Position Control of the Pneumatic Actuator Employing ON/OFF Solenoids Valve

Asst. prof. Munaf F. Badr[1], Lect. Dr. Yahya Abdullah[2], , Engineer Ahmed Kadhiam Jaliel[3]

***Abstract*— This research is concerned with the study of the performance of a position control model used to determine the stroke of the pneumatic actuator driven by (ON/OFF) solenoids valve interfacing with linear position sensor. The proposed model involves two solenoids directional control valves, double acting pneumatic cylinder and electrical control subsystem conducted to proportional position controller unit. To achieve the position control system and to stop the rod of the cylinder at the set point it is required to implement a mathematical calculations as well as an experimental work to realize the best behavior of the system. A laboratory test rig has been set up including the required electrical and pneumatic apparatus for obtaining the practical results and to accomplish the suggested position control system. Simulation was carried out using MATLAB/SIMULINK and a comparison between the experimental and theoretical results was done to investigate the best behavior of the suggested model. The complete verification of the obtained results show that the ability to employ the proposed model with high efficiency.**

Index Term-- **Pneumatic system, linear position sensor, ON/OFF solenoids valve, proportional controller unit.**

INTRODUCTION

Historically, the implementation of the air as a working medium in several applications can be traced back over thousands of years such as using wind as a driving force for sailing ships and windmills. The first air compressors were seen around 3000 B.C. to provide small puffs of air to aid in starting a fire. In the last decades, pneumatic termed to give a name to the science of the motions and properties of the air [1].

Conceptually, pneumatic systems are extensively used in many industrial applications commonly powered and supplied by compressed air or compressed inert gases and including different pneumatic devices such as motors, valves and cylinders. The principles of the pneumatic systems are the same as for the hydraulic system, but the main different between them is that the pneumatic transmits power using air or a gas instead of a liquid to provide the energy necessary to exert significant mechanical forces. Practically, in pneumatic system the compressed air is usually used, but nitrogen or other inert gases can be used for special applications [2].

In Electro- Pneumatic system, the control signal is the electrical signal that is supplied either from AC or DC sources and the working medium is compressed air passing through pipes and hosing to the pneumatic components. In many electro-pneumatic systems, the most devices being controlled are an electrically actuated directional control solenoids valves. These control valves supply air pressure to devices like cylinders that will extend or retract a rod when pressure is applied or removed. Solenoids coil are used to open and close these valves and are activated with appropriate voltage signals [3].Another important component of the electro-pneumatic systems is the feedback elements and sensors. Feedback devices inform the operator of the system status and whether or not the requested task has been completed, or even attempted to realize the start/stop of the process and how to know what the system is doing.

The main objective of this work is to design and implementation of a position controller model of electro pneumatic system based on directional control solenoid valve interfacing with linear position sensors. To achieve the purpose of the proposed model, this work involves building a laboratory test rig containing the electro-pneumatic apparatus and the position sensor to realize the position control action of the pneumatic cylinder. Computer simulation of the employed system involving the mathematical model has been done to investigate the better performance of the position system.

This paper is organized as following; the description of the electro-pneumatic system has been introduced in the second section while the details of the position controller model and the results of the experimental beside simulation work are presented in the third and fourth sections respectively followed by conclusion.

I. THE ELECTRO PNEUMATIC POSITION SYSTEM

The suggested electro pneumatic position control system consists of the directional control ON/OFF solenoids valve, the pneumatic cylinder, compressor unit, and electrical subsystem in addition to many of accessories as shown in figure (1). For technical description of the pneumatic elements, values like pressure and air flow that are used in the input and output ports of these elements and they has been depicted in the circuit diagram.

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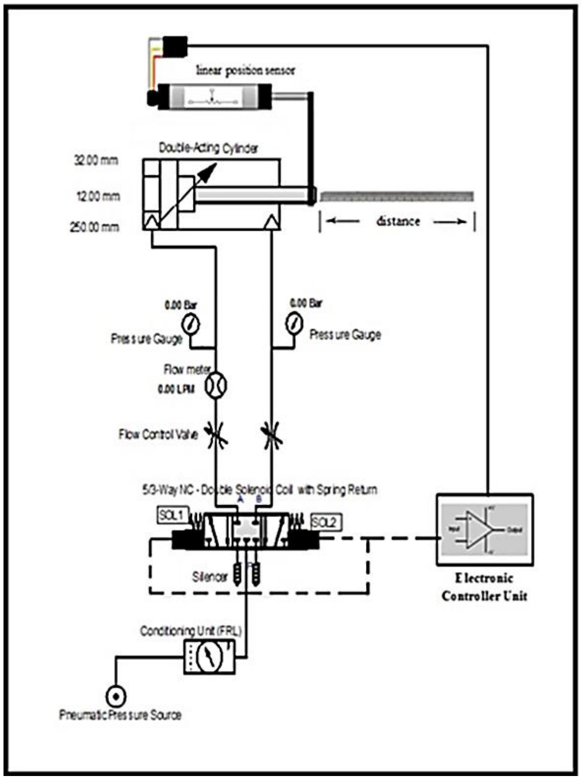

Fig. 1. The Schematic Diagram of the Electro Pneumatic Position System

In the employed pneumatic position system, the directional control solenoids valve represents the essential element of the system and plays a major role in controlling the direction of the pressured air reach towards the cylinder through opening or closing its internal connections.

As mentioned in figure (1) if the solenoid (1) of the directional valve has been activated, and solenoid (2) deactivated then the piston of the cylinder will be moved in the forward direction and vice versa for the backward direction. In this position control system the stroke of the rod has been determined by (20 cm) as a set point. The linear position sensor connected in the system and electrically wired with the controller unit will detect the stroke of the rod.

The linear position sensor represents an accurate electromechanical sensor which is often used in different industrial and practical applications as shown in figure (2). It can be considered as a variable electrical resistor with total value of resistance equal to (5.14 kΩ) measured with respect to (300mm) rod length. The characteristics of the employed sensor will be selected as maximum working speed equal to (10 m/s) with linearity equal to (+/- 0.05%) and the maximum value of the electrical current is equal to 10µA.

Fig. 2. The Linear Position Sensor

II. POSITION CONTROLLER

The position controller unit of the pneumatic actuator has been designed as shown in figure (3).It consists of the electronic controller unit, solenoid valves and linear position sensors to stop the stroke of the cylinder rod at the set point. The linear sensor will be measured and detected the position of the cylinder rod. To provide the control action the controller unit will receive the feedback electrical signal that sent from the sensor and make a comparison with the corresponding set value of the stop position point that previously determined. The controller unit has been demonstrated with suitable electronic circuit to energize or de-energize the solenoid coil with the electrical energy.

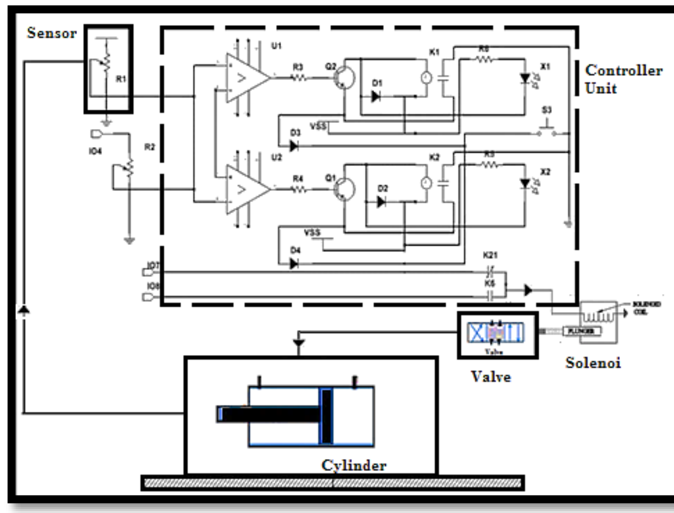

Fig. 3.The Position Controller Unit

The rod of the cylinder was mechanically coupled with the linear position sensor in order to convert the rectilinear motion of the cylinder rod into corresponding electrical signal as shown in figure (4).

Fig. 4.The Pneumatic Cylinder and Linear Position Sensor

To ensure that the linear position sensor will be worked properly, the testing and calibration process of the employed sensor as well as the controller card was done in the electronic laboratory /electrical department in the college of engineering of the Al- Mustansiriyah University. The calibration process was including the simulation of the motion of the sensor in steps to provide different values of voltage signals as shown in figure (5).

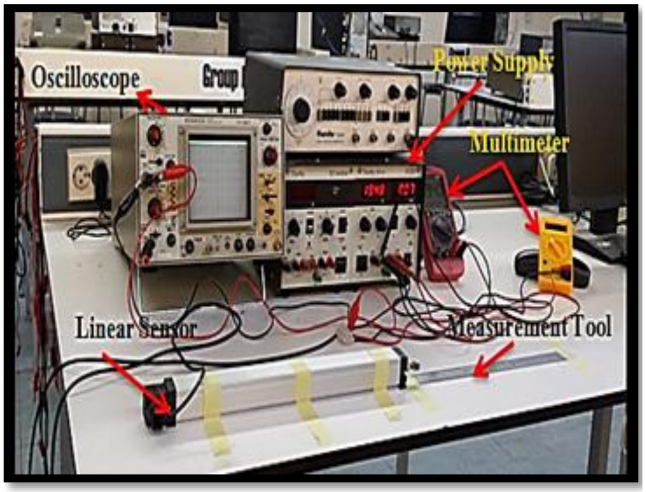

Fig. 5.The Calibration Process of the Linear Position Sensor

The calibration results of the linear position sensor can be listed as shown in table (I).

TABLE I
The Calibration results of the Linear Position Sensor

Steps	Increment Setting (%)	Resistance (kΩ)	Length (cm)	Voltage (V)
1	90%	0.56	1	1.399
2	75%	1.39	6	3.994
3	65%	1.91	9	5.389
4	61%	2.16	10	6.348
5	56%	2.46	12	7.75
6	52%	2.6	13	8.5
7	45%	3.01	15	10.23
8	40%	3.36	17	11.78
9	20%	4.40	23	14.48
10	15%	4.72	25	16.39

After sensor calibration was done and according to the obtained experimental results the electronic design of the controller card has been designed and implemented with taking into consideration the requirement of the position control system as shown in figure (6).

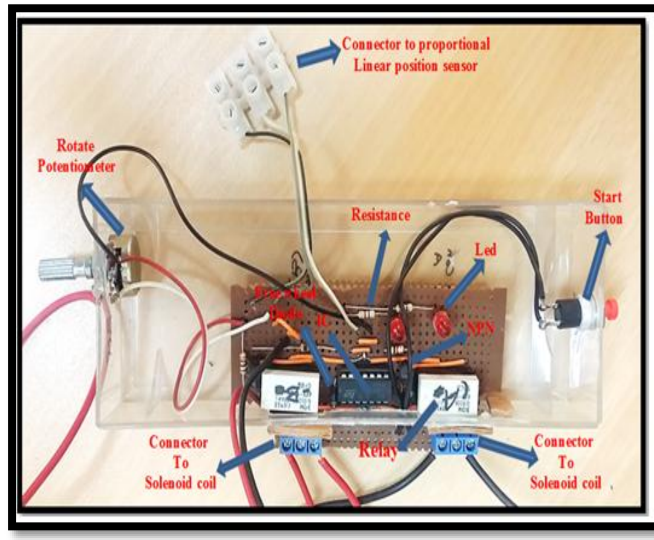

Fig. 6.The Electronic Controller Card

III. SIMULATION AND EXPERIMENTAL RESULTS

Simulation of the electro pneumatic position control system under consideration has been carried out with different software computer programs package such as a Matlab software environment. Firstly the mathematical model of the pneumatic system has been derived involving the dual action pneumatic cylinder and the directional solenoid control valves to obtain their transfer functions. The mathematical model of the pneumatic cylinder includes the major parameters such as the air flow rate, the dynamic of the load, temperature and volumes of the air in the cylinder as shown in figure (7).

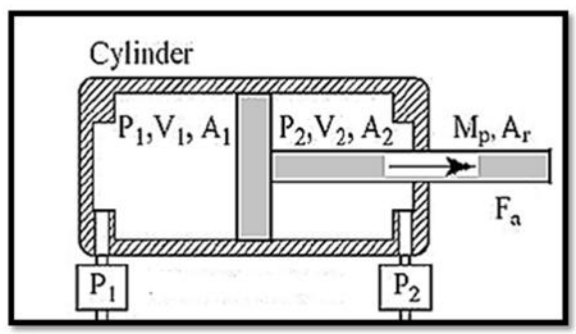

Fig. 7.The Schematic diagram of the Double acting Cylinder

Since the force developed by a cylinder rod is a function of the piston diameter, then it can be expressed as [4, 5]:-

$$\text{Force (N)} = \text{Piston area } (\text{m}^2) * \text{Air pressure } \left({}^{\text{N}}/_{m^2}\right) \quad (1)$$

The area of the piston for the forward stroke is

$$A_1 = \frac{\Pi}{4} * D^2 \quad (2)$$

While the area for returned stroke is

$$A_2 = \frac{\Pi}{4} * (D^2 - d^2) \quad (3)$$

The velocity of the piston rod can be measured as:-

$$V = {}^{Q}/_{Ai} \qquad (4)$$

And the mass flow rate of the air through the cylinder will be equal to

$$\dot{m} = \rho * Q \qquad (5)$$

Where:

D is the piston rod diameter

d is the return cylinder diameter

Q is the flow rate entering the cylinder

A is the area of the cylinder rod

ρ is the density of supply air

Q is the flow rate entering the cylinder

Applying to the Newton's second law for the cylinder piston, the force balance on the cylinder piston in the forward stroke will be expressed as in the following:-[6, 7]

$$M\ddot{y} + B\dot{y} + F_f = P_1A_1 - P_2A_2 - P_{atm}A_r \qquad (6)$$

And in the returned stroke:

$$M\ddot{y} + B\dot{y} + F_f = P_2A_2 - P_1A_1 - P_{atm}A_r \qquad (7)$$

Where:

M is the total mass

B is the damping coefficient,

F is the constant external force such as gravity and it will be equal to (zero) if the cylinder is in the horizontal alignment.

To drive the equation governing the time rate of the change of the pressure inside the air cylinder requires ideal gasses. The ideal gas law is commonly expressed as:-[8]

$$P.V = m.R.T \qquad (8)$$

It can be noticed that the universal gas constant (*R*) is related to the specific heats of a gas, which they is related to each other.

Each chamber in the pneumatic cylinder was treated as a control volume and the air in a chamber has an internal energy that is represent a function of the temperature; hence the internal energy will be:

$$E = C_V\,\rho VT \qquad (10)$$

In an adiabatic process, the time rate of the changing in the internal energy is equal to the rate of energy added to the control volume with the incoming air flow performs on the pneumatic cylinder piston.

$$\frac{d}{dt}(c_v\rho TV) = \dot{m}c_pT - P\dot{V} \qquad (11)$$

$$\dot{P} = \frac{KRT}{V}\dot{m} - \frac{KP}{V}\dot{V} \qquad (12)$$

The volume in each chamber of a pneumatic cylinder can be related to the displacement of the rod piston as in the following:-

$$V_1 = A_Py \qquad (13)$$

$$V_2 = A_r(L-y) \qquad (14)$$

The cylinder pressure dynamic in chamber (1 & 2) in the figure (4-1) of the cylinder can be approximated as:-

$$\dot{P}_1 = \frac{K}{A_Py}(\dot{m}_1TR - P_1\dot{V}_1) \qquad (15)$$

$$\dot{P}_2 = \frac{K}{A_{r(}L-y)}(\dot{m}_2TR - P\dot{V}_2) \qquad . (16)$$

Where:

P_1, P_2 = the pressure inside chambers 1& 2,

V_1, V_2 = the volume of the chamber 1&2,

$\dot{m}_1$,$\dot{m}_2$ = the mass flow in the chamber 1&2,

T = the temperature of the supply air,

k = the ratio of the specific heats of the air

R = the universal gas constant

Hence, the transfer functions of the pneumatic cylinder can be as expressed as in equation (17) under assumption that the air inside the cylinder will be an ideal gas, with the pressures of atmosphere and air source are constant and there is no leakage of the cylinder: [8]

$$\frac{y(s)}{x(s)} = \frac{C_x/Ap}{s(\frac{1}{{W_n}^2}s^2 + \frac{2*\zeta*s}{w_n}+1)} \qquad (17)$$

Where:

ζ is the damping ratio

w_n is the natural frequency.

And w_n and ζ of the pneumatic cylinder can be identified as:-

$$(w_n)c_{yl} = \sqrt{\frac{2*A^2*ka*P_i}{M*V_c}} \qquad (18)$$

$$(\zeta)c_{yl} = \frac{c_f}{2A}\sqrt{\frac{V_c}{2M*k*P_i}} \qquad (19)$$

Where

K = the ratio of the specific heats of the air in the cylinder

M = the total mass

V_c= the volume of cylinder

c_f = the viscous friction of pneumatic cylinder

Hence, the transfer function of the pneumatic cylinder can be plotted in the block diagram as shown in figure (8)

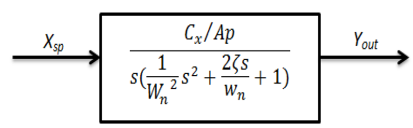

Fig. 8. Transfer Function of Pneumatic Cylinder

Where Y_{out} represents the output position of the pneumatic cylinder and x_{sp} is the spool displacement of control valve.

The directional solenoid valve model that has been employed can be depicted as shown in figure (9).

It can be subdivided into three subsystems; the electrical, Mechanical and electromagnetic subsystems. The electrical involves the current passing through the coil that producing the corresponding magnetic field within the valve.

The producing magnetic field was causing to move the spool into the required direction. So the solenoid valve is used to control the air flow through the valve orifice in order to control the rectinear motion of the cylinder.

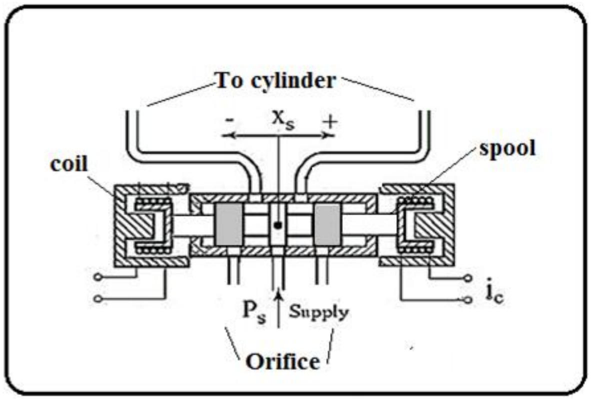

Fig. 9. The Schematic Diagram of the Directional Control Valve

Hence, the differential equation that mathematically describing the solenoid valves can be written as: [6,7]

$$m\ddot{x} = F_{mag} - c\dot{x} - kx \quad (20)$$

$$m\ddot{x} + c\dot{x} + kx + F_f = F_{mag} = k_c i \quad (21)$$

Taking the laplace transform of equation (21) under assumption that the initial condition is zero, then the transfer function of the mechanical and magnetic parts of the directional control valve given by:

$$ms^2x(s) + csx(s) + kx(s) = k_c\, i(s) \quad (22)$$

Where

x =represents the position of the spool
kx= is the combined spring force
k= the spring constant of spring
c = the damping coefficient and
F_f = the coulomb friction and it can be neglected
kc = the coil force coefficient,
i= the coil current

The block diagram of the transfer function of motion for the valve spool will be plotted as shown in figure (10).

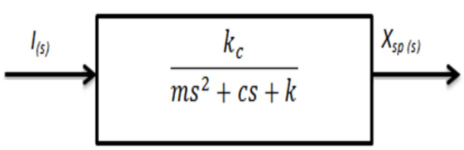

Fig.10.The Transfer Function of the Solenoid Valve.

The flow rate through the directional control valve caused by the displacement of the spool valve can be expressed as:

$$Q = Cx * x_{sp} \quad (23)$$

The simulation model of the proposed position control system including the transfer functions was done in Matlab /Simulink as shown in figure (11) with using the proportional controller model and the linear position sensor with set point that has been determined at 20 cm.

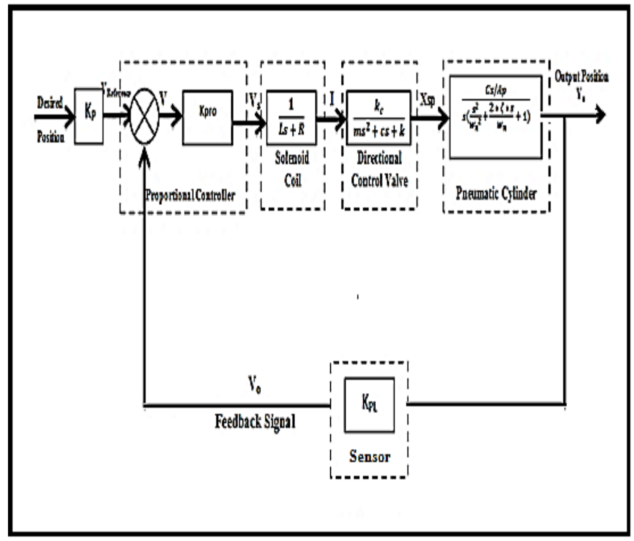

Fig. 11.The Controller Model of the Pneumatic Actuation System.

In the applied Simulink model the values of the natural frequency and damping ratio parameters that have been used are listed as shown in table (2).

TABLE II
The Values of the Natural frequency and Damping ratio of Pneumatic Cylinder at 20 cm set point.

Flow rate (l/min)	W_n (rad/s)	ζ
6	58.11	1.66
8	63.13	1.58
10	65.1	1.44
12	72.58	1.37

Running the Simulink model, with flow rate equal to (6 l/min) the response of the electro pneumatic position system will be displayed as shown in figure (12) and the settling time will be equal(2.6 sec).

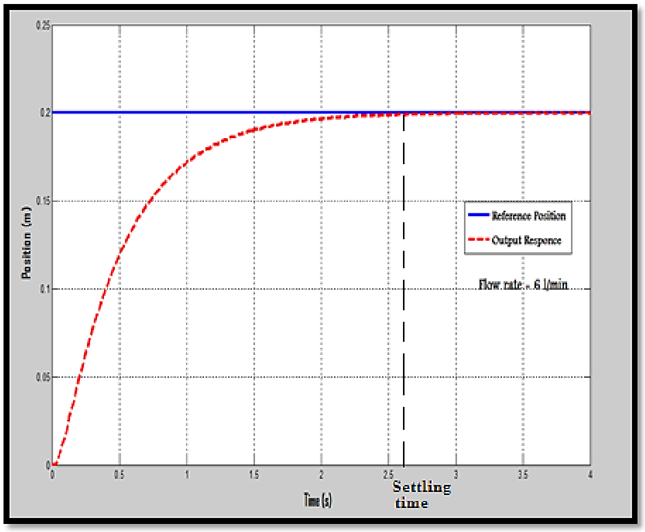

Fig. 12.The Response of the system at flow rate 6 l/min

If the flow rate has been changed from (6 l/min) to (8 l/min) , the settling time was being equal to (2 sec) and the response of the system will become faster as shown in figure (13).

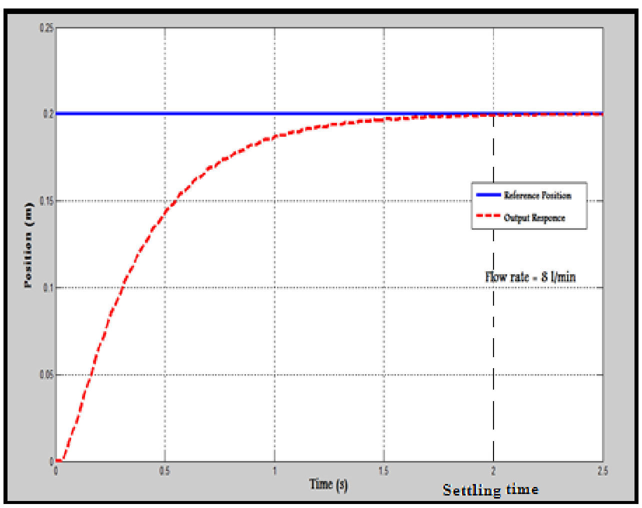

Fig. 13. The Response of the System at 8 l/min Flow Rate.

If the flow rate was being equal to 12 l/min the response of system will be reached to steady state with 1.2 sec as shown in figure (14).

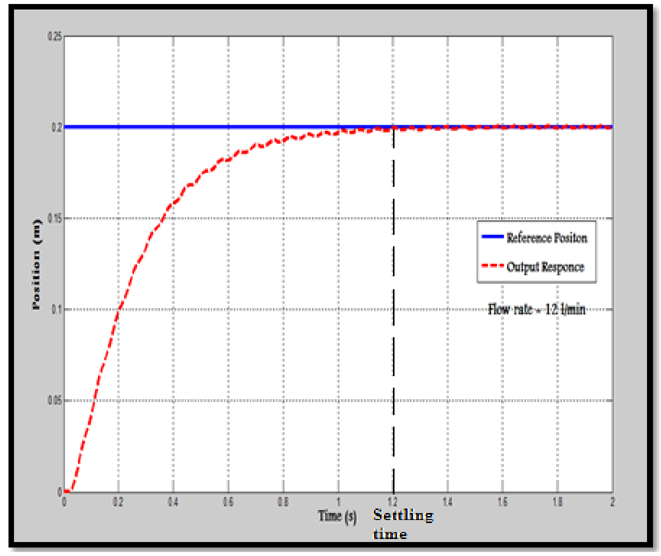

Fig. 14.The Response of the system at (12 l/min) flow rate

In order to make a comparison between the experimental results and the simulation results, the settling time of the cylinder rod when it was reaching the set point will be measured practically in the control laboratory using the manual stop watch and the obtained results are listed as shown in table (3).

TABLE III
Experimental & Theoretical Settling Time

Flow rate (L/min)	Settling Time (sec)	
	Practical (Experimental Model)	Theoretical (Simulink Model)
6	3	2.6
8	2.3	2
10	1.72	1.6
12	1.4	1.2

It can be noticed from the table (3) that the obtained results are nearly similar to the simulation results and the difference between them is due to the manual process of calculation the time. The results in table (3) can be plotted as shown in figure (15).

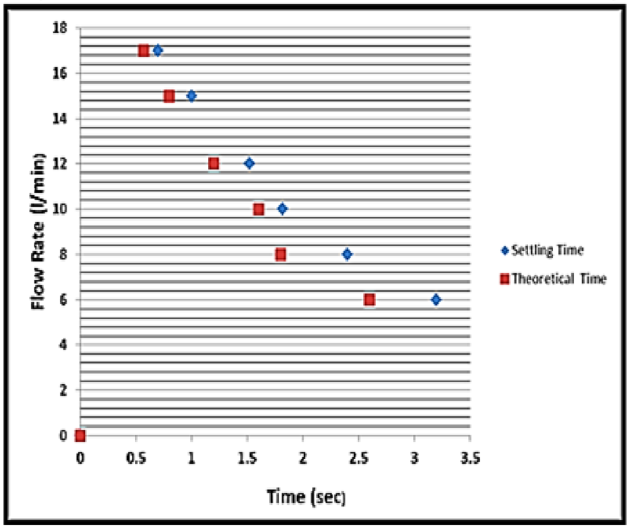

Fig.15.Flow Rate versus Settling Time

(Experimental and Theoretical results)

In the suggested position control system the characteristics of double acting pneumatic cylinder as well as the directional control solenoid valve are listed as shown in table (4).

TABLE IV
The Characteristic of Electro Pneumatic system

Pneumatic Cylinder	
Piston area	A_P= 804.24 mm^2
Rod piston area	A_r = 691.1 mm^2
Piston rod mass	m_p = 0.532 Kg
Air pressure source	Max pressure : 12*10^5 Pa
Viscous coefficient of cylinder	C=75 N(m/s)
The Characteristics of the Solenoid Valve	
	Electrical Power = 2.5 W
	Voltage = 24 V DC
Electrical Properties	Current= 0.104 A
	Resistance = 230.77 Ω
	Inductance = 0.98 H
Mechanical Characteristics	Damping Coefficient Csp=0.01 N/(m/s)
	Spring Stiffens (k=100 N/m)
	Mass Spool (mp=10 g)
	Translational hard stop
	Spool displacement (2 mm)
	Mechanical Converter (Kco =1.3 N/A)

The difference between the experimental and theoretical model at flow rate equal to 10 l/min with set point 20 cm will be plotted as shown in figure (16).

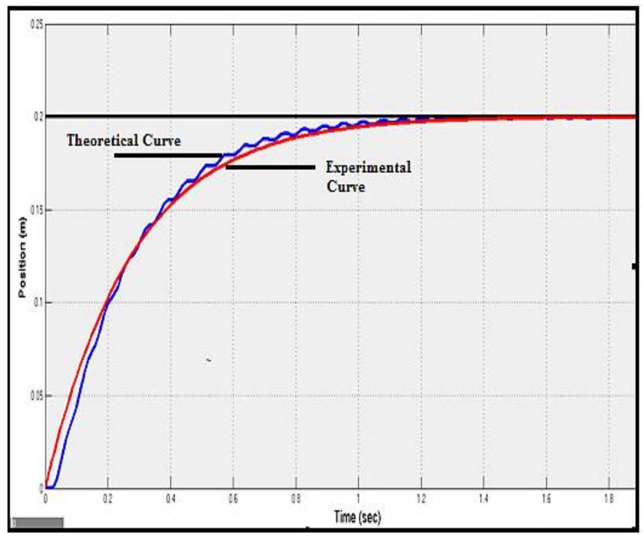

Fig .16. The Step Response of the System at Flow Rate 10 l/min

Experimentally the prototype test rig of the pneumatic position control system has been set up as shown in figure (17) and the obtained results of the employed system will be listed as shown in table (5).

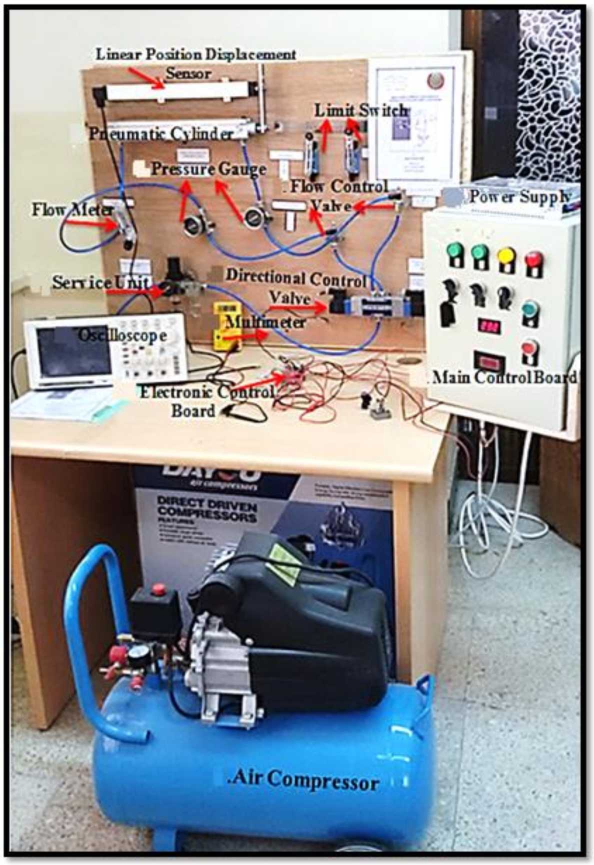

Fig. 17.The Employed Electro Pneumatic Position Control System

TABLE V
The Experimentally Results of the Position controller Based on Proportional Linear Position Sensor

Step	Flow rate (L/min)	Velocity of cylinder rod (m/s)	Stop Position of cylinder rod (m)	Settling Time (s)
1	0	0	0	0
2	4.5	0.093	0.2	3.45
3	6	0.12	0.2	3
4	7	0.145	0.2	2
5	8	0.165	0.2	1.8
6	10	0.207	0.2	1.62
7	11	0.228	0.2	1.4
8	12	0.248	0.2	1.22

IV. CONCLUSION

The objective of this work is to develop a fast, an accurate and inexpensive pneumatic position control system taking into account the different values of the air flow rate. It has been done based on the following remarks:-

1-The proposed position control model has been done using the low cost (ON/OFF) solenoid directional control valve rather than proportional or servo valve.

2-The suggested design employs the linear position sensor as a feedback and measurement device. The calibration process of the linear sensor has been carried out to meet the demand of the high accuracy of the controller unit and to gain acceptable practical results.

3-Simulation has been done using Matlab software package for testing and analyzing of electro pneumatic position controller system in order to get satisfying results and to investigate the best performance of the system.

4-The Simulink model in Matlab environment requires the knowledge of the physical parameters concerning with the employed systems, such as the air flow through pneumatic cylinder, and the mechanical displacement of the directional control solenoid valve.

5-This work deals with merged both, the theoretical simulation analysis and the empirical results. The comparison between the obtained results from the experimental work and simulation model are made to observe the performance of the system and the results are successfully convergence.

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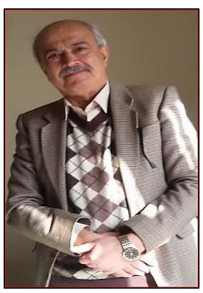
Assistant professor Munaf Fathi Badr

was born in 1967 at Baghdad Iraq. He obtained M.Sc in electrical engineering from Technology University (Iraq) in the field of mechatronics. Now he is working, AL-Mustansiriayah University/Faculty of Engineering /Department of Mechanical Engineering. Academic experience built by giving lectures in the Iraqi Universities, these lectures includes: Experiments in the theory of control system for the 4th year undergraduate students in AL-Mustansiriayah University/Faculty of Engineering /Department of Mechanical Engineering /Academic year (2015- 2016).

Experiments in very large scale integrated circuit (VLSI) for the postgraduate students (M.Sc. course) /Department of computer engineering .Experiments in basics of Electrical engineering for the 1st year undergraduate students and experiments in fundamentals of Electrical engineering laboratory for the 1st undergraduate students in AL-Mustansiriayah University/Faculty of Engineering /Department of Mechanical Engineering / Academic year (2004 till now).

Lec.Dr. Yahya Abdullah



was born in 1952 at Baghdad Iraq .He obtained PhD in mechanical engineering in the field of mechanical control . Now he is working, AL-Mustansiriayah University/Faculty of Engineering /Department of Mechanical Engineering .Academic experience built by giving lectures in the Iraqi Universities, these lectures includes: Experiments in the theory of control system for the 4th year undergraduate students, M.Sc students in AL-Mustansiriayah University/Faculty of Engineering /Department of Mechanical Engineering /Academic year (1992- 2016) and also supervised for many M.Sc thesis in control field

Eng.Ahmed Kadhiam jaliel

was born in 1981 at Baghdad Iraq .He obtained B.Sc in mechanical engineering and now he is postgraduate student in mechanical engineering filed control applied . He published some journal & conference paper in the field of Control applied and material science. Mr ahmed is a member of engineers Iraqi association .He is work in ministry of youth and sports / Directorate of Scientific welfare.