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MATHEMATICAL MODELLING AND ANALYSIS OF CARTRIDGE PROPORTIONAL VALVE

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ABSTRACT

In this study an experimental study was conducted to investigate of open-loop responses for a proportional cartridge valve. Velocity and displacement data were acquired in reference to the sinusoidal waves at the first stage of the experiment. In the second part a mathematical model was created using MATLAB System Identification Toolbox in Matlab Simulink © environment to state the entire system. Position data of the piston were transferred using LVDT (Linear Variable Differential Transformer) to the Simulink. In conclusion It was clearly seen that results of the theoretic mathematical equation and the transfer function acquired from experimental study was convergent 89.8%.

Keywords: Cartridge valve, cartridge proportional valve, hydraulic position control.

I. INTRODUCTION

The valve that is used the most in precision positioning systems is the hydraulic proportional valves (Muraru et al., 2002; Koçer, Canal and Güler, 2000, Swider, Wszolek and Carvalho, 2005). Academicians and researchers are studying on this field to increase the usability of these valves, reduce costs and improve their performance. However, there are very few studies on mathematical modelling with Proportional Cartridge valves and their response to sine wave.

İstif et. al. conducted a study on the control of the position of proportional valve controlled hydraulic cylinder system. In the study, position control was carried out for the proportional valve controlled hydraulic cylinder system where a simulink model was developed (İstif et. al. 2004).

Amirante et.al. conducted an experimental study on open-loop control with a PWM (Pulse Width Modulation) support of a hydraulic proportional valve (2007). After their experiments, they have observed an improvement of 16% to 75% in the proportional valve response times with the use of PWM control technique.

In 2011, Tian et.al. examined and simulated the 2-way cartridges valve structure in AMESIM program. The orthogonal test was applied to the valve by applying different spring hardness. Valve permeability according to different spring hardness was observed according to time. In this study, a method of valve structure was applied which was not tested before. The importance of the optimization of bow characteristics was emphasized.

In the literature survey, most studies focused on valve reaction times when study topics are considered. An important point to note in valve structure is the need to take into account the orifice structure and the opening and closing times. When we look at valve drive systems in general terms; PWM and PID are used as the valve driver. AMESIM and Matlab-Simulink programs were used for the mathematical model of the system.

In the light of the literature studies, general purpose of this study is to integrate to the Proportional Cartridge Valve system, to actuate with the PWM wave and to create the mathematical modelling in Matlab-Simulink program, and then to compare to the results of the experiment.

II. MATHEMATICAL MODEL

The output signals corresponding to the request signal were handled and the transfer function to express the system was created; the mathematical model was created by using the Matlab System Identification Toolbox. With this model, the slide dynamics of the valve will be handled entirely during the experiment.

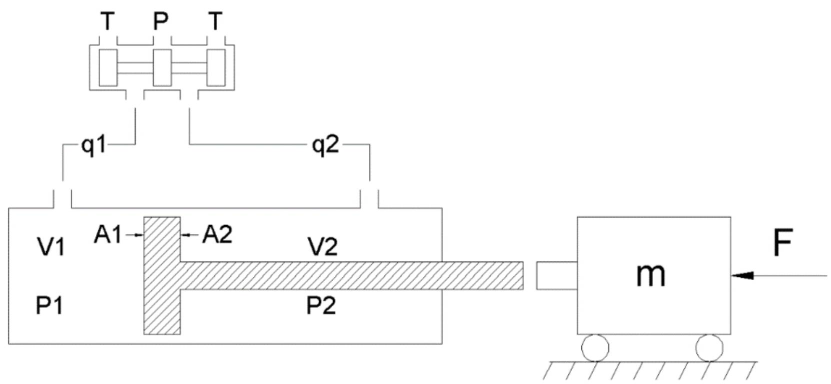

Figure 1. Physical Model of the System

Valve dynamics

The equations which characterize the flow to the sections q1 and q2 of the cylinder can be expressed as follows when the frictions and the leaks in the valve are ignored (Eq. 1.2.3.4.5.6).

$$q_1 = \begin{cases} for\ u \geq 0, & k_1 u\sqrt{P - P_1} \\ for\ u < 0, & k_2 u\sqrt{P_1 - T} \end{cases} \quad (1)$$

$$q_2 = \begin{cases} u \geq 0\ için, & -\ k_3 u\sqrt{P_2 - T} \\ u < 0\ için, & -\ k_2 u\sqrt{P - P_2} \end{cases} \quad (2)$$

k1, k2, k3 and k4 are valve orifice constants.

The correct purified valve dynamic is as follows;

$$Q_L = K_q x_v - K_c P_L \quad (3)$$

$$K_q = k_v c_d \omega \sqrt{\frac{1}{\rho}}\sqrt{P_s - sgn(x_v)P_L} \quad (4)$$

$$P_L = P_1 - P_2 \quad (5)$$

The transfer function of the position dynamics of the valve orifice versus the input current;

$$\frac{Y(s)}{I(s)} = \frac{K_q \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (6)$$

Piston Dynamics

Equation of the motion of the piston according to the second motion law of Newton (7)

$$m\ddot{x} = P_1 A_1 - P_2 A_2 - f_u \dot{x} - F \quad (7)$$

With these equations, when we consider the voltage applied to the proportional valve as the input and the position of the piston as the output, the transfer function (8)

$$\frac{Y(s)}{R(s)} = \frac{K_q \omega_n^2}{As^3 + 2\zeta\omega_n As^2 + A\omega_n^2 s + K_q \omega_n^2 K_{tk}} \quad (8)$$

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III. EXPERIMENTAL STUDIES

Some values of the Proportional Cartridge Valve must be determined numerically. These values are the viscous friction coefficient of the coil inductance and resistance values, the slider mass and the surrounding medium. Since it is theoretically difficult to calculate them, the study was started by recording the response of the system to the reference requests and extracting a transfer function representing the system.

The experiment assembly consists of the Hydraulic cylinder and hydraulic power unit providing the platform movement (Figure 2), Proportional Cartridge Valve connection (Figure 3), LVDT position measuring device (Figure 4), DC power supply and data collection electronic boards (Figure 5).

Figure 2. Experiment Assembly

The body of the experiment assembly consists of 20 mm, 25 mm, 30 mm thick ST37 material, 100x50 standard profile and 4 chrome plated ground spindles with a diameter of 40 mm centering the moving platform and linear ball bearings centering these spindles. The hydraulic cylinder is mounted on the body with a flange. The fixed platform is welded on the profiles using levels. The moving platform is connected with linear roller bearings to 4 pieces of Ø40 mm guide spindles to provide vertical axial movement. In addition, a platform is placed on the upper side of the chrome plated spindles which enable the centering of the moving platform. The vertical movement of the moving platform is provided by a double acting single-spindle hydraulic cylinder. The cylinder has two active areas of different sizes and opposite directions. The pipe of the hydraulic cylinder is manufactured in the standard of Ø65-50 and the spindle is manufactured from chrome plated material with a diameter of Ø30 mm. The highest operation pressure of this cylinder is 250 bar. In the hydraulic power unit of this study, a flange was used to provide a connection between the HYDR-APP brand hydraulic pump of HE series with a diameter of 160, electric motor and tank body (Figure 2).

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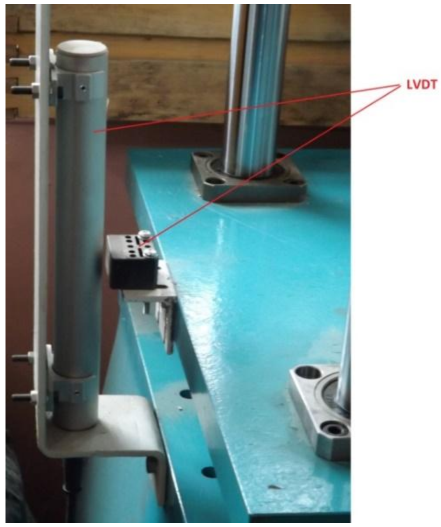

Figure 3. Proportional Cartridge Valve and Block

HYDRAFORCE SP08-47C proportional cartridge valve is used in the experiment assembly. The highest working pressure of the valve is 240 bar. The working rate of the valve is 11.4 l/min. This valve is mounted on the system with a special block with pressure relief valve on it (Figure 3).

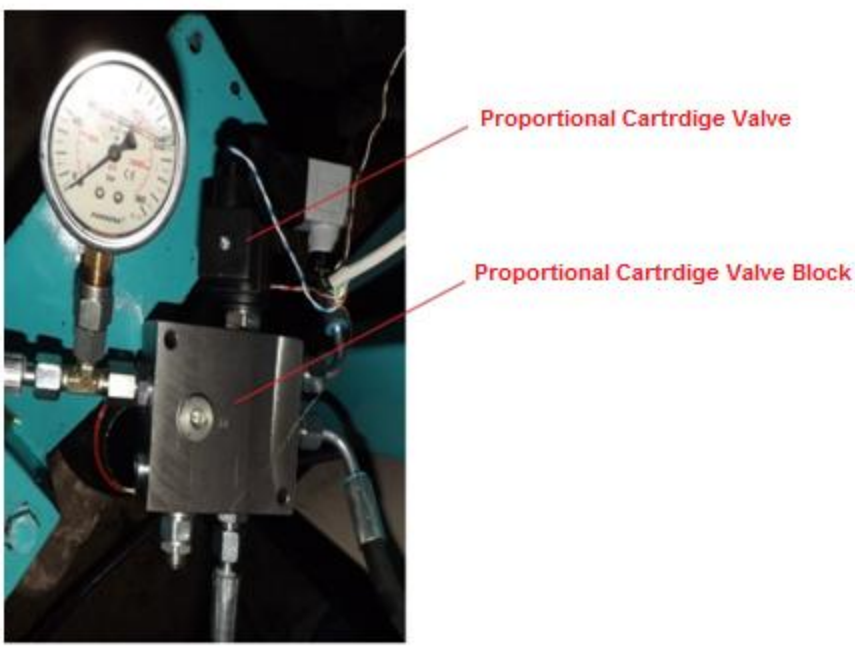

Figure 4. LVDT (Position Measuring Device)

LVDT capable of 25cm linear position measurement was used in the experiment assembly. Care has been taken to avoid axis misalignment during mounting to ensure that the measurements are accurate. The instantaneous position of the platform is easily transferred to the computer environment by LVDT (Figure 4).

Figure 5. Data Collection and DC Power Supply

In the experiment, a power supply is used to operate the data collection board and the valve driver circuits. Results from data collection board and LVDT are transferred to the computer environment (Figure 5).

In the experiment, a sinusoidal signal with an amplitude of 5V, a frequency of 1 rad/sec was used as request signal. As known; since the areas of the two surfaces of the piston are different, different transfer functions are obtained for both directions of the piston. In the forward direction, the system is driven by a pre-set sinusoidal signal and is provided not to receive a negative value, and vice versa for the other direction. Thus, the sinusoidal signal fluctuates between 0-10V. The request signal and the corresponding output signal are shown in Fig.

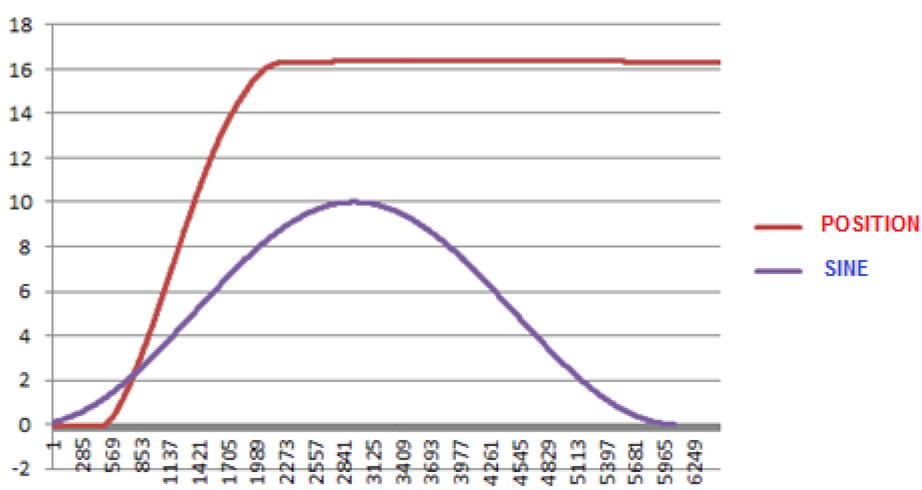

Figure 6. Response of the system to the sine wave

The ident interface in the System Identification Toolbox module of the MATLAB software is used to identify the experiment assembly in the computer environment. In the Ident interface shown in Figure 7, the blocks on the left are reserved for input data, and the blocks on the right are reserved for the models to be created. Modeling is done using the "Working Data" section. The "Validation Data" column shows the actual system data.

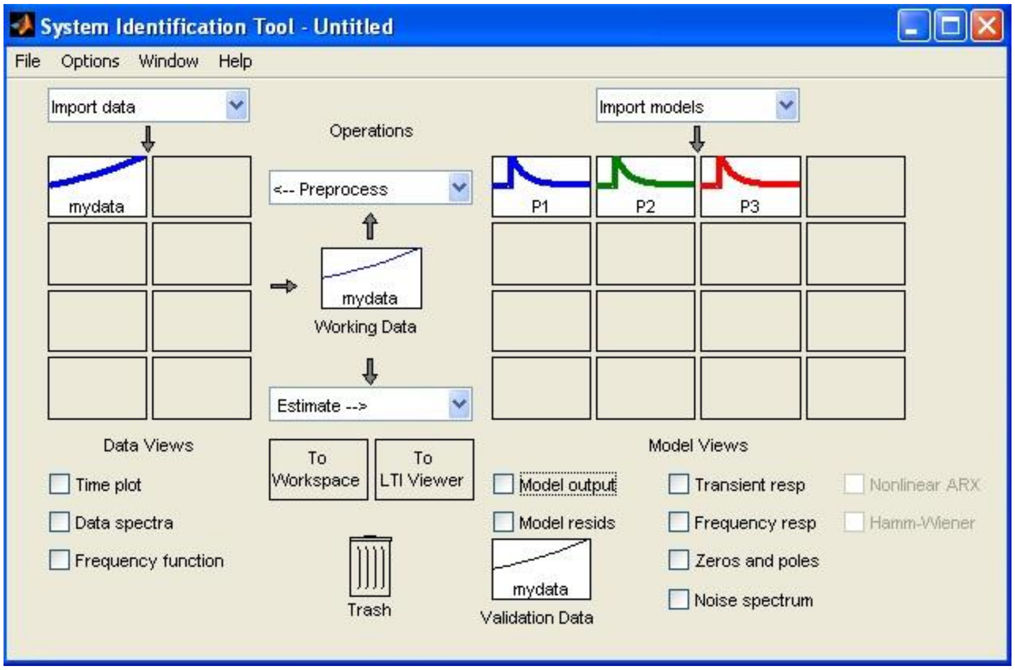

Figure 7. System Identification Tool

The request signal and slide position are loaded into the Ident interface. In this study, "Process Model" was selected from the options shown in Figure 8 of the program in order to express the system with a transfer function. This method adapts type zero or type one transfer function according to given request and response.

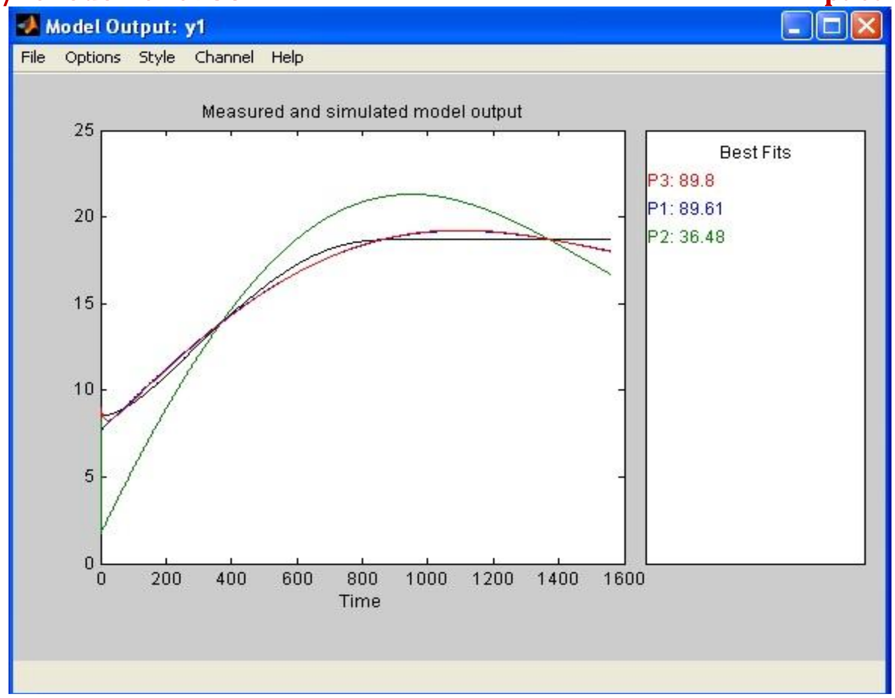

Figure 8. Convergence of the system's sine wave response to the transfer function

The transfer function is obtained in the direction of the results obtained from the test data graph given in Figure 8 (Equation 9).

$$\frac{Y_{(S)}}{X_{(S)}} = \frac{-2{,}842e-0{,}14s^2 - 1{,}998e-0{,}15s + 0{,}002668}{s^3 + 17{,}8s^2 + 1{,}316s + 0{,}0002992} \qquad (9)$$

The transfer function obtained defines the system in a ratio of 89.8%. The open loop transfer function from this closed-loop transfer function can be simply calculated theoretically (Equations 10, 11, 12).

Here,
U (s): Request signal,
Y (s): Piston position,
C (s): LVDT transfer function,
T (s): System's closed loop transfer function,
G (s): System's open loop transfer function.

$$G(s) = \frac{T(s)}{C(s) - C(s)T(s)} \qquad (10)$$

$$G_{(S)} = \frac{\dfrac{0{,}7837}{s^2 + 3{,}853s + 1{,}011\times10^{-5}}}{1 - \dfrac{0{,}7837}{s^2 + 3{,}853s + 1{,}011\times10^{-5}}} \qquad (11)$$

$$G_{(S)} = \frac{0{,}7837}{s^2 + 3{,}853s - 0{,}78368989} \qquad (12)$$

The transfer function obtained is simulated in computer environment using Matlab/Simulink. The diagram generated in Simulink is shown in Figure 9. The request signal and the piston position are shown in Fig.

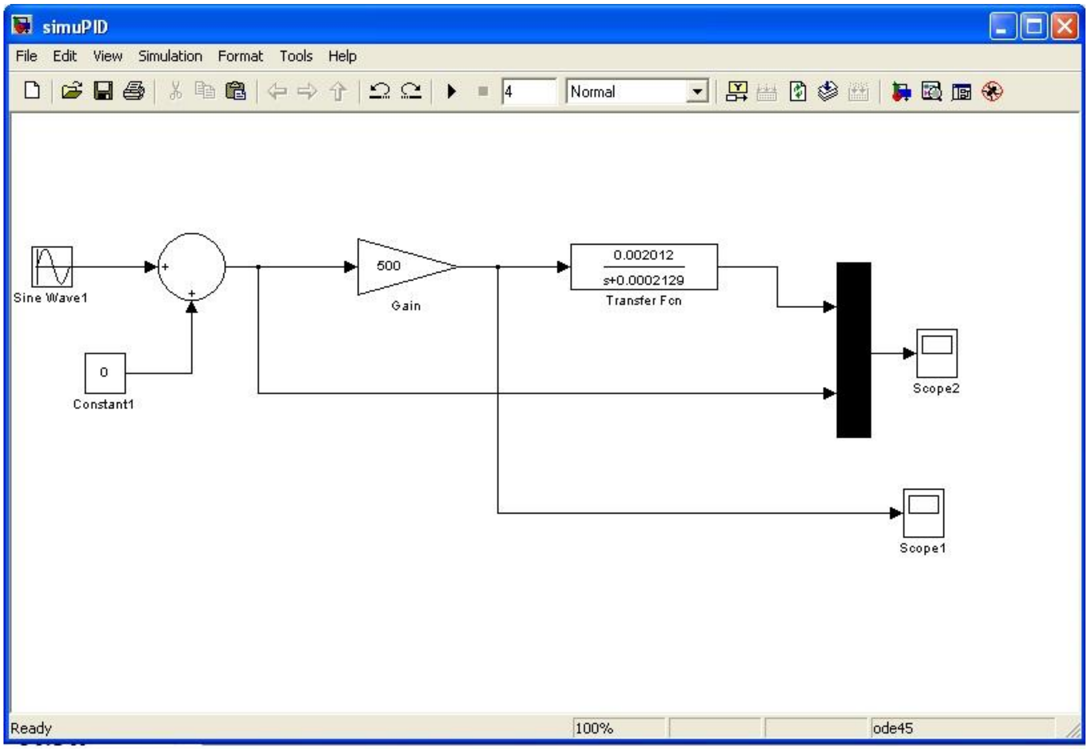

Figure 9. Matlab/Simulink environment

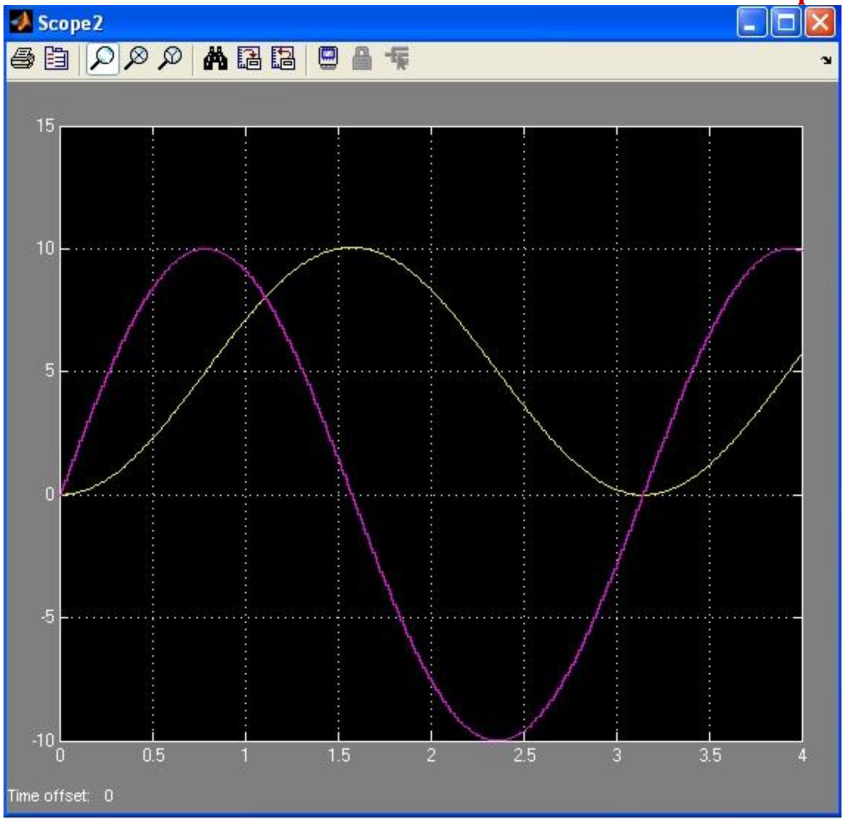

Figure 10. Matlab/Simulink sine wave and system response

IV. CONCLUSIONS AND RECOMMENDATIONS

In this study, mathematicalmodelling and analysis of Cartridge proportional valve was done. Firstly, mathematical modelling of the valve and the system were determined theoretically, then the transfer function was created with the Matlab System Identification Toolbox. With the transfer function obtained, the response of the system to the sinus signal is simulated.

With this study, mathematical models of proportional Cartridge valves were determined and experiments were successfully performed while there were few previous studies. The theoretical mathematical equation obtained and the transfer function determined after the experiment were compared and it was found that the two results converged to each other in a ratio of 89.8%.

It is expected that this work will be directed to the future studies. In further studies, other Cartridge valve types can be examined, and the velocity-time and position-time graphs created after the experiment can be compared to the catalogue values. Moreover, except for constant loads, all experiments can be repeated under variable loads and the results can be compared to each other

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