to oil compressibility. External system leakage is intentionally introduced and the leakage compensation has been achieved by using the proportional electro-hydraulic valve and by controlling the pump speed through frequency modulator. The study aims to highlight the difference between these two control options on the dynamic and steady state response of the system.

## EXPERIMENTAL SETUP

The hydraulic system, under investigation, consists of a double acting actuator with horizontal load and connecting hoses equipped with a position sensor (LVDT) and pressure sensors. The load force acting on the actuator includes the mass and back pressure acting on the actuator in the return line by a throttle valve. A schematic drawing of the studied system is shown in Figure 1 while the experimental test rig has been highlighted in Figure 2.

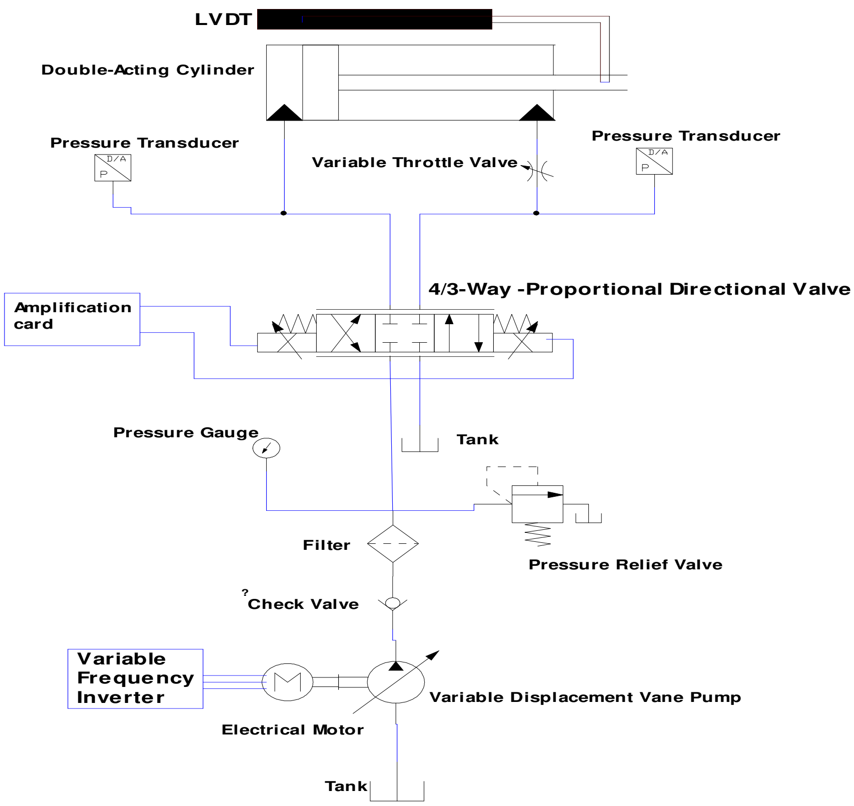


**Fig. 1.** Schematic drawing of the experimental test rig.

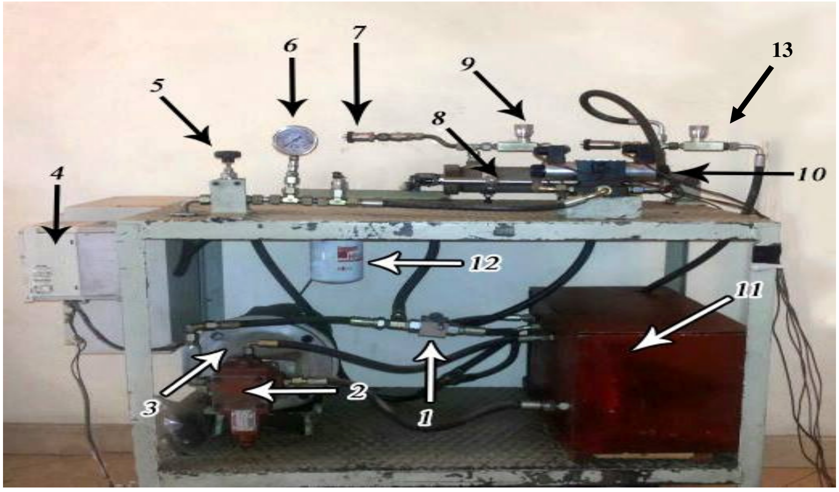


**Fig. 2.** Experimental Test Rig: (1) throttle valve, (2) variable speed vane pump, (3) AC motor, (4) variable frequency driver, (5) pressure relief valve, (6) pressure gauge, (7) Pressure sensor, (8) LVDT sensor, (9) throttle valve, (10) electro-hydraulic proportional control valve, (11) tank, (12) filter, (13) external bleeding valve.

Proportional directional control valve is used to provide a precise flow quantity at the desire time to the actuator chambers to perform the required task. The valve under investigation is a Parker-Hannifin 4/3 electro-hydraulic open loop proportional directional control valve controlled by a proportional electrical solenoid with zero lapping to regulate the flow rate, maximum Flow is 12 L/min with solenoids (9v, 2.7 A). A three phase AC motor with input frequency of 50 Hz/ AC 380V, speed 1430 rpm and power of 3 HP is used to control vane pump of volumetric displacement, $V_g$, of 8.5 cc/rev and output flow of 12 L/min at 1450 rpm.

The hydraulic linear actuator is of dimensions 63/31.5 mm and stroke of 280 mm. The pressure relief valve is used with a cracking pressure of 70 bars. Pressure transducer is used to record the pressure at a certain positions with pressure range up to 40 bar and supply voltage of 12 to 36 VDC and output signal from 4 to 20 mA.

A linear variable differential transformer (LVDT) is used for measuring linear displacement with range up to 200 mm, supply voltage of 9-24 VDC and sensitivity of 200 mV/mm with output signal of 0-5 V.A variable frequency driver (VFD) is used to control the speed of the AC motor by controlling the frequency of electric power supplied to the motor.

To develop an adequate velocity controller for hydraulic cylinder actuators, a hardware-in-the-loop E/H linear actuating system simulator was developed. This interactive simulator was established using LABVIEW software which is consisted of a pulse width modulation (PWM) valve control driver, an electro-hydraulic proportional directional control valve. The control flow chart of the experimental test rig has been illustrated in Figure 3.

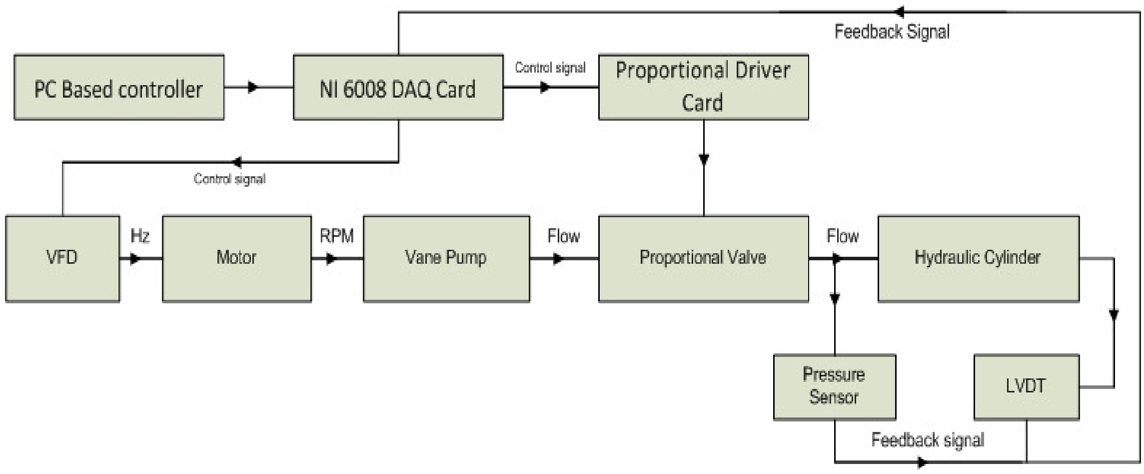


**Fig. 3.** Experimental System Block Diagram.

## EXPERIMENTAL RESULTS

Several experiments have been conducted to the effect of change the directional proportional valve positions and of variable variation of vane pump speed on the dynamic and steady state response of hydraulic system. Intentionally different system external leakages have been introduced to show its effect on the system performance.

Different input voltage for proportional valve and different input frequency for the pump speed have been applied. Piston displacement and velocity have been recorded using a LVDT sensor and velocity values were calculated using LABVIEW software in addition to the pressure and flow rate recording.

### System Performance with Controlling Proportional Valve

System performance, cylinder displacement and velocity, has been recorded for different input volt for the directional proportional control valve for a fixed input value frequency of 20 Hz for the pump inverter of the controlling pump in case of no external leakage.

Piston displacement stroke varies from 0 to 230 mm while directional proportional control valve voltage varies from 4 to 8V, the piston reaches its end in 11s at maximum voltage of 8V and the longest time exceeded 35s at min. voltage of 4V.

Piston displacement has been illustrated for different input volt in Figure 4. With the increase of the input directional proportional volt, the piston displacement reached its steady state maximum displacement rapidly until it has no effect on the cylinder displacement for a range over 7V as shown in Figure 5.

In addition, piston velocity for different directional proportional control valve voltage varies from 0 to 8 m/s while varying proportional valve voltage from 4 to 8V as shown in Figure 6. The piston reaches its maximum velocity in 11s at maximum voltage of 8V while its minimum velocity of 2.5 mm/s was recorded at minimum voltage of 4V and kept constant velocity for about 30 seconds.

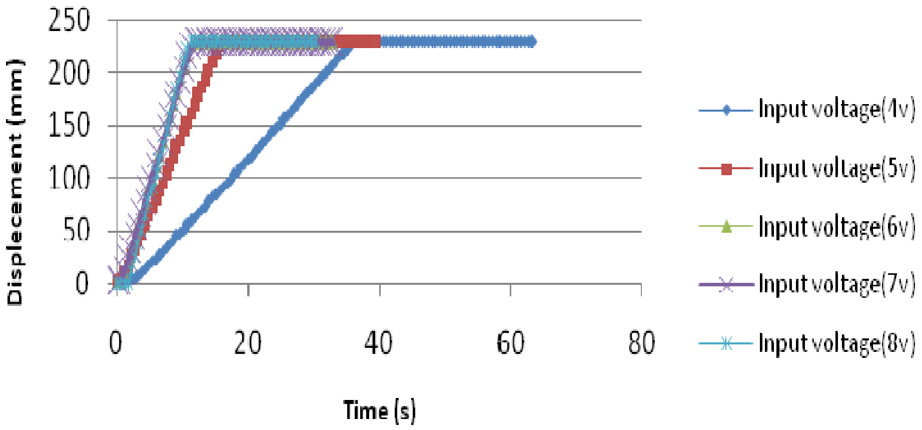


**Fig. 4.** Piston displacement for different input valve control signal.

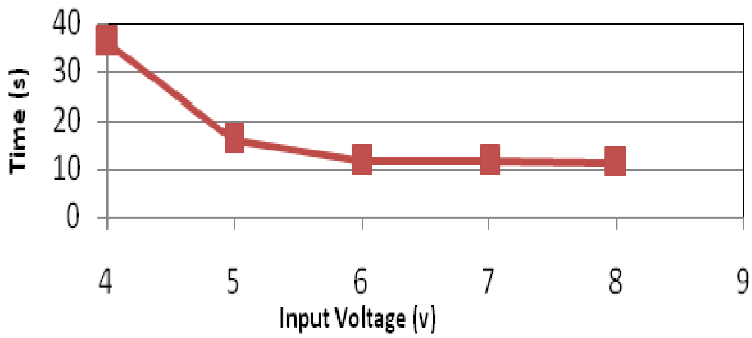


**Fig. 5.** Piston displacement dynamic response time for different input control volt signal for proportional DCV.

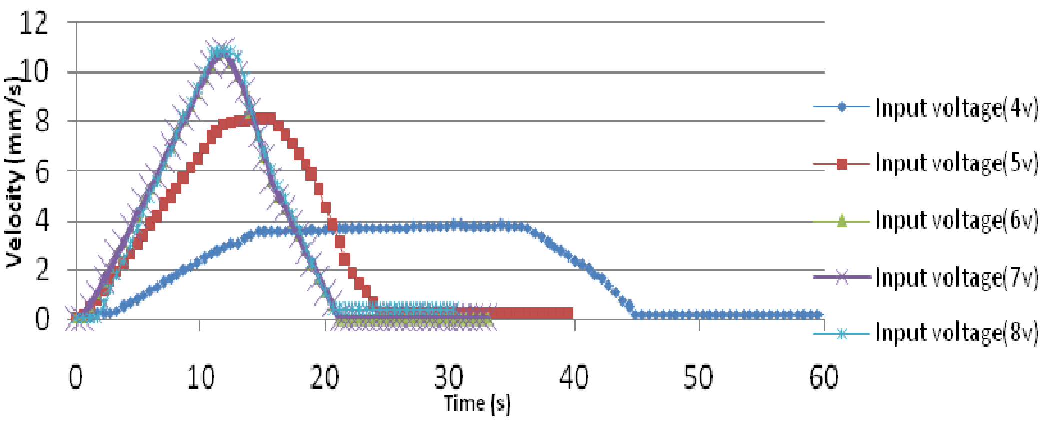


**Fig. 6.** Piston velocity for different input control valve signal for proportional DCV.

**System Performance with Controlling Pump Inverter**

Experimental tests were conducted for fixed input value of 4V for the directional proportional control valve for different input frequency values applied to show their effect on the system performance. The pump inverter frequency has been calibrated to the pump speed as shown in Figure 7.

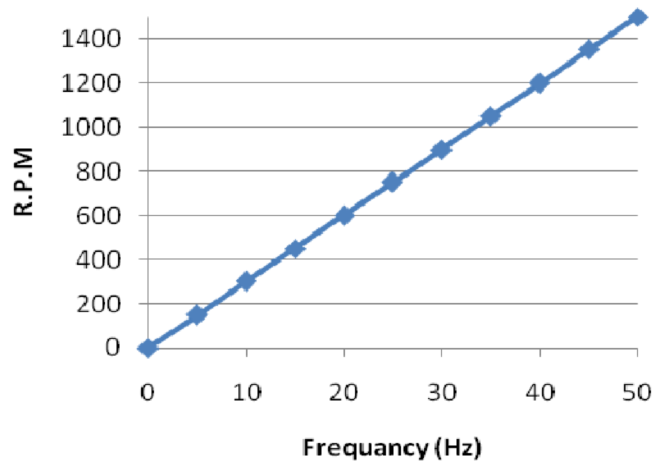


**Fig. 7.** Pump speed calibration to the inverter frequency.

The piston displacement stroke varied from 0 to 230 mm while varying the inverter frequency from 15 to 30 Hz, the piston reached its target in 25s at maximum frequency of 30 Hz and the longest time was 54s at a minimum frequency of 15 Hz.

System performance for different pump inverter has been illustrated in Figure 8. The response time decrease with the increase of controlling the inverter frequency for controlling pump speed which reflects that the cylinder moves faster with the increase of the input frequency as shown in Figure 9.

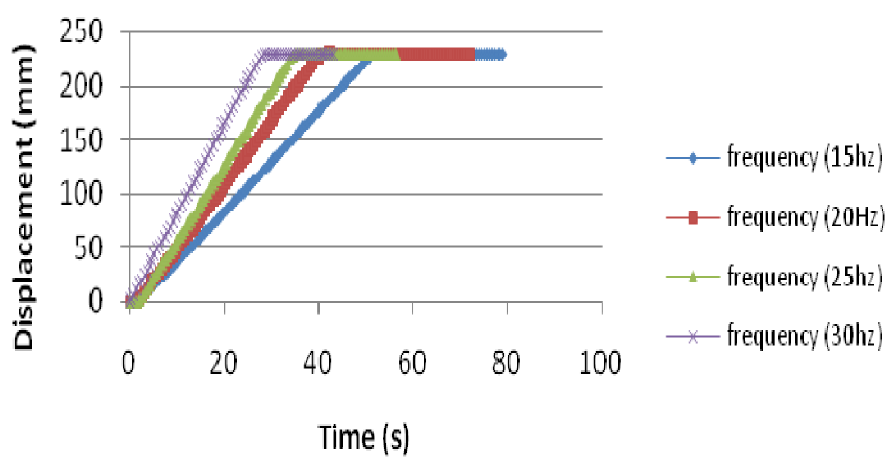


**Fig. 8.** Piston displacement for different control inverter frequency for controlling pump speed.

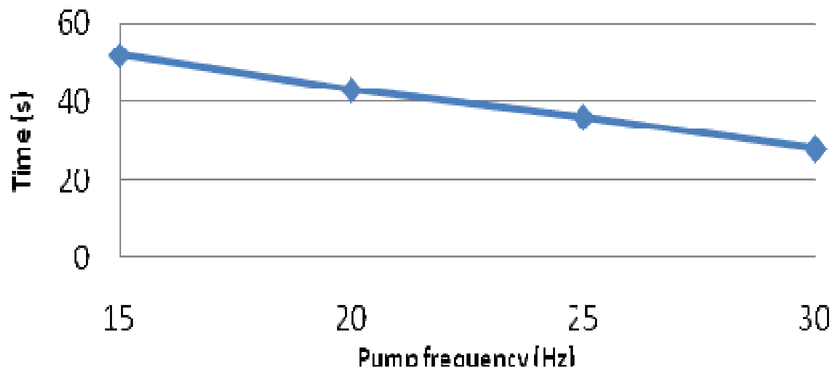


**Fig. 9.** Piston displacement dynamic response time for different control inverter frequency for controlling pump speed.

Piston velocity varied from 0 to 4.5 m/s while varying the inverter input frequency from 15 to 30 Hz and the piston reached its maximum velocity in 10s at maximum frequency of 30 Hz. While the minimum velocity at 2.5 m/s at minimum voltage of 4V, but velocity in this case is kept constant in about 33s of actuation as shown in Figure 10.

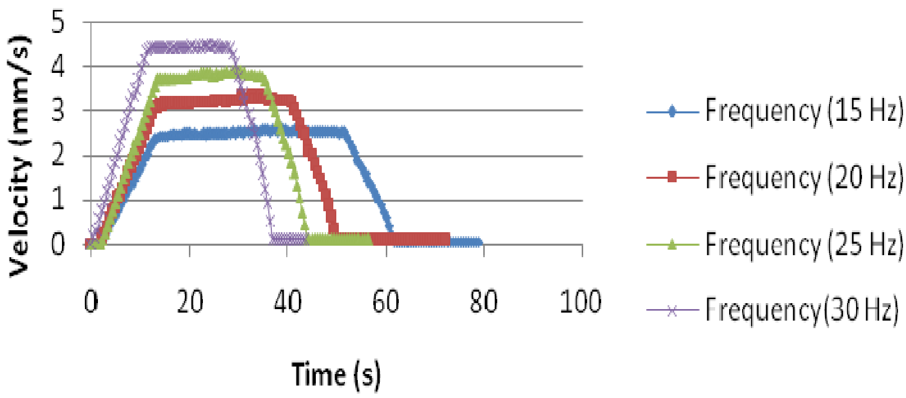


**Fig. 10.** Piston Velocity for different control inverter frequency for controlling pump speed.

## System Performance for Different System Leakage

The tests were conducted while considering the leakage's effect on the expansion stroke of the piston. At a fixed input value of 20 Hz for the inverter controlling pump; several input voltage values were used showing the effect on both displacement and velocity. Piston displacement stroke varies from 0 to 230 mm with a constant inverter frequency of 20 Hz and valve input voltage of 6V. It has been shown that as the leakage increases as the piston displacement response time reaches maximum values faster as shown in Figure 11.

Piston velocity varies from 0 to 11 m/s, such velocity is attained when the inverter input frequency is 20 Hz and the valve input signal is 6V while the piston reaches its maximum velocity 10 mm/s in 10 s and minimum velocity at 3.2 mm/s in 40s as shown in Figure 12.

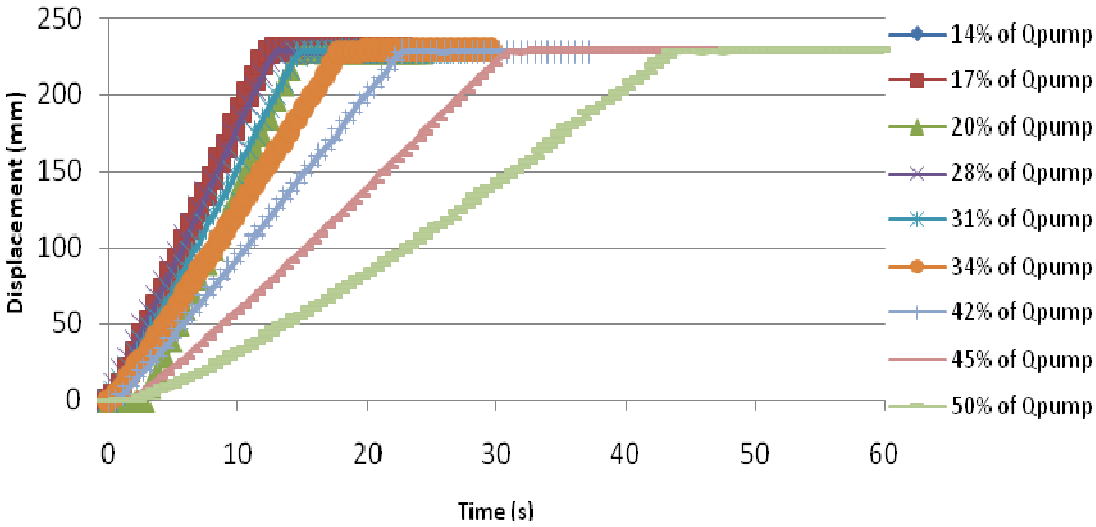


**Fig. 11.** Piston Displacement for different external leakage percent.

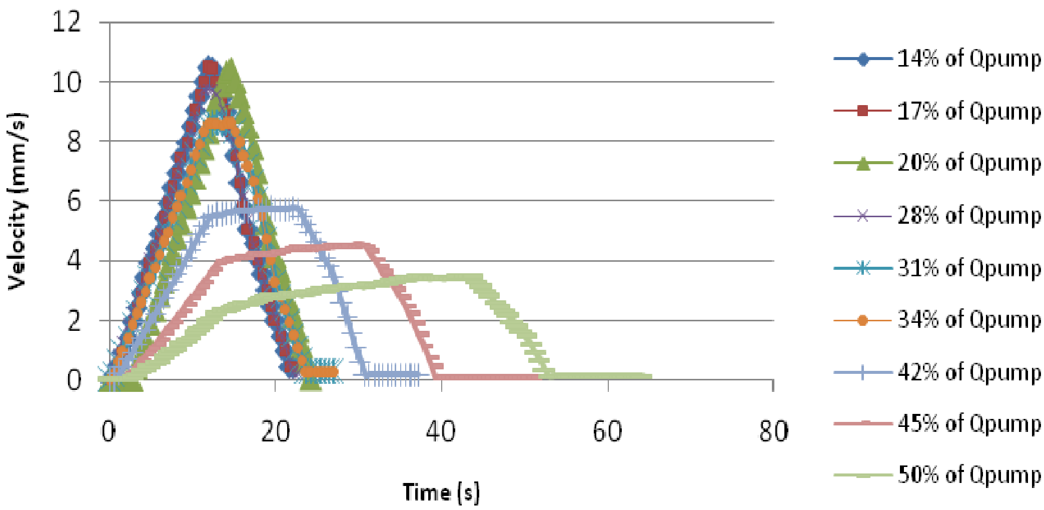


**Fig. 12.** Piston velocity for different external leakage values.

**System Performance with controlling proportional valve for different leakage**

Piston displacement stroke varies from 0 to 230 mm; such displacement is attained while inverter's frequency is kept constant at 20 Hz and valve input voltage is variable and the longest time for the piston to reach the target was with a minimum voltage of 4V as shown in Figure 13 while piston displacement for different input valve control signal with leakage and without external leakage has been illustrated in Figure 14.

Piston velocity varies from 0 to 11 m/s, such velocity is attained while varying Valve input Voltage from 4 to 8V. It has been shown that piston reaches its maximum velocity in 10s at maximum voltage of 8V, and minimum velocity at 2.5 m/s at minimum voltage of 4V. The velocity in this case is kept constant in about 36s as shown in Figure 15.

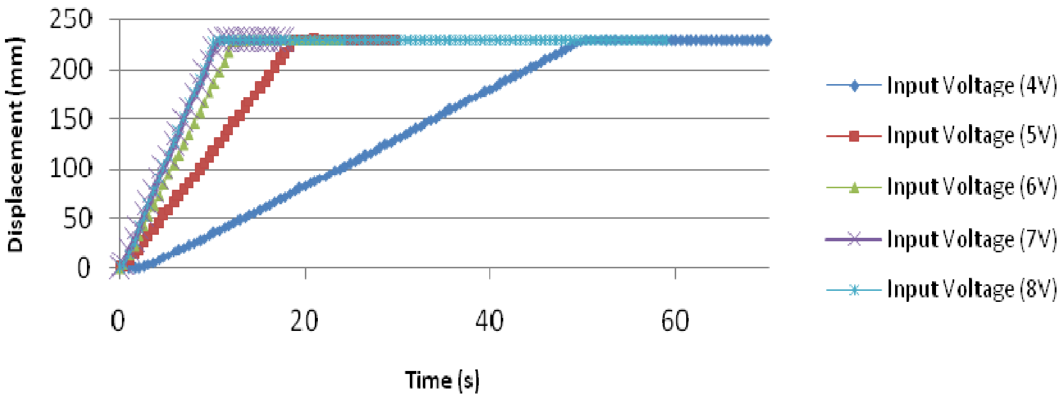


**Fig. 13.** Piston displacement for different input valve control signal.

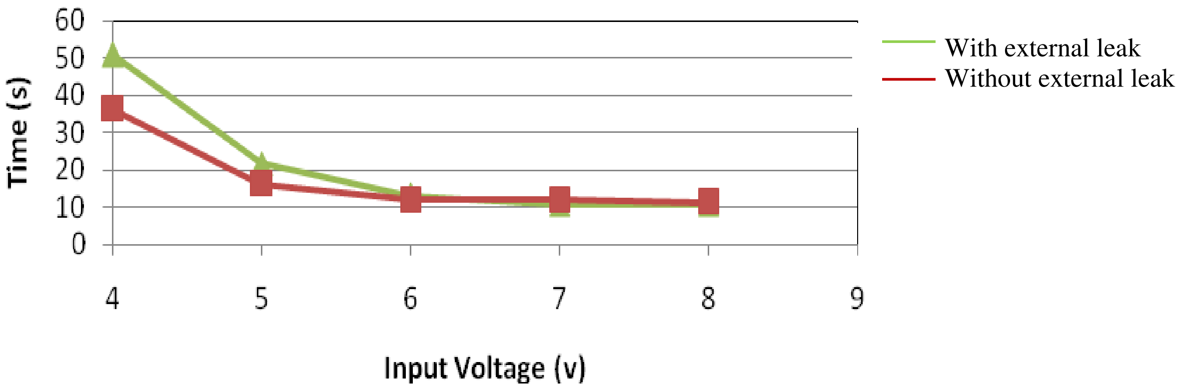


**Fig. 14.** Piston displacement for different input valve control signal with leakage and without leakage.

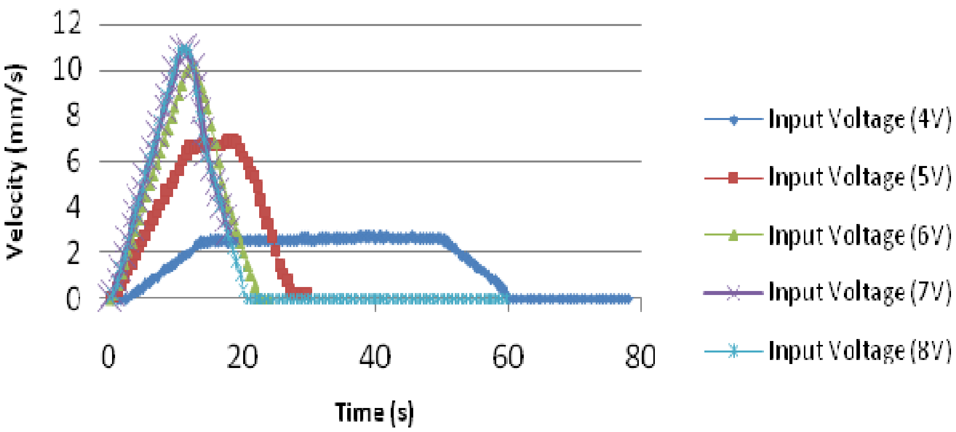


**Fig. 15.** Piston Velocity for different input valve control signal with external leakage.

**System performance with controlling pump inverter for different leakage**
For a fixed input value control signal of 4 V, the piston displacement stroke varied from 0 to 230 mm while varying the inverter frequency from 15 to 30 Hz, the piston reached its target in 40s at maximum frequency of 30 Hz and the longest time was 95 s at a minimum frequency of 15 Hz. System performance for different pump inverter has been illustrated in Figure 16.

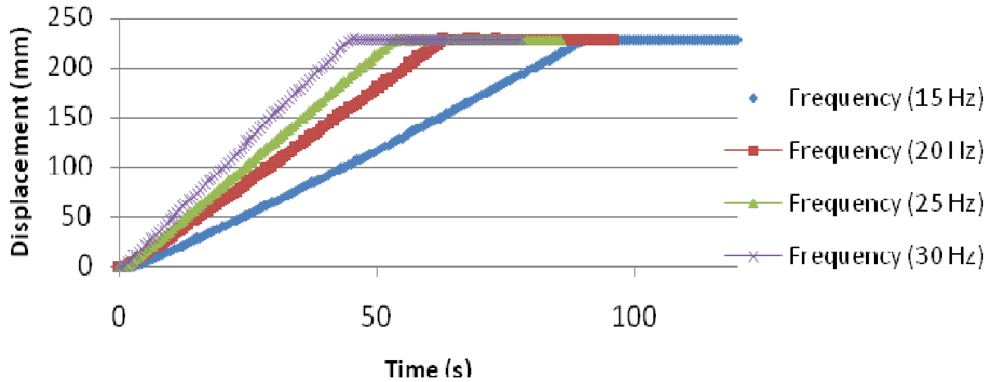


**Fig. 16.** Piston displacement for different inverter Frequency with leakage.

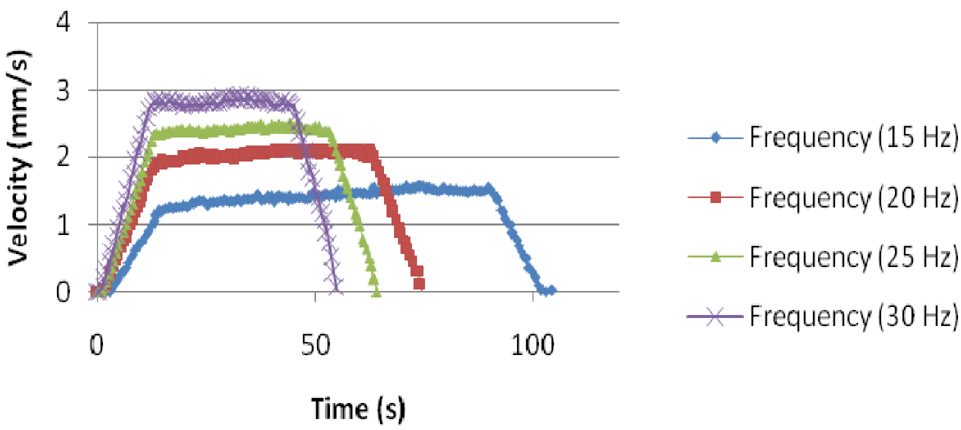


**Fig. 17.** Piston Velocity for different inverter Frequency with leakage.

Piston velocity varied from 0 to 2.8 mm/s while varying the inverters input frequency from 15 to 30 Hz and the piston reached its maximum velocity in 15 s at maximum frequency of 30 Hz. While the minimum velocity at 1.3 mm/s at minimum Frequency 15 Hz, as shown in Figure 17.

**System Dynamic Characteristics**

The system dynamic characteristics affect heavily the overall performance of electro-hydraulic systems. These particular characteristics include overshoot response, settling time and rise time. While conducting the different load and leakage iterations on this system, it was concluded that only settling time and steady state error varied heavily between the existing of external leakage and no external leakage cases. So, more experiments were conducted to highlight this effect to compensate the required voltage levels at leakage cases to match the no external leakage case.

**Voltage needed for leakage compensation while controlling pump inverter**
While controlling the system using pump inverters, leakage has a great effect on response time of cylinder displacement and velocity as shown in Figures 18 and 20, the required controlling voltage values to compensate the leakage effect have been shown in Figures 19 and 21.

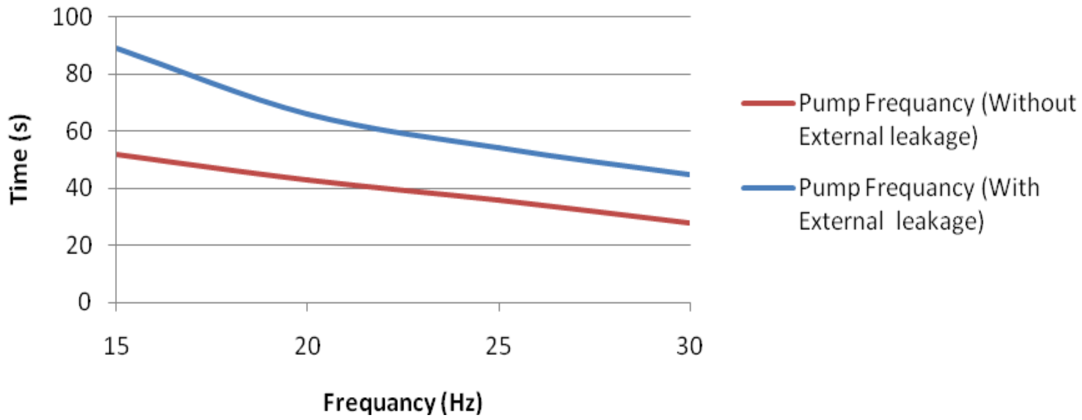


**Fig. 18.** Piston maximum velocity dynamic response time for different pump frequency.

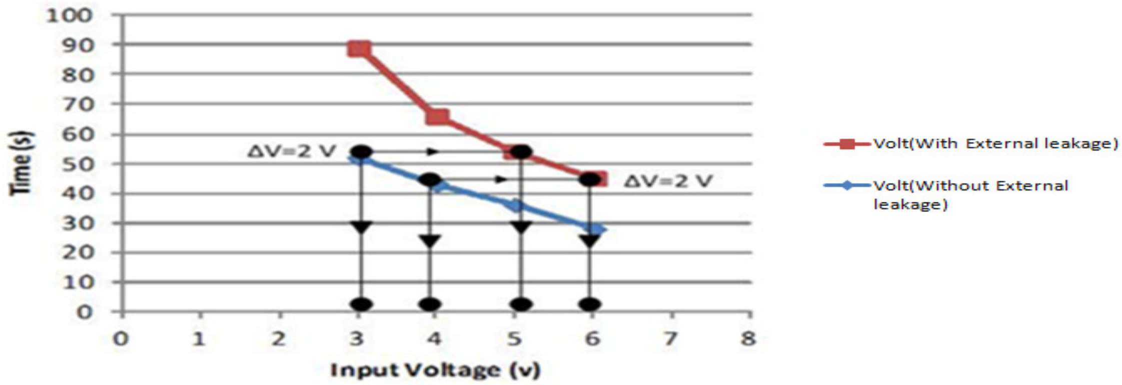


**Fig. 19.** Voltage required overcoming leakage effect.

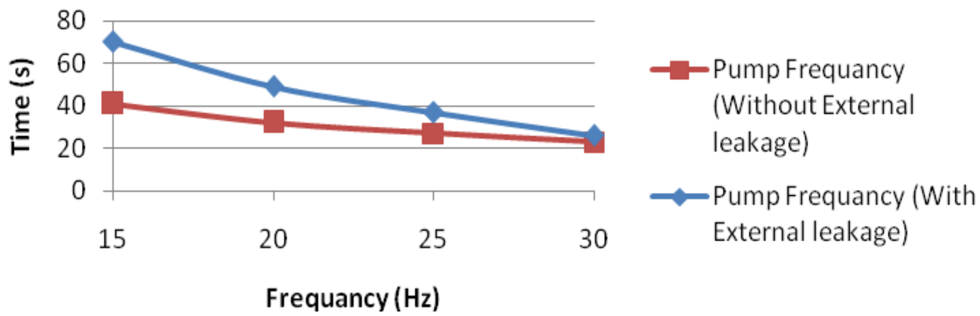


**Fig. 20.** Piston maximum velocity response time for given pump frequency.

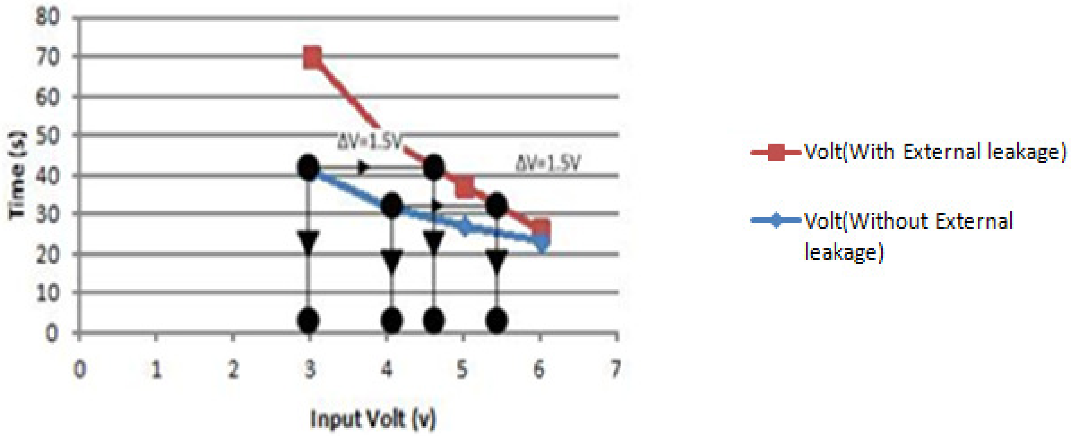


**Fig. 21.** Voltage required overcoming leakage effect.

It has been shown that varying the input frequency for the pump has a great effect on the response time of the actuator velocity as well as the actuator displacement response time.

**Voltage needed for compensation while controlling proportional valve controller**

Also, while controlling the system using valve controller, leakage has a considerable effect on response time of cylinder displacement and velocity as shown in Figures 22 and 24, the required control voltage values to compensate the leakage effect as shown in Figures 23 and 25.

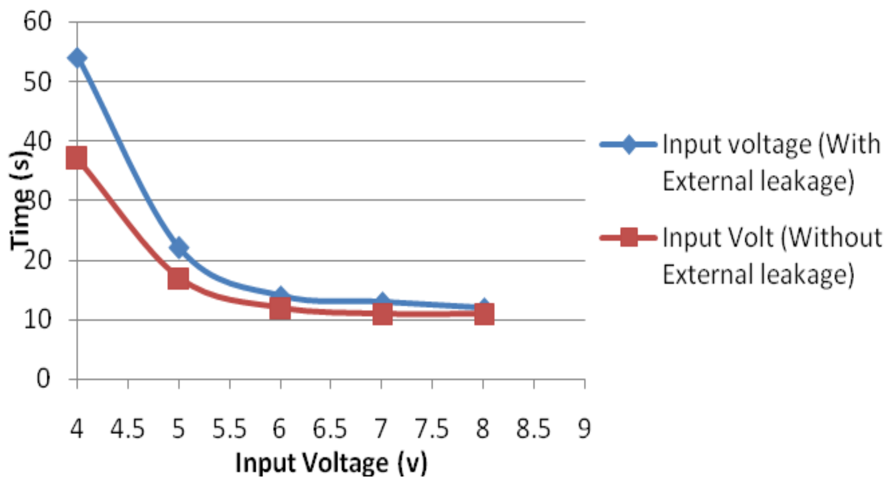


**Fig. 22.** Piston displacement response time for valve voltage.

It has been shown that after the input volt of 6V, there is no effect of varying the proportional valve on the response time of the actuator velocity while it has a minor effect on the actuator displacement response time.

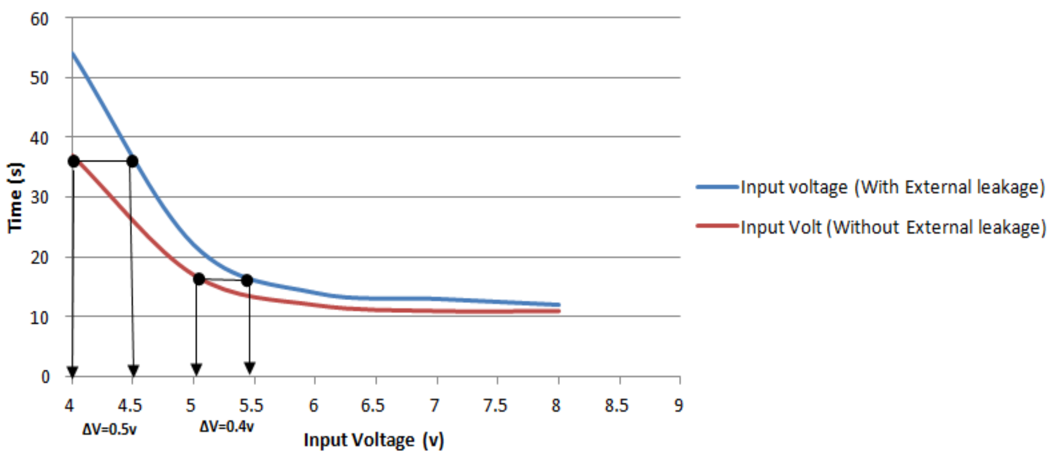


**Fig. 23.** Voltage required overcoming leakage effect.

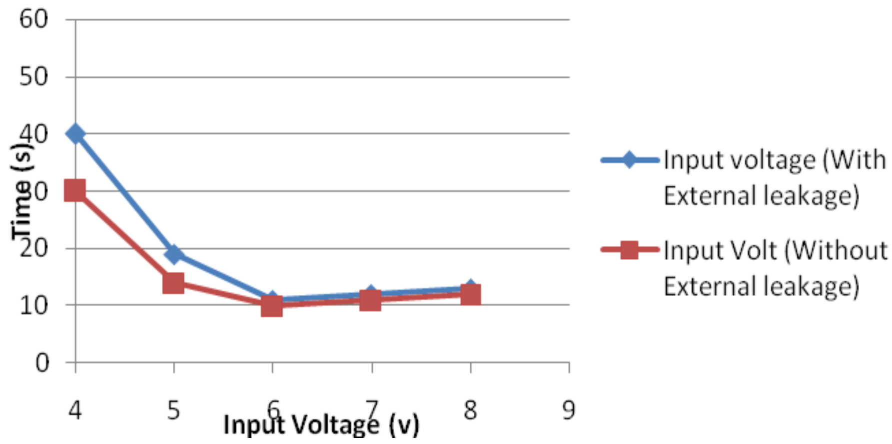


**Fig. 24.** Piston maximum velocity response time for given valve input voltage.

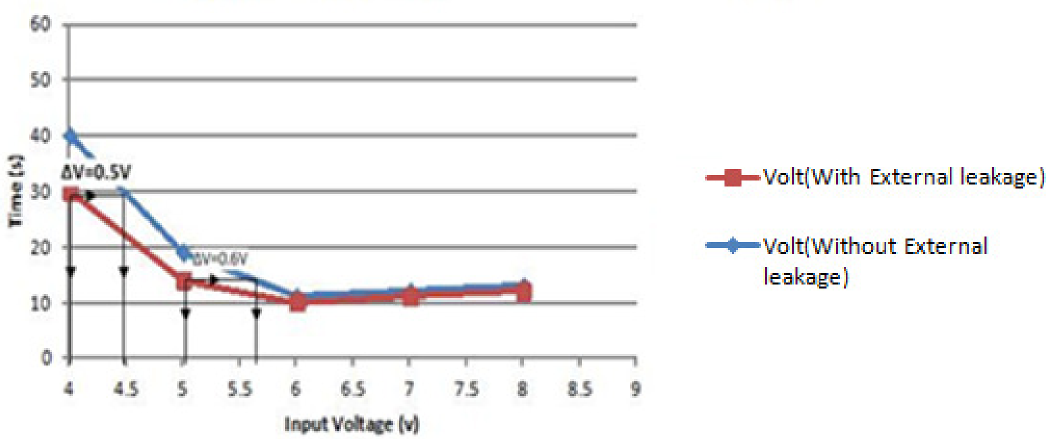


**Fig. 25.** Voltage required overcoming leakage effect.

**Steady state error adjustment while controlling pump inverter**
Steady state error is the difference between the measured flow rate in case of leakage and without leakage. For inverter frequency of 15Hz, the cynlinder displacement in case of leakage and without lekage has been illsutaretd to show the difference steady stae error has been illustrated in Figure 26.

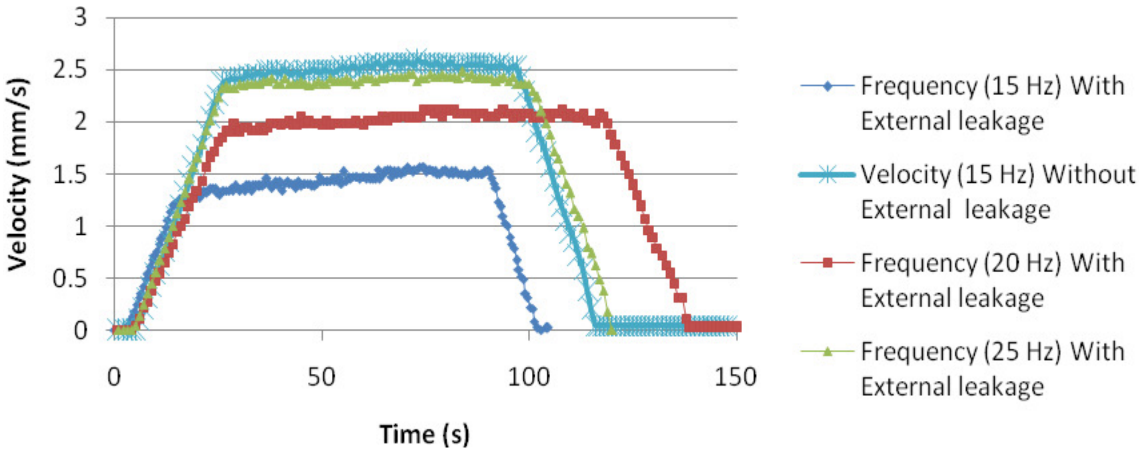


**Fig. 26.** Leakage steady state error in piston velocity during pump control.

**Steady state error while controlling proportional valve controller**
For control volt of DCV of 4 V, the cylinder displacement in case of leakage and without lekage has been illsutaretd to show the difference steady stae error has been illustrated in Figure 27.

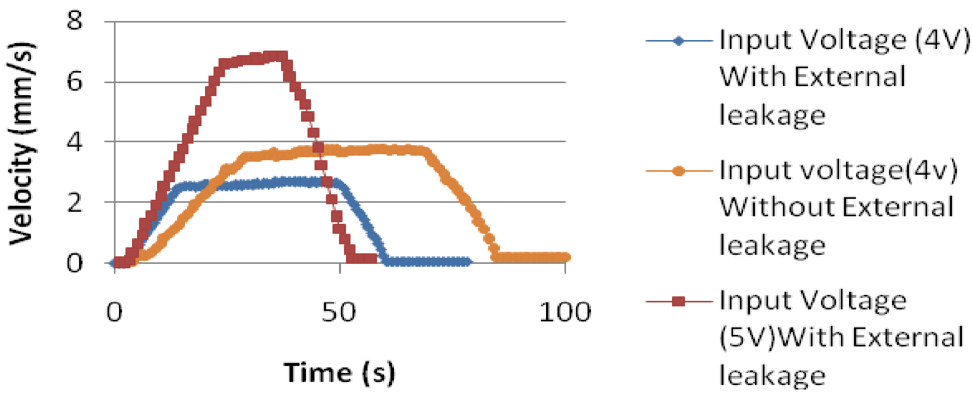


**Fig. 27.** leakage steady state error in piston velocity during valve control.

The volt control signal for proportional DCV and frequency control for pump control will be used for leakage compensation in future work through controller with a precise control algorithm to compensate leakage in electro-hydraulic proportional systems.

## CONCLUSION

Experimental electro-hydraulic proportional valve was tested in a fully functioning hydraulic system. Several measurements were conducted controlling the hydraulic load piston by controlling both the input voltage of the proportional valve and the inverter input frequency.

From the experiments conducted at both cases, controlling the proportional valve has a better effect on load piston than controlling the inverter's frequency. On controlling the valve, the piston's speed reaches 12mm/s in 10s while on controlling the inverter frequency, the piston speed reaches 11.5mm/s as a maximum speed in 11s. The dynamic and steady state system performance have been investigated, it has been shown that only settling time and steady state error are varied from normal while suffering from leakage in the system and these values were detected.

It has been shown that varying the input frequency for the pump has a great effect on the response time of the actuator velocity as well as the actuator displacement response time. It has been shown that after the input volt of 6V, there is no effect of varying the proportional valve on the response time of the actuator velocity while it has a minor effect on the actuator displacement response time.

The volt control signal for proportional DCV and frequency control for pump control will be used for leakage compensation in future work through controller with a precise control algorithm to compensate leakage in electro-hydraulic proportional systems.

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