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Model Identification of Displacement Controlled Linear Actuator in Hydraulic System

Original Article

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Displacement controlled linear actuator, hydraulic system, modelling, pseudo random binary signal, transfer function.

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Abstract

The main goal of this paper is to develop and validate the system identification of the Displacement Controlled (DC) linear hydraulic system. The proposed method depends on finding the transfer function that map the simulated output to fit the actual output. To achieve this goal, several experiments have been performed to collect the required data to estimate the parameters including the order of the estimated transfer function. Experimental results in this paper demonstrate that fifth order model with one zero shows good match between the simulated out and the actual outputs. These results demonstrate that the proposed approach can achieve accurate identification of DC linear hydraulic system. Moreover, the proposed approach is general and can be applied to model any hydraulic system working in the linear zone.

I. INTRODUCTION

Hydraulic systems are considered one of a major type of power transmitting due to many advantages such as robustness, great power to weight ratio, etc. All vehicle, planes, mechanical equipment, and agricultural equipment have at least one or two hydraulic systems. Most of hydraulic systems use the same type of components like control valves, pumps, etc. However, they suffer from low efficiency because of the usage of control valves, which lead to fluid throttling. Thus, there is an urgent need to improve the efficiency of hydraulic systems in terms of eliminating the metering loses associated with hydraulic valves and allowing energy recovery. Moreover, improving the efficiency of hydraulic systems will lead to reduce the pollution, fuel consumption, and running cost, which are considered the current world challenges. One of the main ideas to improve the efficiency of hydraulic system is to use Displacement Controlled (DC) actuator and valve-less hydraulic circuit. The common usage of displacement-controlled actuators was on hydrostatic transmission, which uses symmetrical actuators (hydraulic motors). Recently, the researchers investigate the usage of displacement controlled linear actuator in closed hydraulic circuit without the usage of direction control valves. It is worth mentioning that the new trend of integrating electronic and mechanical systems (mechatronics) open the hope to solve the problem of flow compensation between the two terminals of a linear actuator in an efficient manner. In addition, the reasonable prices of the current variable displacement pumps encourage the investigator to include them in developing any new hydraulic system. Moreover, modern measurements techniques, affordable software, PCs, microcontrollers and precise transducers made testing, identification of any developed system is fast, and accurate compared to the traditional analytical identification techniques. Based on aforementioned advantages of the displacement controlled linear actuator, this paper will mainly focus on developing a simple technique to identify a hydraulic circuit as long as it is in the (close to) linear zone/bandwidth of operating frequencies.

Limitations of the Existing Approaches: The proposed approach of using the data that has been collected during several experiments to estimate the system transfer function. The main advantages of using this method over deriving the transfer function in analytical method are as follows:

- All of the analytical based methods are based on ideal assumption of any system components, which are not true in most/all cases. This may cause a notable deviation between the estimated/simulated output and the actual output.
- It is hard to find an analytical model for each system component.
- For complex system, it is hard to find a closed analytical form to describe the developed system.

II. MATERIAL AND METHODS

In this section, the experimental set-up and the details of the proposed identification approach will be discussed.

2.1 Experimental Set-Up:

All the experimental work in this paper was done on a proportional controlled variable axial piston pump driven by a three phase electrical conduction motor, the pump is linked to a double acting, single rod hydraulic cylinder by means of hoses which is lifting an arm. A bladder type, four liters, hydraulic accumulator is fitted to link to the rod side of the hydraulic cylinder to compensate the fluid flow difference between the cylinder two sides. A solenoid controlled hydraulic on-off valve to hold the cylinder at any position, two relief valves manually adjusted are used to improve the system safety and durability. The hydraulic circuit is considered to be closed because the hydraulic fluid which flows back from the consumer (hydraulic cylinder) is directed directly back to the pump. Here, there is a high-pressure side and a low-pressure side depending on the load direction.

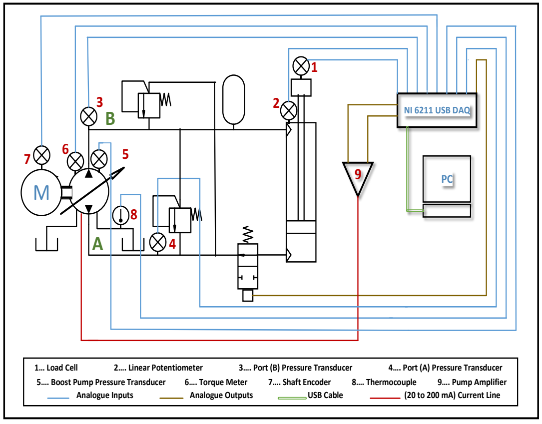

Fig. 1: Setup schematic drawing

All the pre-discussed hydraulic components are equipped with a group of different transducers and devices were used to measure, operate and monitor the system. Data acquisition system (DAQ) with eight differential analogue input channels, two analogue output channels were used to convert the sensors analogue signals to digital ones to send them to the PC to conduct measurements and doing calculations, and plotting results. DAQ controls the hydraulic pump via an analogue output channel by producing (-8) to (+8) volts to the pump amplifier card which convert these voltages to current (200 to 600 mA, Figure 1) to operate and control the pump proportional solenoids. The second analogue channel is used to control the on off valve to hold the hydraulic cylinder to a desired position. DAQ counter is wired to shaft encoder to calculate motor/pump angular speed; a digital output channel is to operate the electrical motor via a relay and soft starter. The hydraulic cylinder is fitted to a loading mechanism consists of an H beam arm and a base, which ascends different weights to apply variable forces to the hydraulic cylinder.

2.2 Input Signals and Preparation of Data:

Since the focus of this paper is testing and molding the linear system, the most common signal in this case is the pseudo random binary signal (PRBS) as demonstrated in Figure 2. PRBS is binary sequence that has the same property of any random sequence, while it is generated by using a deterministic algorithm[1]. The generated PRBS has the following properties:

1) It is a periodic signal.
2) Bipolar signals.
3) Deterministic[1].

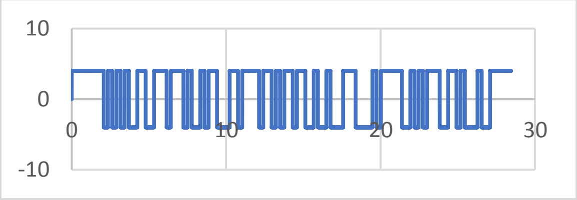

Fig. 2: Illustration of the pseudo random binary signal (PRBS)

The traditional way to generate PRBS is to use a shift register with a XOR gate as a feedback as shown in Figure 3. As demonstrated in Figure 3, the clock is responsible for generating any PRBS with any certain frequency. In this work to avoid using the hardware approach, a Matlab-based approach has been developed to generate PRBS with any certain frequency. The main idea of the developed Matlab code is to use a look up table that simulate n-bits shift register. The length of the generated PRBS (N) can be defined from the following Equation:

$$N = (2^n - 1) \qquad \text{(Eq. 1)}$$

Where n is the number of bits in the shift register.

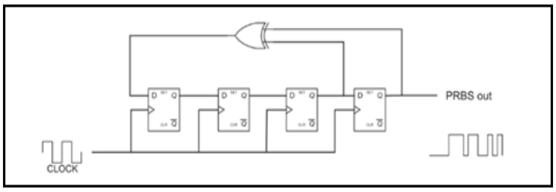

Fig. 3: Schematic Diagram for PRBS generator.

As demonstrated in Figure 2, the generated PRBS is bipolar with amplitude ±a and with duration Δt second. Thus, the total length of the generated PRBS is (T) = Δt N.

Concerning PRBS Power Spectrum, to determine the bandwidth of PRBS, the power spectrum of a PRBS has been calculated by using Discrete Fourier Transform as demonstrated in Figure 4. It is clear from Figure 4 that the main loop of sinc function is limited by the clock frequency (1/ Δt). This finding is also consistence with our estimation for the period of the generated PRBS (Δt N).

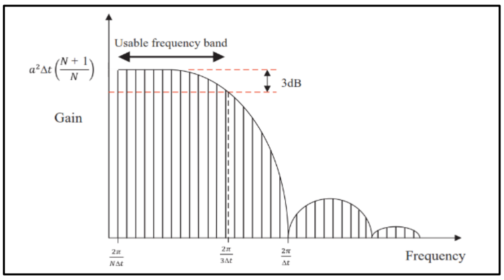

Fig. 4: Power spectrum (FFT) of a PRBS showing the usable frequency band (Fairweather, Foster and Stone[1]).

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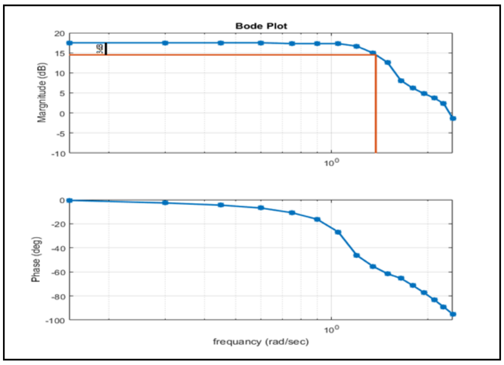

Fig. 5: Bode plot of the hydraulic system: (a) gain and (b) phase versus the hydraulic system frequency.

Based on the Wiener–Khintchine theorem, it is states that the PRBS has a usable frequency range of 1/3 of the clock frequency[1]. This can express as:

$$\mathbf{f_{min}} = \frac{\mathbf{1}}{\mathbf{N\Delta t}} \qquad \text{Eq. 2}$$

$$\mathbf{f_{max}} = \frac{\mathbf{1}}{\mathbf{3\Delta t}} \qquad \text{Eq.3}$$

Thus, the estimated bandwidth of PRBS is

$$\mathbf{f_{band}} = \frac{\mathbf{1}}{\mathbf{\Delta t}}\left(\frac{\mathbf{1}}{\mathbf{3}} - \frac{\mathbf{1}}{\mathbf{N}}\right) \qquad \text{Eq.4}$$

Where 1/ Δt is the clock frequency (fc) of the PRBS.

From Equation (4), we can conclude that the most two important parameters that can affect the bandwidth of the generated PRBS is the fundamental clock pulse frequency (FC) and the number of stages N of the shift register. Based on the Nequest theory, the clock frequency must be selected to be larger or equal two times the maximum frequency[2]. Based on this theory and according to the work proposed by Fairweather et al., the clock frequency will be estimated as follow:

$$\boldsymbol{f_c = 2.5 f_{pmax}} \qquad \text{Eq. 5}$$

Where f_{pmax} is the maximum frequency of interest.

2.3 PRBS Parameter Estimation:

To estimate the parameters of the PRBS that will be used to test and model the hydraulic system, the input voltage to the variable pump is chosen as the perturbation input signal while the output signal is the hydraulic cylinder velocity. To determine the maximum frequency of interest (fpmax) of the process to be identified, the bode plot has been calculated. As demonstrated Figure 5, the 3dB bandwidth of the maximum frequency of interest is 7 rad/sec (f_{pmax} = 1.1 Hz). Based on the estimated maximum frequency of interest (1.1 Hz), in this work, a PRBS signal is designed to have the following parameters: f_{band} = 0.83 Hz. In this work, a new way of estimating the length of PRBS is proposed based on the expected cycle time for earth moving equipment and handling equipment. Based on our practical knowledge, the expected cycle time is about 15 sec to 50 sec. In this work, 27 seconds have been used as an average cycle time for all conducted experiment in this paper.

$\Delta t = 1/f_c = 1/(2.5*f_{pmax}) = 1/(2.5*1.1) = 0.3636$ sec

N = Total Cycle Time/ Δt = 27/0.3636 ≈ 127 (a 7 bits shift register is required to generate the PRBS sequence)

$f_{min} = 1/N\Delta t = 0.0217$

$f_{pmax} = 1.1$Hz

$f_{max} = 1/(3\Delta t) = 1/(3*0.3636) = 0.9168$ Hz

$f_c = 2.5*f_{pmax} = 2.5.*1.1 = 2.5.*1.1$ Hz

III. EXPERIMENTAL RESULTS

The DC hydraulic system is consisted of variable displacement pump, pipes, accumulator, and hydraulic cylinder and loading mechanism. Since the bandwidth of the frequency of interest has been selected to cover only the linear part of the proposed hydraulic system, thus this work will focus only on identifying the proposed system based on using a linear model and PRBS as an input signal. To estimate the transfer function of the hydraulic system, the gray-box system identification method will be followed by the following assumption for each of the system components:

- Variable displacement pump will be modeled by a second order system[4].
- Accumulator will be modeled by a first order system[5]
- Hydraulic cylinder and loading mechanism will be modeled by a second order system[6].
- Pipelines will be modeled by a constant gain.

Thus, the hydraulic system will follow either one of the following fifth order transfer functions[6].

$$\boldsymbol{H_1(s)} = \frac{\boldsymbol{C_0}}{\boldsymbol{C_1S^5+C_2S^4+C_3S^3+C_4S^2+C_5S+C_6}},$$

$$\boldsymbol{H_2(s)} = \frac{\boldsymbol{C_1S+C_0}}{\boldsymbol{C_2S^5+C_3S^4+C_4S^3+C_5S^2+C_6S+C_7}}, \text{ or}$$

$$\boldsymbol{H_3(s)} = \frac{\boldsymbol{C_2S^2+C_1S+C_0}}{\boldsymbol{C_3S^5+C_4S^4+C_5S^3+C_6S^2+C_7S+C_8}},$$

In this work, the designed PRBS signal is used as an input and the output in terms of cylinder position has been recorder as demonstrated in Figure 6.

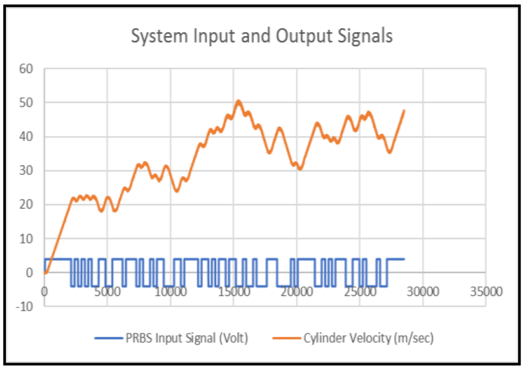

Fig. 6: Illustration of the input and output signals of the proposed system.

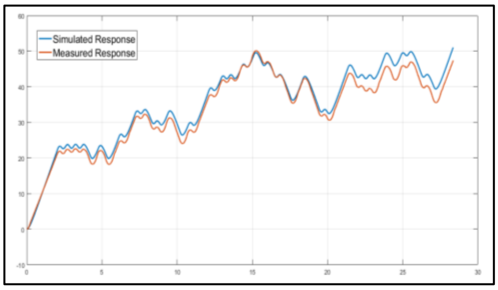

Fig. 7: Illustration of the experimental output and simulated output by using fifth order system with one zero.

To evaluate which one of the above transfer functions will fit the proposed system, we used Matlab toolbox to estimate the coefficients of each transfer function. After estimating the coefficients of each transfer function, the simulated output has been compared with the actual output to pick up the best transfer function. Our experimental results as demonstrated in Figure 7 confirmed that the following fifth order system with one zero has a simulated out very close to the actual output.

$$H_2(s) = \frac{5.034 \times 10^5 S + 2245}{S^5 + 78.5S^4 + 2609S^3 + 4.307 \times 10^4 S^2 + 1.677 \times 10^5 S + 751.2}$$

To evaluate the estimated transfer function, we calculated the bandwidth of the frequency of interest from the estimated transfer function as demonstrated in Figure 7. The results showed that the estimated f_{pMax} =1.1 which is matching the estimated f_{pMax} that has been estimated from the empirical. Moreover, the calculated bode plot from the estimated transfer function follows the same trend likes the bode plot that has been estimated from the experimental data as shown in Figures 8 and 9.

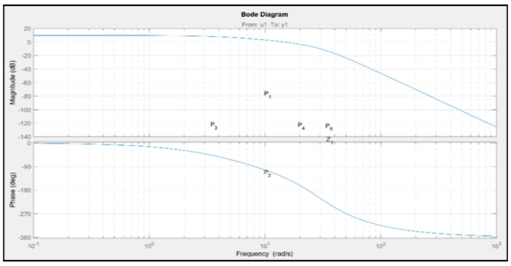

Fig. 8. Calculated bode plote from the estimated transfer function.

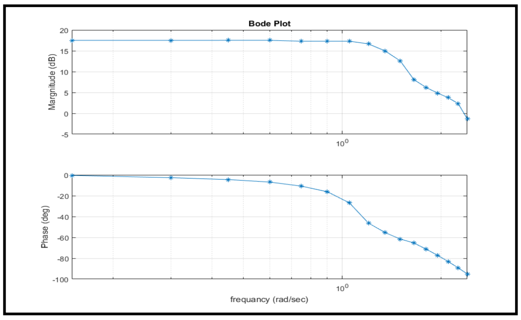

Fig. 9: Calculated bode plot from the experimental-collected data.

To study the stability of the estimated transfer function of the proposed system, analysis based on using root locus diagram has been demonstrated in Figure 10. It is clear from Figure 10 that the proposed system is stables as long as poles P1 and P2 are staying in the left hand side of the root locus diagram. In addition, it is clear that the system has a margin to stay stable as the operating proposed system at different frequency as long as we are in linear range.

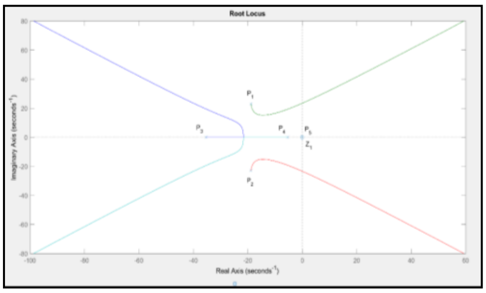

Fig. 10: Illustration of the paths of the roots and poles of the proposed system by using root locus diagram.

To validate the estimated transfer function, two experiments have been performed. The two experimented aimed to compare the actual system response with the estimated response from the system identification process in case of open loop test. Also, it was clear from Figure 11 that the estimate response completely followed the actual system response. Moreover, the second experiment showed that testing the system in case of open loop gave the same results. To conclude, the open loop response tests results highlighted the high accuracy of the estimated transfer function.

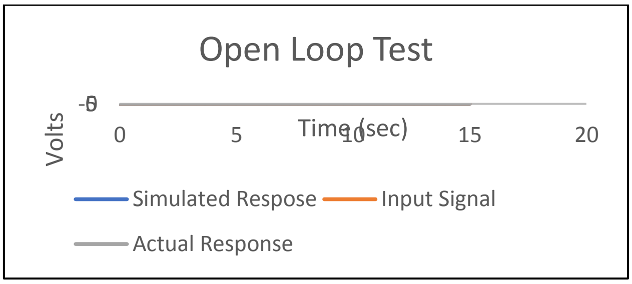

Fig. 11: Illustration of open loop test.

IV. DISCUSSION

The results shave been demonstrated that using the experimental data provide an accurate method to model and to identify the transfer function of the hydraulic system. It is worth mentioning that, this method is accurate as long as the system operating close to the linear bandwidth. Moreover, one of the major factors that helped us to get accurate identification of the transfer function of the hydraulic system is the proposed method of selecting the frequency and length of PRBS. The accurate identification has been proven by measuring the response of the system comparing with the simulated one.

V. CONCLUSION

In this paper, an experimental-based method for accurate identification of hydraulic system has been presented. The experimental results based on bode plot and root locus analysis demonstrated the high accuracy of the proposed method. Moreover, the open loop test demonstrated that the simulated output completely fits the actual output. The future work of our team is to design a suitable controller to control the position/velocity of the hydraulic cylinder in terms of controlling the input voltage to the variable displacement pump.

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