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INVESTIGATION OF A DIGITAL VALVE SYSTEM EFFICIENCY FOR METERING-IN SPEED CONTROL USING MATLAB/SIMULINK

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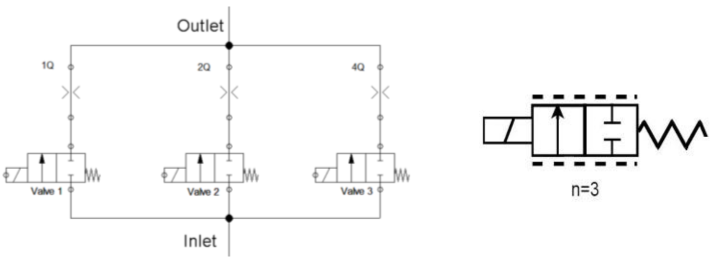
Abstract: *For a long time, servo and proportional valves have ruled in the flow control field. Since the nearly past decade a new method titled "Digital Valve System" has strived in this area, and has proven some advantages over the elderly valves. The importance of this technique rises because of the inability of analog valves to fulfill fault tolerance, energy efficiency, and manufacture standardization. Also, Digital hydraulics concept has the possibility to be extended to replace traditional pumps, accumulators, transformers, motors and many various valves. Moreover, it manages to raid not only the hydraulic field but also water and pneumatic power systems with acceptable results, when compared to the analog valves.*
The digital valve system utilizes a pack of simple 2/2 on/off valves to compete versus the analog valves. The Digital Valve Unit (DVU) is composed of parallel connected on/off valves with a common input and common output ports; and the output flow has discrete values. To determine the flow rate of each valve in the Digital Valve Unit (DVU), a Pulse Code Modulation (PCM) scheme was chosen, in which the valves flow rates have discrete values and can be presented as a geometric sequence with common ratio two. This paper studies the Feasibility of metering-in speed control using digital valve system. Through the paper, four cases modeled to describe and evaluate DVS: an ideal case with four and five valves, a near real case with four valves and a particular comparative case of an analog valve. A simple open-loop controller is used for the speed control in case of DVU using Simulink and Stateflow, while with the proportional valve a closed-loop controller is used.
The results indicated the possibility to regulate the flow rate in the hydraulic circuit using Digital Unit instead of an analog proportional valve, with a dropping of 93% in energy consumption when compared against a two-way proportional valve. The high efficiency is owing to the lower differential pressure in DVU than with the two-way proportional valve. On the other side, the results show high-pressure peaks with DVU which needs further study.
The theory has advantages of high linearity, low hysteresis, less pressure drop at small flow rates, and fault tolerance. The biggest challenges related to DVU can be summarized to a great package size and valve states uncertainty.

Keywords*: Digital valve system, MATLAB Simscape, tracking control, digital hydraulics, pulse code modulation*

1. Introduction

The traditional way of controlling actuator operational speed can be abridged in two primary methods. First: a fixed displacement fixed speed pump controls many actuators. Unemployed fluid flows to the tank through a relief valve. The required flow by any single actuator is lower than the pump outlet; therefore, a restriction device is needed to bind the flow for every single actuator [1]. In fact, this method contributes to a considerable energy loss. Another issue is when an actuator requires varying speeds during operation; these pumps need to be sized to supply the highest flow needed. But unfortunately, when low speed is required, the excess flow delivered from these pumps must be leaking via the exhaust valve at maximum system pressure. This process results in converting the unwanted energy into heat; So, fixed displacement pumps should only be employed in constant speed applications, or in circuits where speed control is of very short duration [2].
Second: another flow control method is by using pump control; where the flow is controlled either by changing the pump drive speed, or by modifying the pump displacement, or both. Its main advantage is dropping hydraulic throttling losses via operating the pump at lower pressure, which can lower the overall power consumption; However, pump control decreases the system

responsiveness and bandwidths needed for critical applications —for example closed-loop position control circuits— because pumps do not ensure the requisite frequency response. While valves can reach into the 150 to 200 Hz frequency responses [3]. Moreover, servo valves can reach to 400Hz [4], whereas the fastest pump frequency response is a small fraction of that.
A new parallel way has proposed and started by Linjama to solve the previously mentioned problems, the concept called Digital Fluid Power (DFP), it replaces the traditional analog devices of the fluid circuit by digital ones [5]. The roots of Digital Fluid Control go back to 1961, which invented by BOWER [6].
A digital system can comprise a digital accumulator, digital supply units, digital cylinder, and digital control valves [7]. Taking a traditional variable flow control valve for demonstrating; in the digital world, the analog valve is replaced by a group of on/off valves, which have several flow rates at similar pressure drop relative to the coding method. These valves have two states either on or off; therefore, the flow output has discrete steps. So, for low desired speeds operate the valve with small flow rate, and for high speeds open more valves.
Digital valves could also refer to Switching valves in which a variable rate capability can be attained by varying the duty cycle [8-10]. The clearest distinction between Digital valves and switching valves is the former needs many parallel valves, but the latter requires only one valve for flow control. The drawbacks of using these switching valves are the necessity of a robust valve owing to the tremendous frequency switching, and the need for a damping device [11, 12].
To determine the flow rate of each valve in the Digital Valve Unit (DVU) various schematic coding can be chosen, for example, Pulse Code Modulation (PCM) (1Q, 2Q, 4Q…) and Pulse Number Modulation (PNM) (1Q, 1Q, 1Q…). PCM is superior over PNM in the capability of having higher resolution with less number of valves; unfortunately, the former suffers from transient uncertainty. An in-depth evaluation is presented in [12]. The designers should select the code suitable for their application. PCM of three parallel flow lines is described through Figure 1. The equivalent proportional control valve is shown in Figure 2.



0: closed valve, 1: open valve			Outlet Flow
V 1 (1Q)	V 2 (2Q)	V 3 (4Q)	(ΣQ)
0	0	0	0
1	0	0	1
0	1	0	2
1	1	0	3
0	0	1	4
1	0	1	5
0	1	1	6
1	1	1	7

(a) **(b)** **(c)**

Fig. 1. (a) DVU of three on/off valves. (b) DVU simplified symbol. (c) Corresponding flow rates

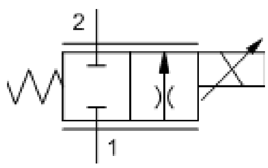


Fig. 2. Two-way electro-proportional flow control valve.

It should be mentioned that DVU is not only limited to replacing the traditional 2-way proportional valves, but it extends to cover many types of valves. Various applications were performed using DVU are shown in [13-15].
Although DFP extends back to 1960's era, it's considered a recent study; as serious researches have been carrying out since the past decade. On the other hand, electrohydraulic servo valves were invented at the end of 1930 as high technology, although the high cost, a solution to accurate motion control was needed. In 1980 proportional valves were presented as a practical and

reasonably priced alternative to servo valves [16]. Till now these valves have dominated over the field of flow control although their faults.
Another aspect considering the future of fluid power in Industry Revolution 4.0 —shorted to I4.0— was studied by Brandstetter et al. [17], via classifying the industrial revolutions into four sections, starting from mechanization (I1.0), electrification (I2.0), and digitalization (I3.0) till connection/Internet revolution (I4.0). Unfortunately, the fluid power currently is still struggling in the I3.0 Industry. This paper takes the path to put a step in the I4.0. Which characterizes by I) Reduction in unit cost by standardization of the components. II) Connecting fluid components to cyber-physical systems, so alive remote access to all system data enables much easier technical support. III) Finally running the valve group by only editing a few commands in the valve software, with no need for replacing a valve when requiring a different task —which decreases resource waste [18].
Continuing on the research studied by Linjama in the field of Digital Valve System (DVS). This paper will review the strength and weaknesses points of using DVU over proportional valve. A selected case of low flow rates and relatively small loads was chosen for investigation.
The paper is divided into three main parts: 1) Modeling and simulation of DVU using MATLAB Simscape Fluids. 2) Velocity control of a hydraulic cylinder using DVU. 3) Performance Comparison between DVU and 2/2 electro-proportional valve.

2. Modeling and Simulation of DVU

2.1 System Overview

The existing below components are founded on real ones, in which experimental validation will be investigated in a future research work. The system comprises a supply unit with DVU of 4 on/off solenoid operated valves against a maximum load of 1000 N. The used code is PCM as a result of its compact size and acceptable flow steps. The velocity output has 15 steps starting from 1 to 15 l/min. Note that in the case of PNM coding, 15 valves are needed with 1 l/min output flow from each valve, to achieve the same purpose.

2.2 System components

The used software is Simscape Fluids, which provides components library for simulating fluid circuits. To solve the Differential Equations in the model, MATLAB recommends ode15s and ode23t for Simscape hydraulic models [19]. In this model, ode15s was selected for higher accuracy [20]. The hydraulic circuit model is shown in Figure 3. The system components are:

- Induction motor and variable displacement pump blocks were selected. The Pump performance curve provides data at 1800; however, the available motor has a rated speed of 1410 rpm, without the need to use affinity laws. Coupling the motor and pump using Simscape provides the value of pump max delivery 19.3 l/min when limiting the pump differential pressure to 20 bar and loading the cylinder with 1000 N. As only the desired flow goes through the DVU is a fraction of this value, so the excess flow is dumped into the tank.
- Electric Motor. A single-phase induction motor with a rated speed of 1410 rpm and 1.5 KW rated power.
- Pump. A variable displacement pump (HYDURA PVQ-06); the pump swash plate angle is stationary at a max delivery of 0.0139 l/rev, the rated speed of the pump is 1800 rpm.
- DVU. Digital valve system can consist of more than one DVU, here one DVU of four valves (Sun Hydraulics-DTDB-XCN) is used [21]. DVU is shown in Figure 4.
- Orifices. Over each 2/2 valve, an orifice is positioned, the orifices used were selected from Hydra Force company have diameters (0.85, 1.3, 1.8, and 2.5) mm, with output flow rates (0.9, 2.2, 4.3 and 8) l/min at the operational pressure [22]. The flow was supposed to be perfectly binary formulated (1, 2, 4, and 8) l/min, but due to the requirements of a high precision diameters values, the mentioned diameters were accepted.

- 4/3 valve. A PONAR (4WE6 E-12/G24 N Z4) spool valve with tandem center [23]. The valve has a small pressure drop of 2 bar at 15 l/min. A better choice is to select a closed center valve with a variable pressure compensated pump, then vary the swash plate angle according to the pressure. But valve and pump bandwidth should be considered when designing this circuit. [24]. Also, the valve response time was disregarded. Here the paper focuses only on flow control using valve digitalized method, and the valve is mainly needed to retract the actuator.
- Actuator. (ϕ32/22—250) mm Cylinder, with a maximum pressure of 100 bar.
- Relief valve. A (VMDR40) relief valve with max pressure set to 20 bar, at this pressure the relief valve can handle 40 l/min flow rate [25].
- Sensors. LVT position sensor is used for circuit operation. A pressure transducer and flow meter sensors are used only for setting up the circuit.

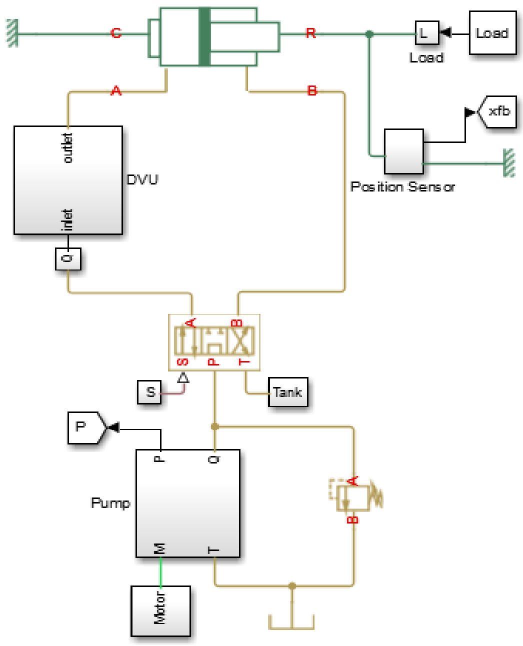


Fig. 3. System Model.

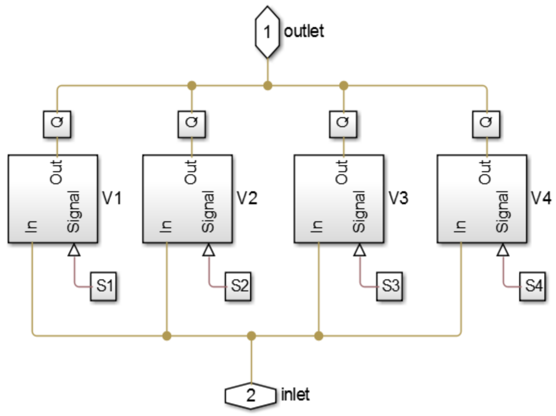


Fig. 4. Digital Valve Unit Model.

2.3 Modeling an Ideal Isolated Case

To fairly judge DVU concept; an optimum case is modeled (Figure 5), this model has a perfect binary PCM code, constant supply pressure, no relief valve bypasses flow, no pressure drop over the 4-way directional valve, and immediate valve response. At constant 20 bar supply pressure, the new precise orifices diameters allow for accurate flow rates (1, 2, 4 and 8) l/min.

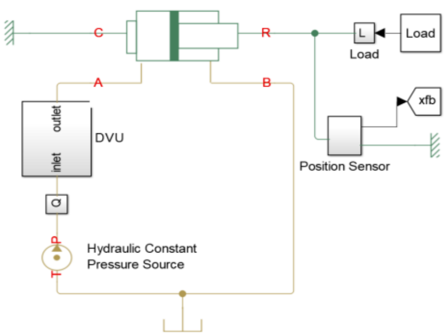


Fig. 5. Ideal Hydraulic Circuit Model.

3. Control and Operation Methodology

Controlling actuator speed can be achieved by using a hydraulic block contains needle valve and return check valve, which is called "metering-in." In the metering-in circuit, cylinder speed is controlled as fluid enter the cylinder; this block is connected to the piston side.
Metering-in circuits are much preferred as long there is no runaway load —runaway load can be prevented by using a counterbalance valve (V2) as shown in Figure 6 consequently preventing cavitation— its best application is for extending an opposing vertical load against gravity force. Another advantage when controlling the feeding in the extension direction; is a precise cylinder speed can be achieved as more fluid entering the piston side than leaving the rod side [1, 26].

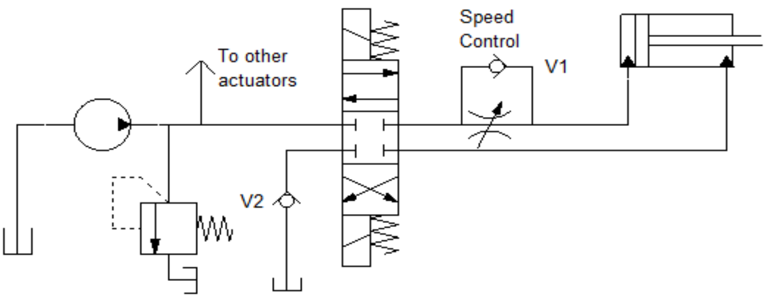


Fig. 6. Meter-in speed control. [1]

The model presented in this paper is based on the meter-in flow control concept, except instead of using conventional analog flow control valve as in Figure 6, a DVU is used.

3.1 Controller Design

An open-loop controller was utilized for the speed control; consequently, there isn't any sensor noise problem, but the system has two issues left, which are Disturbances and Variations in process dynamics. If they are well known, the open-loop controller is an excellent choice, which happened in our case, as the primary purpose of the paper is concentrating on the methodology of speed control using DVU [24].
A simple controller was constructed using MATLAB Stateflow viewed in Figure.7. The controller inputs are the desired flow rate and the position. Also, Position control isn't the paper interest.

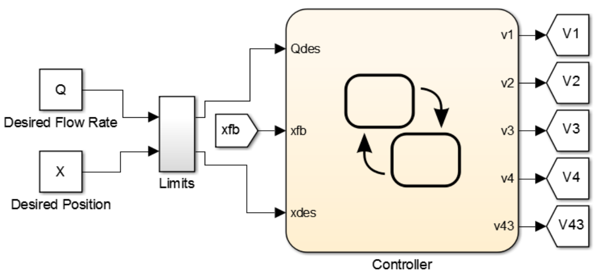


Fig. 7. Velocity Controller.

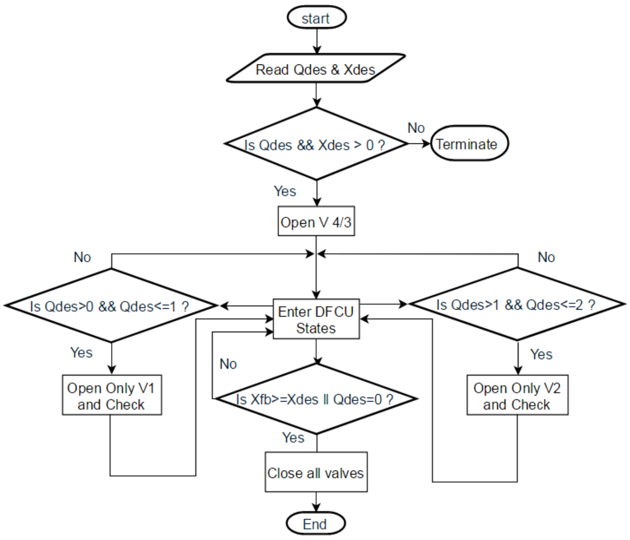


Fig. 8. Controller Flowchart.

As regards to the inputs, the Stateflow control logic selects the suitable "scenario" and opens the combination of valves corresponding to the desired flow rate.
Hence if the desired flow is 7 l//min, with knowing the step size and the valves flow rates values, the corresponding opening valves combination is V1, V2, and V3. The available output flow rate is divided into ranges, thus for 6.8 l/min, the same opening combination will be selected since the minimum step size is 1 —due to the system (DVU n=4) smallest valve has 1 l/min at the rated pressure.

3.2. System Operation

The Flowchart in Figure 8 represents the process steps of the ideal case. Only two valves were selected for presentation, with two valves there are three states: V1 open, V2 open, and both are opened. The third state isn't represented in the flowchart for simplification reason.
The symbols Xdes, Xfb, and Qdes, represent desired output position, feedback position reading from the sensor and desired output speed respectively.

4. Model and Control of Two-Way Electro-Proportional Flow Control Valve

A Sun Hydraulics-FPCCXAN proportional valve is selected for comparison with the modeled DVU [27]. They both are cartridge poppet valves and have an equal maximum flow rate. The maximum valve flow is 15 l/min at 215 bar pressure drop, while the proposed DVU requires only 6.7 bar.
Proportional valves refer to controlling valve output flow proportional to the commanded signal [24]. Proportional valve circuits can be abridged in four paths: I) Open-loop proportional valve system. II) Closed-loop proportional valve system by a mean of an LVDT transducer mounted on the valve. III) A closed-loop proportional valve system, with LVDT linked to the actuator. IV) A closed-loop proportional valve system, with LVDT connected to both the valve and the actuator. More information can be found in [28]. In this model, the third configuration was chosen for comparison with the DVU.
Proportional valve performance curve was uploaded to the model, and I-controller was used as depicted in Figure 9. The controller transfer function is (3.644/s). All the remaining parameters of proportional valve circuit model are the same as the "Near Real DVU Model."
Knowing that the proportional valve hysteresis, linearity, repeatability and dead-band are: <4%, <8%, <2%, <2% and 25% respectively [27]. The valve hysteresis, repeatability, resolution and step response were neglected. These previous issues will be much reduced in the case of using DVU.
Figure 10. shows the tracking performance of output flow of the 2/2 proportional valve to the reference sinusoidal reference with amplitude 15, and 1 rad/sec frequency. It can be seen that the result is nearly consistent with the reference signal after 0.2 seconds —when passes the dead-band zone.

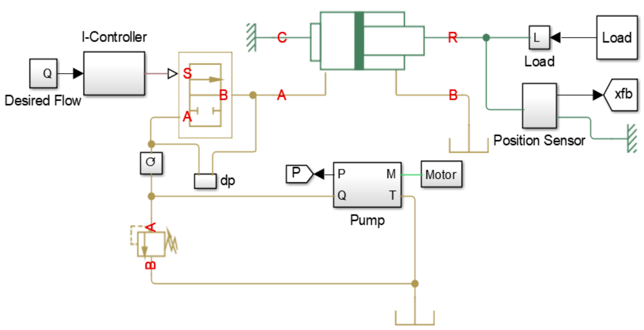


Fig. 9. Proportional Valve Circuit

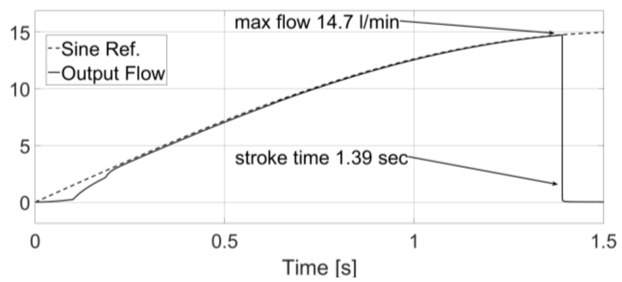


Fig. 10. Proportional Valve. Sine input reference and the response output.

5. Results and Discussion

5.1 Ideal Case

The system's valves have two states, either be operated by 1 input signal or be closed by 0 signal. The controller signals are sent to 24V DC solenoids to activate the valves. In Figure 11, the maximum flow rate 15 l/min is achieved when a ramp input signal of slope 12 is selected. Therefore, all the four valves (n=4) needed to be opened as described in Figure 12.

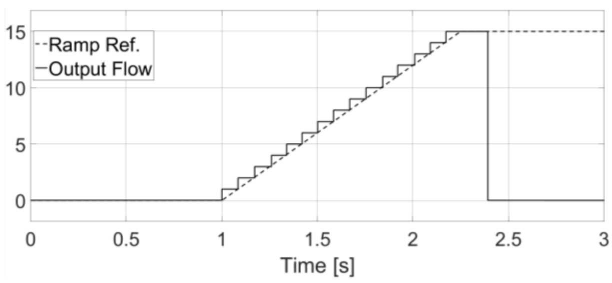


Fig. 11. Ideal DVU (n=4). Ramp input reference.

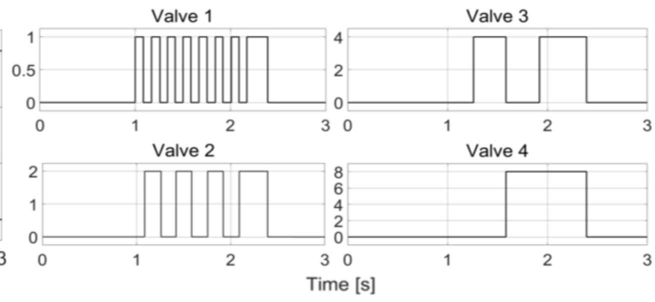


Fig. 12. Ideal DVU (n=4). Output flow from each valve for a Ramp input.

As the number of valves increments by one, the valves' states output increase according to the relation: N_states=2^(n-1), where n is the number of valves in DVU, and N_states is the total number of the states a DVU can possess. Therefore, a DVU output resolution is clearer as the number of valves increases. A comparison demonstrates this point shown in Figures 13 and 14 when a sinusoidal input with 1 rad/sec frequency and xdes = 250mm is used. Also, the output flow rate for the DVU (n=5) is 15.5 l/min which is more than DVU (n=4) by 0.5 l/min.

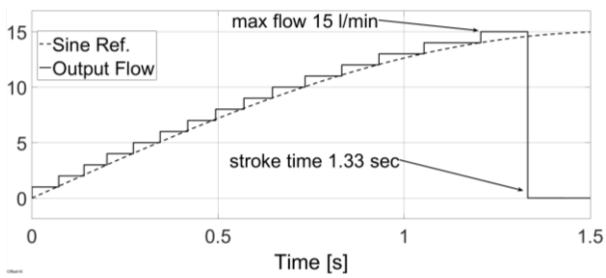


Fig. 13. Ideal DVU (n=4). Sine input reference and the response output.

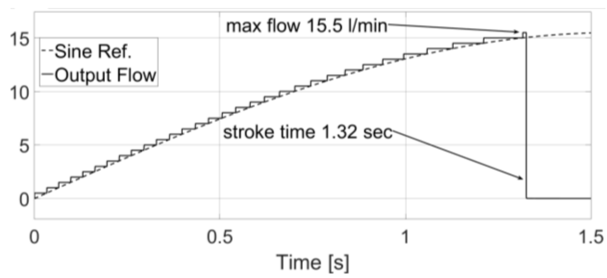


Fig. 14. Ideal DVU (n=5). Sine input reference and the response output.

5.2 Near Real Case

In Figure 15, a trapezoidal input of amplitude 15 for 0.5 sec is used, the corresponding output flow is 14.7 l/min, due to the low precision orifice diameters used.

In Figure 16. When tracking a sinusoidal signal with amplitude 15, and 1 rad/sec frequency, flow peaks were seen, this is caused by the switching on and off delay time of the valves.

More explanation of the flow peaks is as follows: consider the first desired output is 7 l/min this will require a state (V1: on, V2: on, V3: on, V4: off). Secondly, a transition value of 8 l/min is required, this will need an opposite state which is (V1: off, V2: off, V3: off, V4: on). Due to the delay in opening and closing the valves; a transient state appears in which all the valves are opened altogether for a variable period. This issue can be resolved either by using a high response valves, or another suitable coding scheme such as PNM coding, or both. In paper [29], delay problem is solved by delaying the valve closing time based on the measuring values of the inherent characteristics of valve switching time. The valve opening uncertainty can also cause pressure peaks, which can be resolved by using accumulators, relief valves, and suitable controllers [30].

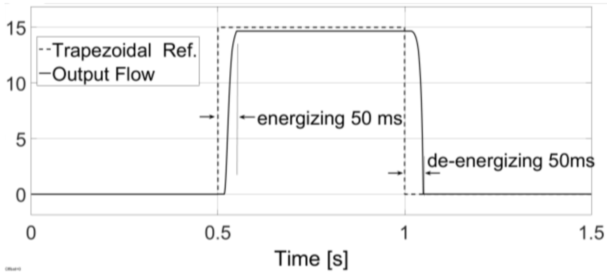


Fig. 15. Near Real DVU. Trapezoidal input reference and the response output flow.

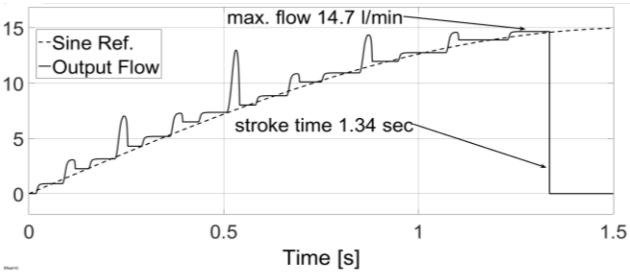


Fig. 16. Near Real DVU. Sine input reference and the response output flow.

5.3 Two-Way Electro-Proportional Flow Control Valve and DVU Comparison Points

In Table 1, data extracted from simulations through Figures 10, 13, 14 and 16 are listed. Here the hydraulic energy consumption is taken for evaluation —of course the prime mover needed to operate the pump will consume higher energy— the energy is calculated as formula (1):

$$Energy_{Hydraulic} = \int_{t=0}^{T} Power_{pump}\,(t)\,dt \quad (1)$$

The cumulative root mean square (CRMS) error was integrated over the cylinder stroke time as shown in formula (2): [31]. U(t) is the variation between the output flow and the reference signal.

$$CRMS = \sqrt{\frac{1}{T}\int_{t=0}^{T} \|u(t)\|^{2}\ dt} \quad (2)$$

Table 1: Comparison layout

system configuration	energy consumed (kJ)	CRMS error	stroke time (sec.)
Proportional valve	11.85	0.31	1.39
Near Real/DVU (n=4)	0.82	0.89	1.34
Ideal/DVU (n=4)	0.40	0.54	1.33
Ideal/DVU (n=5)	0.40	0.28	1.32

It's obvious in Table 1 that the proportional valve consumed greater energy than DVU; this is because the proportional valve operates at much higher pressure drop than DVU to achieve similar flow rates. Also, the energy consumption for Ideal/DVU (n=5) and Ideal/DVU (n=4) is equal due to both operate at fixed pressure source of 20 bar, and the only difference is an excess flow of 0.5 l/min (0.5+1+2+4+8) of the former over the latter (1+2+4+8).
Another important remark, is here the primary cause of CRMS in proportional valve arises from the valve dead-band, and no compensations were made to reduce this error. In fact, both CRMS error and response time in Near Real/DVU and Proportional valve can be decreased with the aid of a more advanced controller. The comment on achieving maximum stroke with Ideal/DVU (n=5) in a shorter time than Ideal/DVU (n=4) is due to a higher maximum flow rate of Ideal/DVU (n=5) by 0.5 l/min. The energy consumption reduction ratio when calculated from equation (3), is 93%.

$$R_{e.c} = \frac{E_{\text{Proportional valve}} - E_{Near\ Real\ DVU}}{E_{Proportional\ valve}} \quad (3)$$

6. Conclusion

In this research, a proposed Digital Valve Unit (DVU) was presented, which showed the possibility to control the flow using DVU instead of the traditional proportional valve. Comparison between the proposed system and the analog 2/2 proportional valve was carried out. The results showed a reduction in energy consumption with the aid of DVU. The system has advantages such as I) Low hysteresis. II) High linearity. III) The possibility of programming valves by many functions. IV) Less pressure drop with small flow rates. V) Fault tolerance, as the system could still operate with less performance when a working valve is malfunctioned. V) Standardization, by substituting different valves for a group of semi-similar programmable ones. It's clear that the concept difficulties are large package size, valve states uncertainty, and pressure peaks. The studied model in this paper can be considered an initial step for digital hydraulic separate meter-in and separate meter-out (SMISMO) control which is a major competitor to load sensing circuits. The present study suggests that DVU can provide a significant improvement in flow control field, especially concerning energy saving.

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