Design and Development of a Pneumatic Circuits Bench for Education Purposes

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Abstract – **As feed response from academia and industry, the University of Khartoum had successfully designed and developed an educational pneumatic circuit bench. The bench included various basic pneumatic system components such as filters, lubricators, regulators, pressure gages, valves, actuators, switches, magnetic sensors, fittings, tubes and relays. The developed workbench had overall dimensions of 2400mm length, 400mm width and 1800mm height. The bench had four laboratory activity exercises namely control of a double acting cylinder, pushing device, pneumatic press, and picking device. Various exercises had been designed and developed to operate pneumatically and electrically. The electrically operated picking device consisted of a commercial air compressor, 1 unit of FRL unit, 4 units of double solenoid valves 5/2, 1 unit of rod less cylinder, 1 unit of double acting cylinder, 1 unit of rotary actuator, 1 unit of check and 6 units of relays. A filing device had been also successfully designed and developed. The pneumatically operated filling device consisted of the commercial air compressor, 1 unit of FRL unit, 1 unit of pilot valve 5/2, 3 units of mechanical valves 3/2, and 1 unit of volumetric displacement filling device fixed together by one rod to the 1 unit of double acting pneumatic cylinder. Cut-away section of various pneumatic components for the pneumatic circuit bench is also developed for demonstration. The developed bench is self-contained mobile unit that can be used wherever electrical power is available. The total cost of the unit is less than 8,700 US Dollars.**

Index Terms – University of Khartoum, Engineering education, pneumatic, Teaching Aid

INTRODUCTION

The transmission and control of power by means of fluid under pressure is becoming increasingly used in all branches of industry. The extensive use of hydraulics and pneumatics system to transmit power is due to the fact that properly constructed fluid power systems posses a number of favorable characteristics. They eliminate the need for complicated systems of gears, cams, and levers. Also, they transmit motion without the slack or delay inherent in the use of solid machine parts. Fluid power is a term covering both pneumatic and hydraulic power. Pneumatic deal with the use of compressed air as the fluid whilst hydraulic power covers the use of oils and other liquids.

Pneumatic systems are very common, and have much in common with hydraulic systems with a few key differences. The reservoir is eliminated as there is no need to collect and store the air between uses in the system. Also because air is a gas it is compressible and regulators are not needed to recirculate flow, but the compressibility also means that the systems are not as stiff or strong. Pneumatic systems respond very quickly, and are commonly used for low force applications in many locations on the factory floor.

Historically, the modeling, analysis, and synthesis of suitable controllers for pneumatic actuators have been largely restricted to a classical transfer function approach that ignores nonlinearities like friction in the system. Much of the original modeling work can be found in authors like Blackburn *et al*. [1], Burrows [2], and Botting *et al*. [3] in the 1950's and 1960's.

The advent of electro-pneumatic PWM (pulse width modulation) came around in the 1980's in the works of Noritsugu, and Morita. In 1985, both parties separately implemented such a system in a pneumatic manipulator and they found that it is possible to obtain continuous feedback control without the use of servo valves [4]. In addition, Lai *et al.* [5] utilized the PWM method and they are able to achieve good position accuracy with a pneumatic actuator without using any mechanical stops.

Various software were developed for design, control and simulation of hydraulic, pneumatic, and motion control [6]. Hypneu processed the information in the graphical circuit and allowed the user to assign specific element to the system, to run both steady state in a meaningful manner. Several powerful add-on packages were also available, such as Frequency Analyzer, Thermal Simulator, CAE Co-simulator, Client/Server Module, etc.

Knowledge and understanding of hydraulic and pneumatic systems and their components make engineers better qualified to performance their job in industrial. The significant feedback received from employers in industry stated that the department's graduates need better training in hydraulics and pneumatics. As a response to that feedback, the Agricultural Engineering Department, Faculty of Engineering and Architecture, University of Khartoum has initiated its Hydraulics and pneumatics laboratory to include benches with industrial motor, pumps, cylinders and valves. Kheiralla *et al.* [7] had successfully designed and developed

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an educational hydraulic circuit bench for the department as the first phase of the initiative project. Their bench had facilities to measure oil hydraulic flow, pressure and temperature. The main bench testing circuit options include circuit to operate hydraulic pump, hydraulic motor and hydraulic cylinder and can be upgraded. Before starting the proposed hydraulic and pneumatic initiative project, the department did not offer an undergraduate course dedicated to hydraulics and pneumatics in its curriculum. The skills offered by such a course are required in industry. However, there are no similar courses that were offered through other departments at University of Khartoum, while the existing other related courses do not cover many important hydraulic and pneumatics skills required in agricultural and biological engineering that suits its own need. Therefore, the department staff needed to create the second phase of its new laboratory in pneumatic system that is most relevant to the agriculture and food industries.

The overall objective of the project is to design and develop a pneumatic circuit bench based on fundamental components to be used for educational purposes.

MATERIALS AND METHODS

The following criteria were considered in establishing the basic design concepts of pneumatic circuits bench:

1. Completely integrated system capable for be used for education purposes.
2. The system included various basic pneumatic components to build current and future knowledge technology of pneumatic design information for students.
3. The system facility had ability to implement as much as possible circuits on it and can be upgraded.
4. Simple in design construction and operation.
5. Low cost with in the reach of the development in Sudan.

COMPUTATION AND SELECTION IN PNEUMATIC CIRCUITS

The design of pneumatic circuits depends on standard tables [8]. These tables allow selecting actuators and valves where needed depend on force required and pressure allows.

Theoretical Force (Push or Extend) for a given cylinder is computed from the following expression:

$$F = \frac{\pi \times D^2 \times P}{4} \qquad (1)$$

where F is force in N, D is bore diameter in mm and P is air pressure in MPa. Knowing the pressure at a compressor of 11 bar (1.1MPa), maximum pressure in the cylinder of 10 bar (1MPa), diameter of bore of 20 mm (A_a= 314.16), the computed theoretical force was 314.16 N.

Theoretical Force (Rull or Retract) for a given cylinder is computed from the following expression:

$$F = \frac{\pi \times (D^2 - d^2) \times P}{4} \qquad (2)$$

where F is force in N, D is bore diameter in mm, d is piston rod diameter in mm and P is pressure in bar. Knowing the pressure at a compressor of 11 bar (1.1MPa), maximum pressure in the cylinder of 10 bar (1 MPa), bore diameter of 20 mm, rod diameter of 8 mm (A_b=263.89), the computed theoretical force was 263.89 N.

The compressed air consumption for a given cylinder is computed from the following expression:

$$Q_n = (A_a + A_b) \times L \times \frac{P + 0.101}{0.101} \times n \times 10^{-6} \qquad (3)$$

where Q_n is compressed air consumption in L/min, A_a is piston area of in mm^2, A_b is piston area of B in mm^2, L is stroke of cylinder in mm, P is air pressure in MPa, and n is cycle of operation in cycle/min. Knowing the maximum pressure in the cylinder of 10 bar (1 MPa), diameter of bore of 20 mm (A_a= 314.16), bore diameter of 20 mm, rod diameter of 8 mm (A_b=263.89), cylinder stroke of 250mm, operation cycle of 2.5 cycle/min, the computed compressed air consumption was 0.719 L/min.

Pneumatic valve direct the air to actuator, they may be used in combination to provide logic function for control systems. Valves are available in different types, sizes and configuration. The flow capability of a valve is determine by using flow coefficient, C_v. C_v is USA measurement and is based on an equivalent flow of water through the valve in US gallons/minute with a pressure drop of one psi. There are several C_v formulas in use but the one used is based on the NFPA recommendation.

The formula below has limited accuracy for pressure drops greater than 15% of the inlet pressure. Correction is made for compressibility of air and temperature of 20^0C. The air flow (L/s) for the valve is computed using the following expression:

$$Q = 6.694 C_v \sqrt{(P_2 + 1.013) \times dP} \qquad (4)$$

where is P_2 is downstream pressure in bar, dP is pressure drop across valve in bar, and Q is standard air flow in L/s.

The K_v value is similar to C_v but it corresponds to the flow of water in L/min with a 1 bar pressure drop. The formula is also restricted in its use to pressure drops less than 15% of the inlet pressure. The air flow (L/s) for the valve in term of Kv is computed using the following expression.

$$Q = 0.468 K_v \sqrt{(P_2 + 1.013) \times dP}$$
$$\text{with } K_v = 14.3 \times Cv \qquad (5)$$

DEVELOPMENT OF THE WORKBENCH

The workbench had been successfully designed and developed as the platform for laboratory activity exercises, and displaying and accommodating various pneumatic components in pneumatic circuit bench for education purposes. The workbench frame was fabricated from 40mm × 80mm mild steel hollow tube and 4mm sheet metal. The bench included one large drawer of size 2300mm × 400mm × 200mm to accommodate tubes and two small drawer of size 1000mm × 400mm × 200mm to accommodate fitting, valves, actuators, etc. The work-bench overall dimensions were 2400mm ×1800mm × 400mm. The laboratory activity exercises for the developed bench included four applications namely control of a double acting cylinder, pushing device, pneumatic press, picking device, in addition to a filling device. The developed bench for pneumatic laboratory is shown in Figure 1.

FIGURE 1
OVERVIEW OF THE PNEUMATIC CIRCUITS BENCH

PNEUMATIC CIRCUITS LABORATORY ACTIVITY APPLICATIONS

The laboratory activity applications for developed workbench included five applications. Every application can be controlled pneumatically and electrically.

Control of a Double Acting Cylinder

A double acting cylinder exercise was successfully designed and developed. The pneumatically double acting cylinder consisted of a commercial air compressor driven by electric motor 4 kW 3-phases @ 1440 rpm and maximum pressure of 11 bars with air reservoir having 270 L capacity, 1set of FRL unit, 2 set of mechanical operated valve 3/2 (two positions three ways), 1set of pneumatically operated valve 5/2 (two positions five ways), 1 unit of double acting mini-cylinder, and 2 set of speed controller. Figure 2.a illustrates the circuit diagram of a double acting cylinder operated pneumatically.

In the pneumatically operated double acting cylinder, compressed air is supplied from compressor (1), through FRL (2) filtered, regulated and lubricated, and distributed to foot valve (3) to start progress and give pilot signal to pilot controlled valve (4) which allow air cross (4) to speed controller (5), finally air enter to cylinder (6) to give expanding stroke, in retracting stroke to control by other position for (4) by limit switch valve (3).

The electrically operated a double acting cylinder laboratory application consisted of the same compressor, one set of FRL unit, one set of double solenoid operated valve 5/2 (two positions five ways), one set of mechanical operated valve 3/2(two positions three ways), one set of magnetic sensor, and one unit of double acting mini-cylinder. Figure 2.b illustrates the circuit diagram of a double acting cylinder, operated electrically.

In the electrically operated double acting cylinder, compressed air is supplied from compressor (1), air through cross FRL (2) filtered, regulated and lubricated, distributed and entering (3) solenoid valve to direction air , after air entering (4) speed controller and last station air entering cylinder to give expanding and retracting motion , sensor inside to give continuous motion. Figure 3 explains the path step diagram for both pneumatically and electrically operation of a double acting cylinder circuits.

Pushing Device

The pushing device application was successfully designed and developed. The pneumatically operated pushing device consisted of the air compressor, one set of FRL unit, one set of pilot operated valve 5/2 (two positions five ways), one set of mechanical operated valve 3/2 (two positions three ways), and one unit of double acting mini-cylinders. Figure 4.a illustrates the circuit diagram of a pneumatically operated pushing device.

In the pneumatically operated pushing device, compressed air is supplied from compressor (a), air through cross FRL (b) filtered, regulated and lubricated, distributed and entering (c) start valve, air across (c) to enter limit

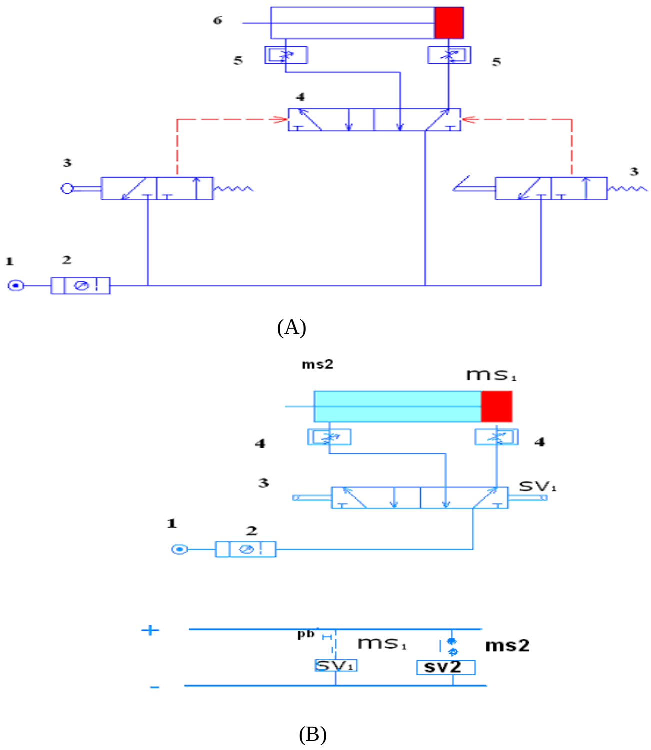


FIGURE 2
A DOUBLE ACTING CYLINDER CIRCUIT, (A) PNEUMATICALLY OPERATED, (B) ELECTRICALLY OPERATED A

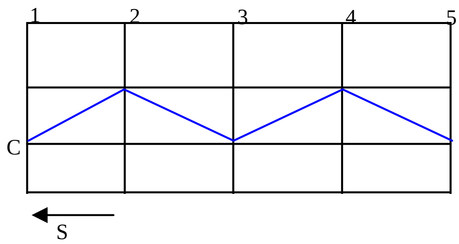


FIGURE 3
PATH STEP DIAGRAM OF A DOUBLE ACTING CYLINDER CIRCUITS

switch valve (ls1) , when cylinder (e1) is stated the air a cross (ls1) to enter (ls2) to give a pilot signal to pilot operated valve (d1) to let air entering cylinder (e1), as a result of that (e1) will make expanding stroke and in the end of it is stroke will touch limit switch valve (ls3) to give air signal to pilot operated valve (d2) to let air entering cylinder (e2) to make expanding stroke and touch limit switch valve (ls4) to give air signal for pilot valves (d1 & d2) and at one time, after that retracting stroke will happened to both cylinders (e1 and e2).

The electrically operated a push device laboratory application consisted of the same compressor, one set of FRL unit, one set of double solenoid operated valves 5/2(two positions five ways), one set of magnetic sensors, and two unit of double acting mini-cylinders. Figure 4.b illustrates the circuit diagram of a pushing device operated electrically.

In the electrically operated pushing device compressed air is supplied from compressor (a), air through cross FRL (b) filtered, regulated and lubricated, distributed and entering (c1) double solenoid operated valve with push button to start, then air across (c1) to enter cylinder (d1) to give expanding stroke, when cylinder (d1) is reach its end stroke, it will touch magnetic sensor (ms1), (ms1) will give a signal to double solenoid operated valve (c2) to open allowing the air to pass, as a result the cylinder (d2) will give expanding stroke, and then (d2) will touch the magnetic sensor (ms2). Sequentially, (ms2) will give a signal to double solenoid valves (c1& c2) causing retracting strokes in both cylinders (d1 and d2) at the same time. When cylinder (d1) reaches the end of retracting stroke it will touch magnetic sensor (ms3), next (ms3) will give a signal to double solenoid valve (c1) to repeat the process continuously. Figure 5 explains the path step diagram both pneumatically and electrically operated pushing device.

Pneumatic Press

The pneumatic press application was successfully designed and developed. The pneumatically operated press consisted of the air compressor, one set of FRL unit, two set of pilot valve 5/2 (two positions five ways), five set of mechanical valve 3/2 (two positions three ways), two set of pilot valve 3/2 (two positions three ways), four set speed controller, and two unit of double acting mini-cylinders. Figure 6.a illustrates the circuit diagram of a pneumatically operated pneumatic press.

In the pneumatically operated pneumatic press, compressed air is supplied from compressor (a), air through cross FRL (b) filtered, regulated and lubricated, distributed and entering a start valve (c), when the push button of start valve was pressed the air will crossed (c) to limit switch valve (ls2), then from (ls2) to limit switch valve (ls1). (ls1) will send a pilot signal to pilot operated valve (d1). (d1) will supply cylinder (e1) by air through speed controller (f1), then (e1) will make it's an expanding stroke and in the end of it is an expanding stroke it will touch the limit switch valve (ls3). (ls3) will send a pilot signal to pilot operated valve (d2), then(d2) will supply cylinder (e2) by the air through the speed controller (f3) to make it is an expanding stroke, when (e2) reach to the end of it is stroke it will touch limit switch valve (ls4), (ls4) will supply pilot operated valves (g1 & g2),

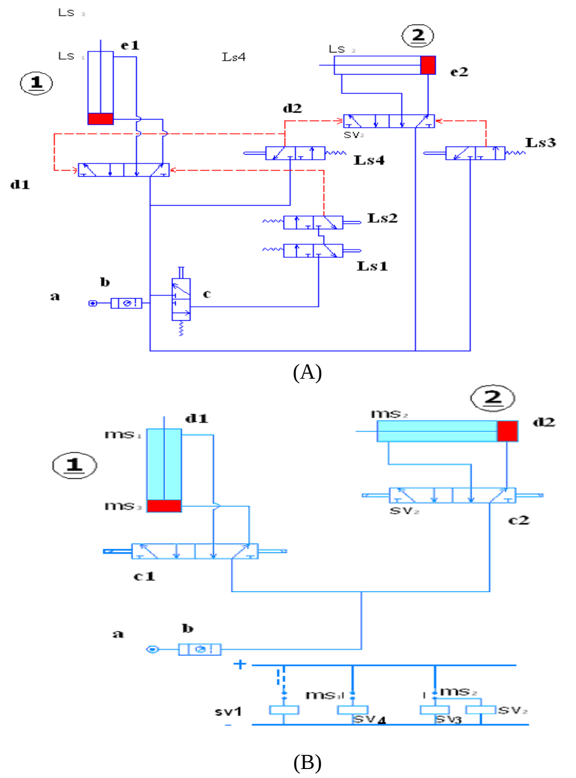


FIGURE 4
A PUSHING DEVICE CIRCUIT, (A) PNEUMATICALLY OPERATED, (B) ELECTRICALLY OPERATED

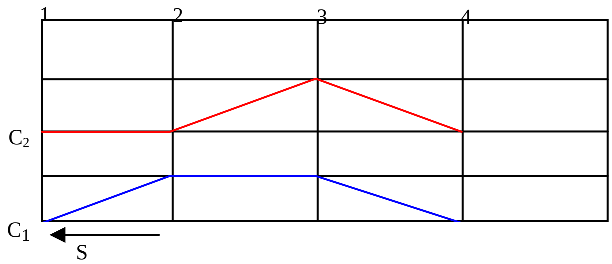
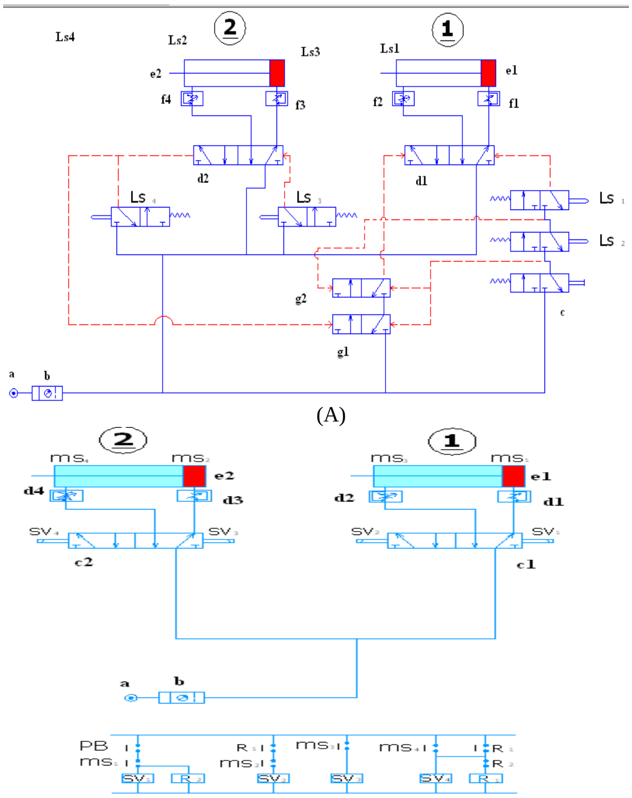


FIGURE 5
PATH STEP DIAGRAM OF A PUSHING DEVICE

also will send a pilot signal at the same time to (d2) to supply cylinder (e2) by air through speed controller (f4), as a result of that (e2) will make it is retracting stroke, and at the end of it is retracting stroke it will touch limit switch valve (ls2) will supply (g1 & g2), then (g1 & g2) will give a pilot signal to pilot operated valve (d1) to let air enter cylinder (e1) through speed controller (f2) to make it is retracting stroke. When (e1) reach to it is retracting it will touch limit switch (ls1) to start the progress again.

The electrically operated a pneumatic press laboratory application consisted of the same compressor, one set of FRL unit, two set of double solenoid operated valves 5/2 (two positions five ways), four set speed controller valves, four set of magnetic sensors, two set of relays, and two unit of double acting mini-cylinders. Figure 6.b illustrates the circuit diagram of a pneumatic press operated electrically.

In the electrically operated pneumatic press compressed air is supplied from compressor (a), air through cross FRL (b) filtered, regulated and lubricated, distributed. When the push button was pressed the progress will started, the air will entered the double solenoid valve (c1) and from it through speed controller (d1) to cylinder (e1) to make it do it is an expanding stroke, at the end of it is an expanding stroke it will touch magnetic sensor (ms3), as a result of that (ms3) will send an electric signal to (c2) to let air cross it through speed controller (d3) to enter cylinder (e2), then (e2) will make it is expanding stroke and at the end of it is stroke it will touch (ms4), as a result of that (ms4) will send an electric signal to (c2) to let air a cross it through speed controller (d4) to enter (e2) to let it make it is retracting stroke, when (e2) reach the end of it is stroke it will touch (ms2), then (ms2) will send an electric signal to double solenoid valve (c1) to let air a cross it through speed controller (d2) to enter (e1) to let it make it is retracting stroke. Also there are two relays (r1 & r2) to make signal sensor regulated. Figure 7 explains the path step diagram both pneumatically and electrically operated pneumatic press.



(B)

FIGURE 6
A PNEUMATIC PRESS DEVICE CIRCUIT, (A) PNEUMATICALLY OPERATED, (B) ELECTRICALLY OPERATED

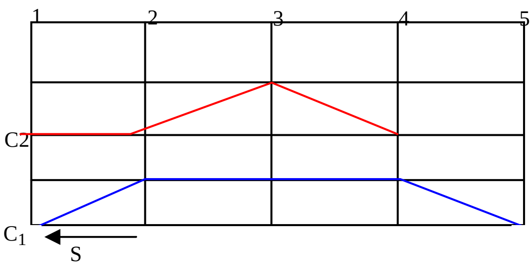


FIGURE 7
PATH STEP DIAGRAM OF A PNEUMATIC PRESS

Picking Device

The picking device application was successfully designed and developed. The electrically operated picking device consisted of a compressor, one set of rod less cylinder, one set of rotary actuator, one set of double acting cylinder, one set of chock, one set of FRL unit, four sets of solenoid operated valve 5/2 (two positions five ways), one set of push button spring return operated valve 3/2 (two positions three ways), nine set of relays, and eight set of magnetic sensors. Figure 8.a illustrates the circuit diagram of electrically a picking device.

In the electrically operated picking device, compressed air is supplied from compressor (a), air through cross FRL (b) filtered, regulated and lubricated, and entering mechanical operated valve (c). When the push button was pressed, the progress will started and the air will arrived to solenoid valve (sv1), to let air enter the rod less cylinder (d) through speed controller (d1). As a result of that the rod-less cylinder (d) will make it is an forward stroke, in the end of its stroke the air will arrived to solenoid valve (sv3) to let air enter the rotary actuator (e) through speed controller (e1). As a result of that the rotary actuator (e) will make it is a rotating stroke with 90º. When the rotary actuator (e) reached to the end of its stroke the air will arrived to solenoid valve (sv5) to let air enter the double acting cylinder (f) through speed controller (f1). As a result of that the double acting cylinder (f) will make it is an expanding stroke, in the end of its stroke the air will arrived to solenoid valve (sv7) to let air enter the chock (g) through speed controller (g1), as a result of that the chock (g) will make it is an clamping stroke. When the chock (g) reached to the end of its stroke the air will arrived to solenoid valve (sv6) to let air enter the double acting cylinder (f) through speed controller (f2). As a result of that the double acting cylinder (f) will make it is retracting stroke, in the end of its stroke the air will arrived to solenoid valve (sv2) to let air enter the rod less cylinder (d) through speed controller (d2). As a result of that (d) will make it is backward stroke. When (d) was back the air enters the rotary actuator (e) across solenoid valve (sv4) through speed controller (e2) to let (e) make backing rotate at 90. Then the air will arrive to (sv8) and across it to enter the chock (g) through speed controller (g2). As a result of that (g) will retracting. Figure 9 explains the path step diagram electrically operated picking device.

FILLING DEVICE DEVELOPMENT

The filing device had been successfully designed and developed in Sudanese German Hydraulic System Factory (SUGA) workshop for filling sells oil (Figure 10). The pneumatically operated filling device consisted of a commercial, 1 set of pilot valve 5/2 (two positions five ways), 3 set of mechanical valves 3/2 (two positions three ways), and 2 unit of double acting mini-cylinders joint together in one case. Figure 11 illustrates the circuit diagram of the pneumatically operated filling device.

In the pneumatically operated filling device, the compressed air is supplied from compressor (a), air through cross FRL (b) filtered, regulated and lubricated, distributed.

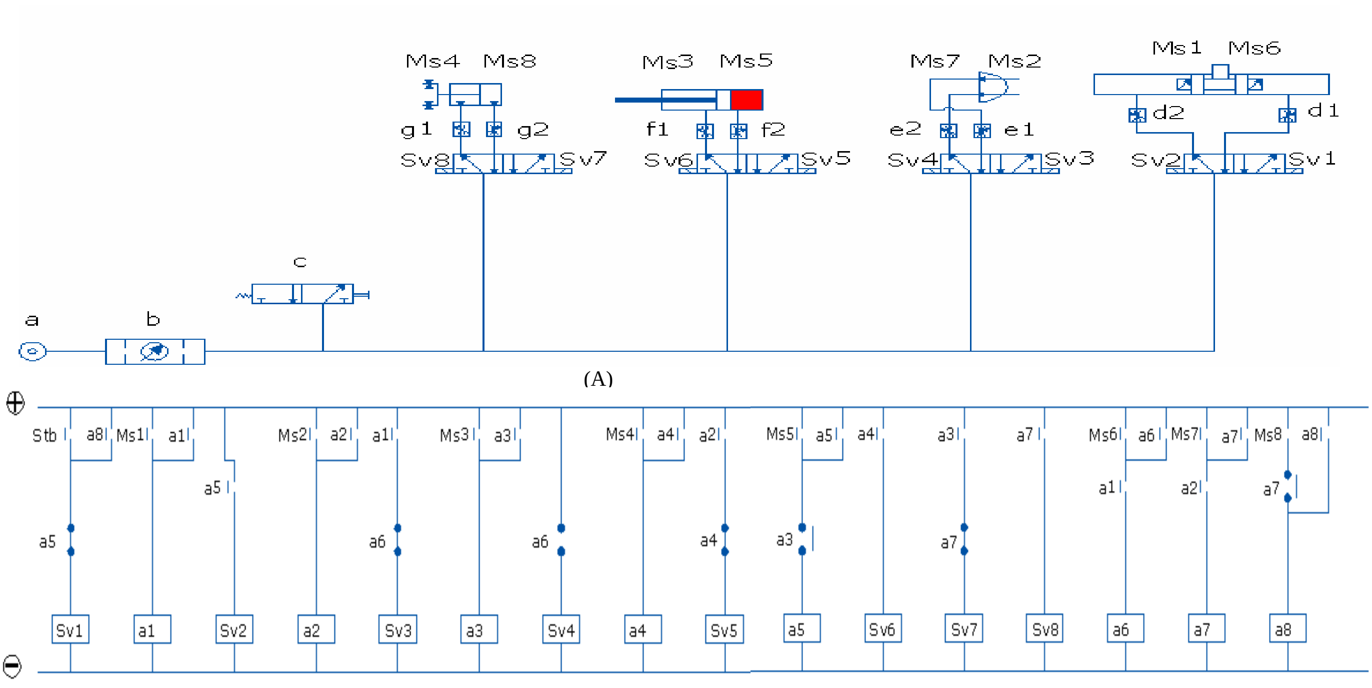


FIGURE 8
ELECTRICALLY OPERATED A PICKING DEVICE, (A) PNEUMATIC CIRCUIT, (B) ELECTRICAL CIRCUIT

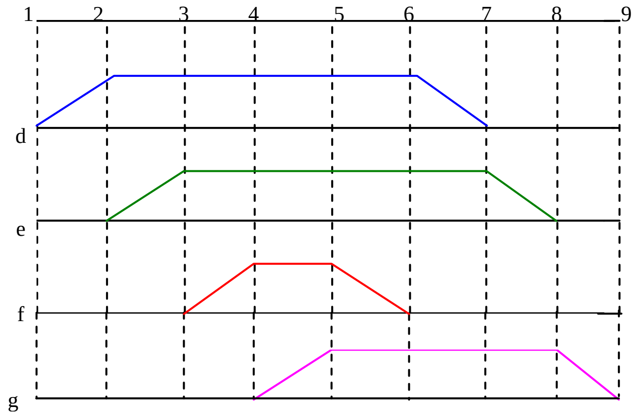


FIGURE 9
PATH STEP DIAGRAM OF A FILLING DEVICE

When the foot pedal valve (c1) was pressed the air will arrived to pilot operated valve (d), when the cam on the leader cylinder (f1) touch the limit switch valve (c2) it will give a pilot signal to pilot operated valve (d) to allow air entering (f1) through speed controller (e1), as a result of that (f1) will make it is an expanding stroke, as will as filling stroke for cylinder (f2). When (f) reached the end of it is expanding stroke it will touch limit switch valve (c3) by another cam, then (c3) will give a pilot signal to (d) to let air enter (f) through speed controller (e2), as a result of that (f1) will make it is retracting stroke, and that let (f2) to be discharge. Figure 12 explains the path step diagram for pneumatically operated filling device.

FIGURE 10
OVERVIEW OF THE DEVELOPED FILLING DEVICE

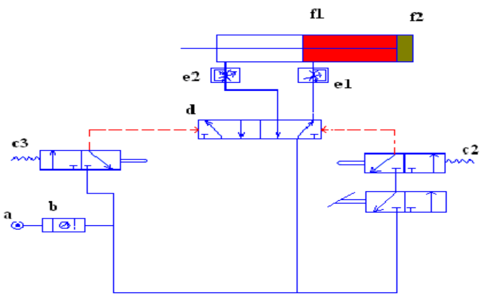


FIGURE 11
A PNEUMATIC FILLING DEVICE CIRCUIT

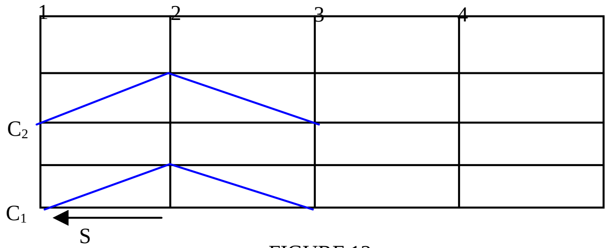


FIGURE 12
PATH STEP DIAGRAM OF A FILLING DEVICE

CUT-AWAY SECTIONS OF PNEUMATIC COMPONENTS

Cut-away sections for various pneumatic components were also developed for demonstration. The cut-away sections include filters, lubricators, regulators, pressure gages, valves, actuators, switches, sensors, fittings, tubes. The main functions of these cut-away sections are to show the internal parts of these components. These developed cut-away sections give in depth understanding and allows coherent viewing of circuit configuration, parameters setting components assembly. Figure 13 depicted a typical sample of cut-away sections.

FIGURE 13
A TYPICAL SAMPLE OF CUT-AWAY SECTIONS
(ROTARY ACTUATOR)

CONCLUSIONS

The following conclusions could be drawn from the obtained results:

- Pneumatic laboratory circuit bench had been successfully designed and developed for education purposes as a response to feed back from industry. The system included various basic pneumatic system components such as filters, lubricators, regulators, pressure gages, valves, actuators, switches, sensors, fittings, tubes and relays.
- The bench had four laboratory activity exercises namely control of a double acting cylinder, pushing device, pneumatic press, and picking device. Various exercises had been successfully designed and developed to operate pneumatically and electrically. The filing device had also been successfully designed and developed.
- Cut-away sections of various pneumatic components for the pneumatic circuit bench were also developed for demonstration.
- The developed workbench had overall dimensions of 2400mm length, and 400mm width and 1800mm height and the total cost of the unit is less than 8,700 US Dollars.
- The developed bench was participated on the Scientific Forum for Engineering and Computer Students, Khartoum, Friendship-Hall, 12-14 Dec. 2006 and on 24th International Fair of Khartoum 24 January -2 Feb. 2007.

Recommendations and Further Research

The following agenda are to be taken for this study work:

- The new developed facility should be provided for Hydraulic and Pneumatic Laboratory at Agricultural Engineering Department due to response feedback from the industry and rapid development.
- Design, control and simulation of pneumatic and motion control software should be incorporated in the new laboratories to process and run information in the multimedia circuit and allow to display the results in meaning full manner.

ACKNOWLEDGEMENTS

The research project is sponsored by University of Khartoum under laboratories budget allocations. The authors are very grateful to Sudanese German Hydraulic System Factory for technical support.

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