JTMAE
The Journal of
Technology,
Management, and
Applied Engineering

VOLUME 38, NUMBER 1

Jan-Mar 2022

Optimizing an Electrohydraulic Position Control System using the DOE Method

Article
Page 2

References
Page 14

Author

Dr. Yuqiu You, Ph.D.
Associate Professor in the Department of
Engineering Technology & Management
at Ohio University

Mustafa Shraim, Ph.D.
Assistant Professor in the Department of
Engineering Technology & Management
at Ohio University

Keywords:
Design of Experiment (DOE), Electrohydraulic System, Closed-Loop Control, PID Control, Performance Optimization

PEER-reviewed Research Paper

ATMAE
486 Cornell Road
Blairsville, PA 15717

www.atmae.org

Optimizing an Electrohydraulic Position Control System using the DOE Method

Dr. Yuqiu You is an Associate Professor of Engineering Technology and Management at Ohio University. She earned her B.E. degree from HuaZhong University of Science and Technology in China, MS from Morehead State University of Morehead, KY, and Ph.D. (Technology Management, 2006) from Indiana State University. Dr. You is currently teaching at Ohio University. Her research interests are in computer-integrated manufacturing, automation control, and remote control systems. Dr. You may be reached at youy@ohio.edu.

ABSTRACT

Hydraulic systems are widely used in industry, since they can produce large torques, high-speed responses with fast motions and speed reversals. Automatic control of hydraulic systems has evolved into an increasingly superior alternative for many industrial applications [3]. Advances in hydraulic hardware and electronics have combined to make the design and implementation of these systems more intuitive, reliable, cost effective, repeatable and user friendly. Controlling the position of a cylinder is one of the most demanding hydraulic motion control applications [11]. In a closed-loop position control system, the system performance is determined by various factors such as controller settings, system pressure, environment temperature, etc. To optimize system performance, a study was conducted utilizing Design of Experiment (DOE) on an automated hydraulic position control system. In the designed experiment, four controllable factors are considered at two different levels – three controller settings and the system pressure. The controller setting parameters include the proportional gain (P), the integral gain (I), and the derivative gain (D). These are the critical parameters for typical PID-based control systems [7]. The step response time and the position accuracy were selected as key measurements of the system performance. The step response time measures how fast the control system can respond to a position error, and the position accuracy measures how accurate the system is in terms of position control. Statistical analyses, including Analysis of Variance and factorial plots, were carried out using statistical software. The paper illustrates the physical control system in hardware setup and software programming, the DOE method applied, data collection, and statistical analysis. The results and future study are explained and discussed.

INTRODUCTION

This paper introduces a study collaborated between a Quality Management course and a Hydraulics course in the program of Engineering Technology and Management. The study demonstrated the implementation of design of experiments (DOE) in optimizing the performance of a real-world application.

Automatic control of hydraulic systems has evolved into an increasingly superior alternative for many industrial applications. According to the records from Parker Hannifin, a global leader in motion and control technologies, controlling the position of a hydraulic cylinder is one of the most demanding motion control applications [11]. In this study, an automated hydraulic position control system was designed to control the linear motion position of a hydraulic cylinder through a touch screen HMI (Human-Machine Interface). The major components of the system include a Parker 3L hydraulic cylinder, a position sensor, a DF Plus electrohydraulic servo valve, a PID controller, a touch screen HMI display, and a H-Pack hydraulic power supply. The control method applied is a classic PID (proportional, integral, and derivative) control.

In a typical closed-loop position control system like this, the system performance is determined by various factors such as controller settings, system pressure, environment temperature, etc. In order to optimize the system performance, this study utilized DOE methods. In the experiment, four controllable factors were considered at two different levels – three controller settings and the system pressure. The controller setting parameters include the proportional gain (P), the integral gain (I), and the derivative gain (D). These are the critical parameters for typical PID-based control systems. The system performance was measured in step response time and the position accuracy. The step response time measures how fast the control system can respond to a position error, and the position accuracy measures how accurate the system is in terms of position control. Statistical analysis, including analysis

Mustafa Shraim is an Assistant Professor in the Department of Engineering Technology & Management at Ohio University in Athens, Ohio. He received both of his B.S. and M.S. degrees from Ohio University, and a Ph.D. in Industrial Engineering from West Virginia University. He teaches courses in quality management systems, statistical quality control, and leadership. He has over 20 years of industrial experience as a quality engineer, corporate quality manager, and a consultant in quality management systems, statistical methods, and quality improvement. He is a Certified Quality Engineer (CQE) and Six Sigma Black Belt (SSBB) by ASQ, and a certified QMS Principal Auditor by IRCA. He is also an ASQ Fellow since 2007.

of variance (ANOVA), was used on the data collected from to the designed experiment. The paper illustrates the physical control system in hardware setup and software programming, the DOE method applied, data collection, and the statistical analysis. The results and future study are explained and discussed.

LITERATURE REVIEW

Position control of hydraulic systems is widely implemented in various industry applications, such as machine tool controls. The performance of such systems can be evaluated based on various measurements according to the requirements of specific industry applications. Research has been conducted in this area to improve the performance of hydraulic system position controls. L. Fei and P. XiWei's study has shown the improvement of tracking precision on position control by the use of self-adapting fuzzy-PD (proportional and derivative) strategy [5]. J. Guo, C. Ye and G. Wu have established a mathematical model of hydraulic system position control by using MATLAB and Simulink. Their study has approved the improvement of system performance in reduced overshoot and system response by applying the fuzzy neural network control strategy in the simulated mathematical model [4]. Z. Li and K. Xing also have verified approved system performance of position control in a hydraulic system on precision and response speed by implementing fuzzy PID control [6]. Most research studies on position control of hydraulic systems are focused on impacts of different control strategies and some of them are purely based on theoretical study of simulated models. None of these studies is suitable for improving system performance in industrial environment, and none of them considered the implementation of quality control methods which are more practical in real world.

In order to effectively and efficiently study the electronic hydraulic system using experimentation, a robust methodology with a feedback loop should be used. According to W. Edwards Deming, prediction requires theory and builds knowledge through systematic revisions based on comparison of prediction with observation [1]. For example, demonstrating a competency in an engineering lab requires instructions or a procedure. Based on the procedure, we predict a certain outcome when procedural steps are performed as prescribed. The outcome of the demonstration (observation) is compared to prediction (expectation). A noticeable difference between observation and expectation may require revision of the procedure (theory) then applying it again to gain knowledge.

A robust methodology for acquiring knowledge is the Deming Cycle of Plan-Do-Study-Act or PDSA. Deming refers to it as the Shewhart Cycle [9]. Figure 1 shows that the PDSA cycle is continuous and thus guarantees the temporal dimension for the theory of knowledge. In other words, knowledge is gained after each cycle and future cycles are undertaken with accumulated knowledge. Such knowledge can be gained through experimentation. The purpose of experimentation is to gain the knowledge about reducing and controlling variation in the process or the product by determining which process factors significantly impact the outcome [12]. Determining optimum conditions can be realized through advanced experimental methods such as Taguchi's Parameter Design [13].

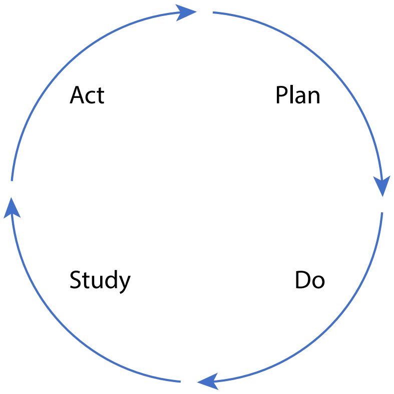

Figure 1: Plan-Do-Study-Act (PDSA) Cycle

For experiments to be run and analyzed efficiently, a scientific approach in planning must be followed. While one-factor-at-a-time is extensively used in experimentation through trial-and-error, design of experiment methods, particularly factorial design, have advantages over the one-factor-at-a-time methods. These advantages include, but not limited to, the ability to estimate interactions and utilize fractional factorial design. Table 1 shows the phases of the PDSA cycle along with what each phase involves when using the traditional DOE methodology.

Table 1: PDSA Details

Phase	Description
Plan (P)	• Identify controllable factors affecting performance • Identify performance (response) variables • Design the experiment (e.g., factorial, or fractional factorial design)
Do (D)	• Run the experiment • Collect data
Study (S)	• Analyze data graphically and statistically. • Use earlier analysis to build a temporal picture.
Act (A)	• What was learned and what changes are needed? • Are there issues with the learning process? • If another PDSA cycle is needed, go back to Plan (P)

In DOE methodology, the process allows for appropriate data to be collected and analyzed using graphical and statistical methods for objective and valid conclusions [10]. Additionally, economic considerations such as the cost for running each of experimental combinations are always factored in when utilizing design of experiments [8]. If process historical data is available, regression analysis may be conducted to learn how included factors affect a response. However, design of experiments is a planned methodology while regression analysis is not. Therefore, without the benefit of design and forethought, regression analysis will have less power than a comparable controlled, designed experiment.

PID THEORY AND CLOSED-LOOP CONTROL

A typical closed-loop control system contains the process variable, sensor feedback, the set point, the compensator, the actuator output, and the system to be controlled, as shown in Figure 2.

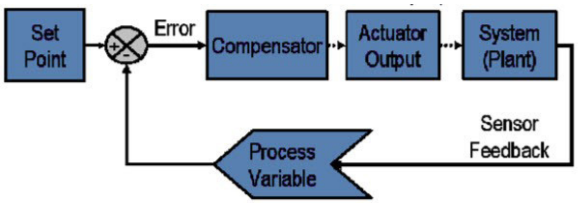

Figure 2: A closed-loop control system (Courtesy of National Instruments)

The system is the physical setup to be controlled by the controller, such as the hydraulic position control system in this project. The process variable is the parameter that needs to be controlled, like the position of the hydraulic cylinder in this case. The sensor feedback is the signal sent from the sensor based on the current measurement. The sensor used in this study is the position sensor integrated on the hydraulic cylinder. The set point is the desired value for the process variable. The set point for this hydraulic position control system is the set position of the cylinder. At any given moment, the difference between the process variable and the set point is used by the compensator, the control algorithm programmed to the controller, to calculate the desired actuator output to drive the system (the hydraulic system).

The PID algorithm is a classic and robust control algorithm that determines the actuator output by summing up three different components derived from the error to reduce the response time and minimize the steady state error. These three components include the proportional component, the integral component, and the derivative component. A block diagram of a basic PID control algorithm indicating all three components is displayed below in Figure 3.

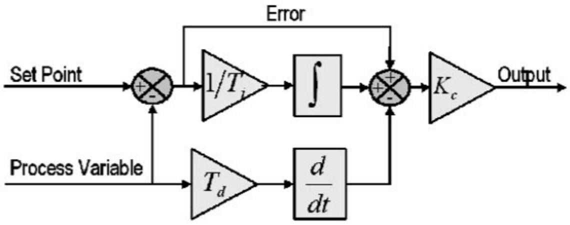

Figure 3: A basic PID control algorithm (Courtesy of National Instruments)

The PID algorithm also is described in the format of an equation as:

$$u(t) = ke(t) + k_i \int_0^t e(t)dt + k_d \frac{de}{dt}$$

where u is the actuator output and e is the control error (the difference between the process variable and the set point). The control parameters are proportional gain k, the integral gain k_i, and the derivative gain k_d.

As illustrated in the equation above, the proportional component acts on the current value of the error. The output of this component is proportional to the error signal. The error will decrease with increasing gain value, but the system could become more oscillatory and unstable. The integral component sums the error signals over time and provides an output proportional to the overall error. Therefore, the integral output will continually increase over time unless the error is zero. The system can respond to errors faster for larger integral gains, but the system also becomes unstable. The derivative component is proportional to the rate of change of the process variable. Therefore, the result will decrease the output if the process variable is increasing rapidly. Increasing the derivative time will cause the control system to respond strongly to error signals and then increase the speed of the overall system response. If the sensor feedback signal is noisy or the control loop rate is too slow, the derivative response can make the control system unstable. Therefore, determining three different PID gains for the control algorithm is critical for the performance of the hydraulic position control system in this study.

SYSTEM OVERVIEW

The Electrohydraulic position control system consists of a hydraulic cylinder, a proportional valve, a position sensor, a fluid PID controller, and a HMI touch screen. The specifications of these major hardware components are listed in Table 2.

Table 2: List of hardware components

Part Name	Component Type	Part Number
Parker Fluid PID Controller	PID controller	
DF Plus Valve	Proportional directional control valve	D1FPE50FB9NB00 20
Parker 3L Cylinder	Hydraulic cylinder	01.50 F3LLUS23A 12.000
Parker H-Pak	Hydraulic power supply	H1B2 7T10P0X13909/13
Parker HMI	HMI display	XPR06VT-2P3

The layout of the system with major components is shown below in Figure 4.

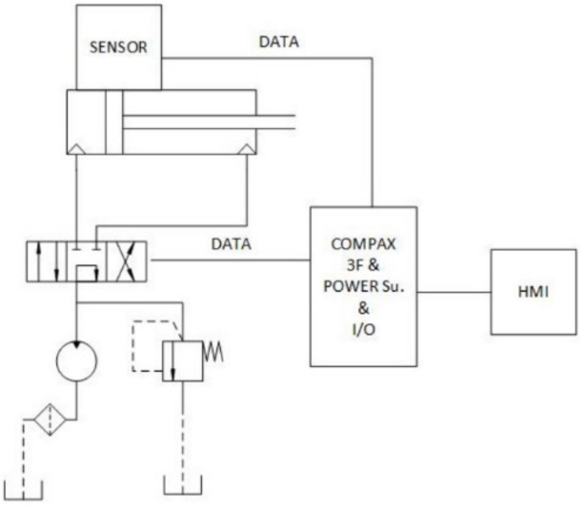

Figure 4: System layout with major components

The controller was programmed in CODESYS software and a PID control method was implemented [2]. The DF Plus Valve from Parker was used as the proportional directional control valve for this system. The proportional directional control valve controls the position of the cylinder based on DC signals ranging from -10v to +10v. A linear variable differential transformer (LVDT) provides position feedback to validate the cylinder position for improved accuracy and repeatability. The LVDT generates a feedback voltage proportional to the position change of the cylinder. The feedback voltage is then used by the controller to determine the control variable of the system. A picture of the system physical setup is shown in Figure 5.

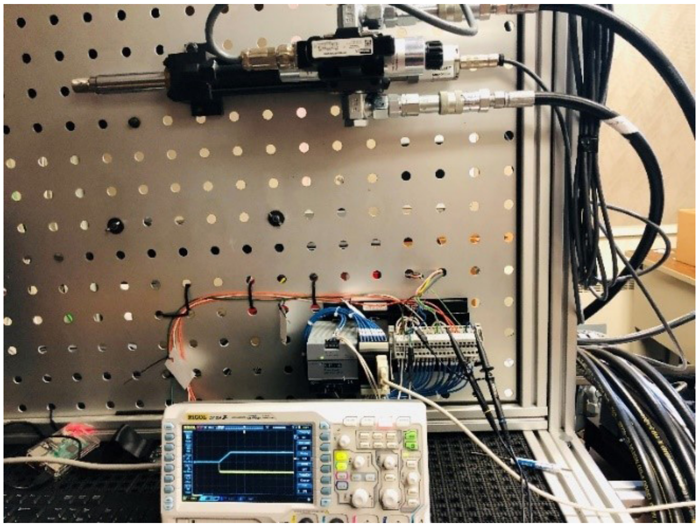

Figure 5: Picture of the system physical setup

An HMI interface was developed to provide a control panel to the position control system. The interface was programmed in Interact Xpress software, the layout of the control is shown in Figure 6.

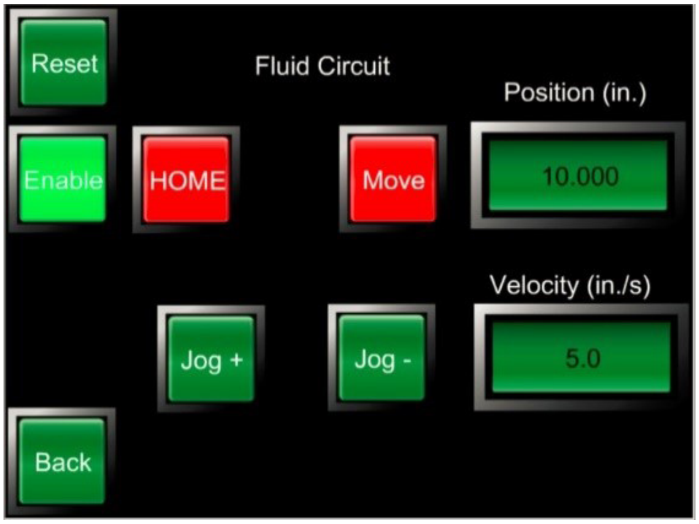

Figure 6: Position control panel

The control panel contains seven buttons and two variable input boxes. The Enable and Reset buttons are Boolean buttons to enable the proportional valve and reset the input variables for position and velocity control, respectively. The Home button brings the cylinder piston to the pre-configured home position, and the Move button enables the motion control according to the input variables. Two Jog buttons (Jog+, Jog-) are used to allow manual jogging of the cylinder piston in both directions. There are variable input boxes to set position and velocity values for the motion control. A Back button can be used to navigate back to the previous window. The interaction between this HMI interface and the application in Parker Servo Manager software is based on data tags created in Interact Xpress and the connection between the data tags and variables used in CODESYS program.

EXPERIMENTAL DESIGN FOR SYSTEM OPTIMIZATION

In a closed-loop position control system, system performance can be analyzed based on the step response time (rise time), the steady-state error, and the peak overshoot. Due to the limitation of time and equipment, the step response time is selected as the parameter to be collected and analyzed in this project. The step response time is defined as the time the system responds to a step input signal from 10% to 90% of the steady state response. The steady-state error describes the accuracy of position with respect to target position. In this study, the step response time and position accuracy are measured and analyzed using design of experiments.

As mentioned above, four controllable factors are selected: the proportional gain (P), the integral gain (I), the derivative gain (D) of the controller setting, and the system pressure. The P, I, and D gains play critical roles in the controller's control behavior. For example, P gain is the proportional gain of the PID controller. Increasing the proportional gain will increase the amount of current to the valve proportional to the amount of error the system produces. Therefore, the response time to the step signals should decrease. However, increasing the P gain further will cause the valve current to quadruple which may result in oscillatory performance, and the valve could be damaged.

With four controllable factors to consider at two levels each (24), a full factorial design was generated and displayed in Table 3. This factorial design allows us to investigate the main effects as well as their possible two-way interactions. This factorial design has 16 experimental combinations (runs).

Table 3: Experimental Design

ID	Factor 1	Factor 2	Factor 3	Factor 4
1	-1	-1	-1	-1
2	-1	-1	-1	1
3	-1	-1	1	-1
4	-1	-1	1	1
5	-1	1	-1	-1
6	-1	1	-1	1
7	-1	1	1	-1
8	-1	1	1	1
9	1	-1	-1	-1
10	1	-1	-1	1
11	1	-1	1	-1
12	1	-1	1	1
13	1	1	-1	-1
14	1	1	-1	1
15	1	1	1	-1
16	1	1	1	1

One of the constraints for running an experimental design in real life situations is the amount of time it takes to run the whole experiment including changing factors from one level to another. Therefore, it is important to minimize the time it takes so that the total research and development time is reduced. This becomes more urgent if the process is already in production and needs to be taken out for running the experiment. It was determined that changing the *Pressure* setting from low to high, or vice versa, would take the longest of any factor setting changes. Therefore, *Pressure* was assigned to Factor 1 in Table 3 which is evident with actual levels in Table 4. This means that it will only have to be changed once (from low to high) during the entire experiment. The P, I, and D gains can be readily configured through the controller interface software. Therefore, ordering these three factors from most difficult to easiest for setting changes would not cause any delays. Additionally, randomization for carrying out the experimental runs was not needed since no systematic build-up of variation is expected from changing factors from one level to another. Table 4 displays the actual levels for the controllable factors with the data collected for the *Response Time* in milli-seconds as well as the percentage of *Deviation from Target*. The target position was set at 4.895 inches which is the actual maximum extension position of the cylinder used in this study. Actual positions are also included in Table 4 for reference.

DATA ANALYSIS

The data from the experiment was analyzed utilizing a statistical software program. The software was used to generate the design first that is appropriate for the case. As mentioned above, a full factorial design at two levels was chosen. The statistical software was also utilized to generate a data collection sheets for Response Time and Position. The Deviation from Target was calculated accordingly. The analysis conducted includes ANOVA as well as factorial and interaction plots. It should be mentioned here that all three-way interactions or higher were not included in the model and considered negligible (random variation). Therefore, they are used to estimate the error term in ANOVA. The first part of the analysis deals with Response Time which should be minimized. Table 5 displays results from ANOVA. Based on the analysis, both the *Derivative Gain* and *Proportional Gain* are statistically significant at α=0.05 level. The *Proportional Gain* is highly significant and may require more attention (control) in applications. It should also be mentioned that *Pressure*, although not significant at α=0.05, appears to be important. Figure 7 puts the significance of these factors in perspective. Additionally, the interaction between *Derivative Gain* and *Proportional Gain* in Table 5 shows a significant effect. This means that the impact of changing *Derivative Gain* from low to high or vice versa depends on which level of *Proportional Gain* is set. Another interaction close to being significant at is *Proportional Gain* and *Pressure*.

Table 4: Experimental Data

ID	Pressure	Proportional Gain	Integral Gain	Differential Gain	Response Time (ms)	Position (in)	Dev from Target
1	400	10	0	-100	4,250	4.854	0.838%
2	400	10	0	100	10,000	5.019	2.533%
3	400	10	99.9	-100	6,600	4.859	0.735%
4	400	10	99.9	100	9,600	5.011	2.370%
5	400	1000	0	-100	720	5.311	8.498%
6	400	1000	0	100	720	5.31	8.478%
7	400	1000	99.9	-100	720	5.31	8.478%
8	400	1000	99.9	100	720	5.305	8.376%
9	800	10	0	-100	4,300	4.865	0.613%
10	800	10	0	100	4,700	5.028	2.717%
11	800	10	99.9	-100	5,500	4.908	0.266%
12	800	10	99.9	100	7,000	5.037	2.901%
13	800	1000	0	-100	700	5.296	8.192%
14	800	1000	0	100	700	5.305	8.376%
15	800	1000	99.9	-100	700	5.3	8.274%
16	800	1000	99.9	100	700	5.304	8.355%

The mean plots of factors (main effects) for the *Response Time* are displayed in Figure 8 and the interactions in Figure 9. These figures provide information on whether the statistically significant effects found in the ANOVA table are practically significant. They also indicate at what levels the insignificant effects should be left in future experiments.

Table 5: Analysis of Variance for Response Time

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Der Gain	1	7088906	7088906	6.94	0.046*
Int Gain	1	1856406	1856406	1.82	0.235
Prop Gain	1	133807056	133807056	131.03	0.000*
Pressure	1	5096306	5096306	4.99	0.076
2-Way Interactions					
Der Gain *Int Gain	1	170156	170156	0.17	0.700
Der Gain*Prop Gain	1	7088906	7088906	6.94	0.046*
Der Gain*Pressure	1	2932656	2932656	2.87	0.151
Int Gain*Prop Gain	1	1856406	1856406	1.82	0.235
Int Gain*Pressure	1	150156	150156	0.15	0.717
Prop Gain*Pressure	1	4917306	4917306	4.82	0.080
Error	5	5105781	1021156		
Total	15	170070044			

*Significant at a=0.05 (See Pareto chart and factorial plots)

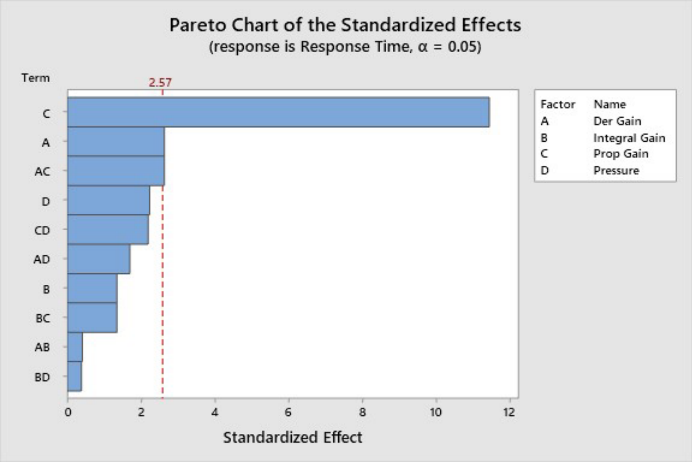

Figure 7: Pareto Chart of Significant Effects for Response Time

The second part of the analysis is related to the percentage of *Deviation from Target*, which should be minimized. Both the *Derivative Gain* and *Proportional Gain* are statistically significant at α=0.05 level as shown in Table 6. It is obvious that *Proportional Gain* is highly significant here as well. Additionally, the interaction between *Derivative Gain* and *Proportional Gain* in Table 6 shows a significant effect. This means that the impact of changing *Derivative Gain* from low to high or vice versa depends on the setting of *Proportional Gain*. As a result, care should be exercised when changing the level of one

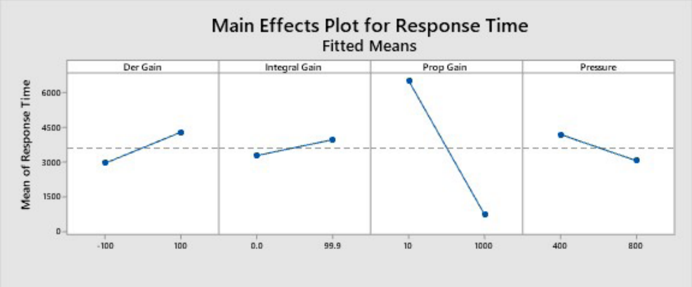

Figure 8: Plots of Factors (Main Effects) for Response Time

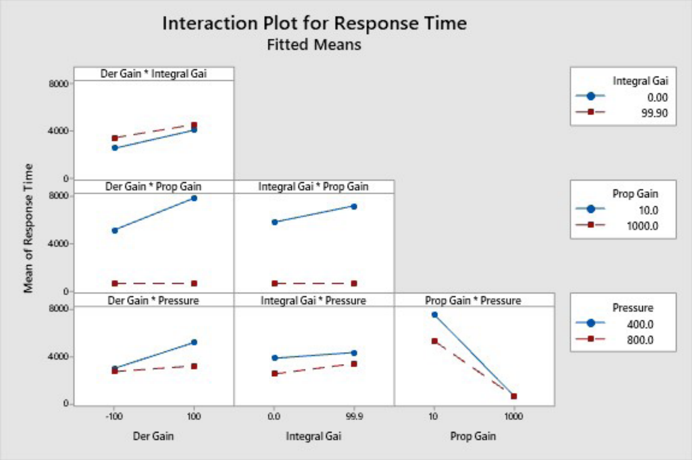

Figure 9: Plots of Interactions for Response Time

factor without studying the impact from the interaction. Another interaction that is close to being significant at is *Derivative Gain* and *Pressure*. Figure 10 puts the magnitude of significance of these effects in perspective.

The mean plots of factors (main effects) for the percentage of *Deviation from Target* are displayed in Figure 11 and the interactions in Figure 12. As the case for *Response Time*, these figures provide information on whether the statistically significant effects found in the ANOVA table are practically significant. They also indicate the levels at which insignificant effects should be left when conducting future experiments. Typically, they are left at the most economical level of operation.

Table 6. Analysis of Variance for Deviation from Target

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Der Gain	1	0.000422	0.000422	154.67	0.000*
Int Gain	1	0.000002	0.000002	0.55	0.491
Prop Gain	1	0.018262	0.018262	6701.11	0.000*
Pressure	1	0.000002	0.000002	0.86	0.396
2-Way Interactions					
Der Gain*Integral Gain	1	0.000001	0.000001	0.19	0.683
Der Gain*Prop Gain	1	0.000393	0.000393	144.09	0.000*
Der Gain*Pressure	1	0.000020	0.000020	7.41	0.042*
Integral Gain*Prop Gain	1	0.000001	0.000001	0.31	0.602
Integral Gain*Pressure	1	0.000001	0.000001	0.19	0.683
Prop Gain*Pressure	1	0.000003	0.000003	0.98	0.368
Error	5	0.000014	0.000003		
Total	15	0.019119			

*Significant at *a*=0.05 (See Pareto chart and factorial plots)

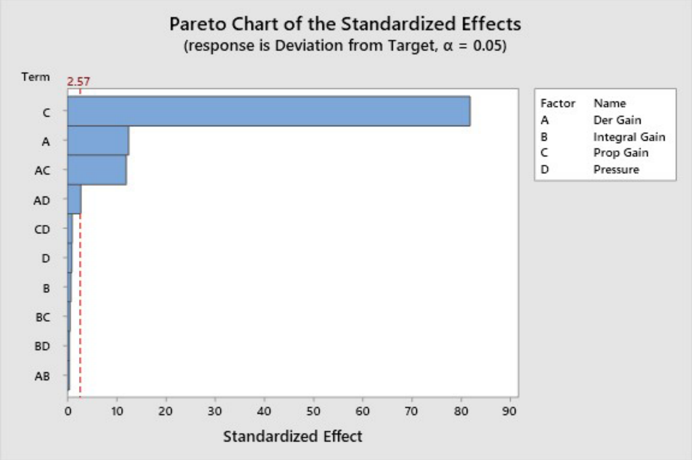

Figure 10. Pareto Chart of Significant Effects for Deviation from Target

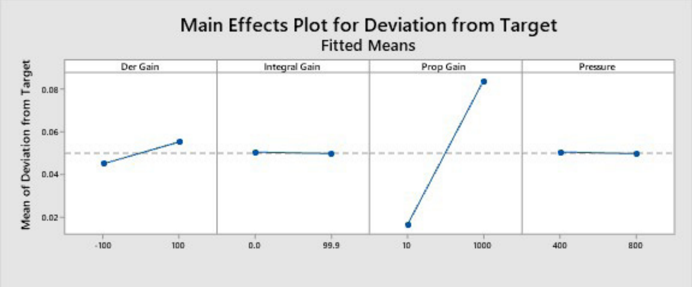

Figure 11: Plots of Factors (Main Effects) for Deviation from Target

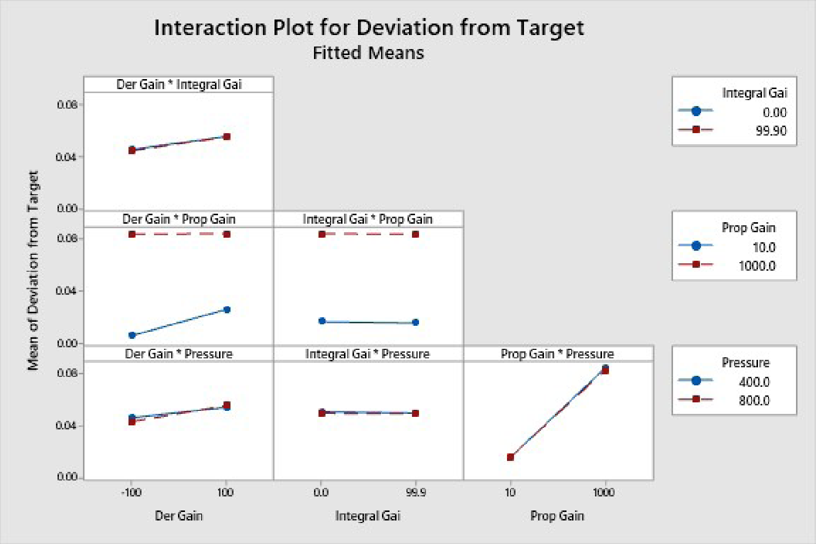

Figure 12: Plots of Interactions for Deviation from Target

DISCUSSION OF RESULTS

After evaluating the analyses for both *Response Time* and the percentage of *Deviation from Target*, we can draw the following conclusions:

- The *Proportional Gain* setting has the most significant effect on both *Response Time* and the percentage of *Deviation from Target*. However, there is a conflict here in the fact that increasing the *Proportional Gain* tends to decrease *Response Time* while, at the same time, increasing *Deviation from Target*. While decreasing the *Response Time* is desirable, increasing the *Deviation from Target* is not. The reason for that is in the fact that increasing the *Proportional Gain* of the PID controller will increase the amount of current to the valve proportional to the amount of error the system produces. Therefore, the response time to the step signals should decrease but the error produced would make it less likely to hit target. Since these are competing objectives (i.e., shortest response time and on-target position), the actual application of the electrohydraulic system would determine which objective is more important.

- The *Derivative Gain* setting seems to decrease both the *Response Time* and *Deviation from Target*. Therefore, keeping the factor at lower settings seems to be desirable.

- While changing the *Pressure* setting from 400 to 800 PSI made no impact on the *Deviation from Target*, it did have an impact of over one second on *Response Time* (from 3,037 to 4,166 ms). If one second is not practically significant, it may be economically desirable to keep this system pressure at the lower setting.

- *Integral Gain* has no significant effect on either the *Response Time* or *Deviation from Target* and can be set where economically feasible.

- The interactions *Proportional Gain x Pressure* as well as *Derivative Gain x Pressure* on *Response Time* should be considered when setting up the process. The *Pressure* setting has low to no impact on the *Response Time* when *Derivative Gain* is set at the low level. On the other hand, *Pressure* has low to no impact on the *Response Time* when *Proportional Gain* is set at higher levels.

The results from the statistical analysis indicate how the controllable factors might impact the performance in terms of the response time and the deviation from the target. In real world applications, this type of electrohydraulic position control system can be optimized according to the real needs of the application. The results can be us as guidelines with sets of ranges for these studied controllable factors.

FUTURE RESEARCH

To continue this research in the future, factors determined to be significant will be used in future experiments for optimization based on the application at hand. This may include more levels to investigate and whether the relationship is linear or nonlinear in nature within the range of experimentation. Additionally, and since real-life applications may have fluctuation in environmental (noise) conditions, ambient temperature and humidity should be studied to determine their effect and select the best settings that are least sensitive to such fluctuations. This can be realized by using Taguchi's experiments with signal-to-noise ratios for the analysis

REFERENCES

1. Deming, W. E. (2018). *The new economics.* 3rd ed., Cambridge, MA: The MIT Press.
2. Hanssen, D. (2017). *Programmable logic controllers: A practical approach to IEC 61131-3 using CODESYS.* Wiley.
3. Fundamentals of motion control. (2014). Retrieved February 8, 2017, from http://www.ni.com/white-paper/3367/en/.
4. Guo, J., Ye, C., & Wu, G., 2019, Simulation and research on position servo control system of opposite vertex hydraulic cylinder based on fuzzy neural network, 2019 IEEE International Conference on Mechatronics and Automation (ICMA), pp. 1139-1143, doi: 10.1109/ICMA.2019.8816371.
5. Li, F., & Peng, X., 2015, On application of proportional valve-controlled hydraulic cylinder position servo system, 34th Chinese Control Conference (CCC), pp. 3642-3647, doi: 10.1109/ChiCC.2015.7260202.
6. Li, Z., & Xing, K., 2017, Application of fuzzy PID controller for electro-hydraulic servo position control system, 2017 3rd IEEE International Conference on Control Science and Systems Engineering (ICCSSE), pp. 158-162, doi: 10.1109/CCSSE.2017.8087915.
7. Liu, B., & Tang, W. (2008). *Modern control theory.* Beijing: China Machine Press.
8. Mitra, Amitava. (2016). *Fundamentals of quality control and improvement,* 4th Edition, Wiley.
9. Moen, R., and Norman, C. (2009), The history of the PDCA Cycle, Proceedings of the 7th ANQ Congress, Tokyo 2009".
10. Montgomery, D. C. (2013). *Design and analysis of experiments,* 8th ed., Wiley.
11. Parker Hannifin Corporation (2007). *Electrohydraulic system engineering.*
12. Ross, P. J. (1996). *Taguchi techniques for quality engineering,* 2nd ed., McGraw Hill.
13. Taguchi, G., Chowdhury, S., & Taguchi, S. (2000). *Robust engineering,* McGraw Hill.