1. Siti Fatimah SULAIMAN[*,1], **2. Nurul Aini NGATENI**[1], **3. Khairuddin OSMAN**[1], **4. Sharatul Izah SAMSUDIN**[1], **5. Noor Asyikin SULAIMAN**[1], **6. Noorhazirah SUNAR**[2]
Centre for Telecommunication Research and Innovation (CeTRI), Fakulti Teknologi dan Kejuruteraan Elektronik dan Komputer, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia (1)
Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia (2)
ORCID: 1. 0000-0001-8251-8038

doi:10.15199/48.2024.02.36

Modeling and Development of Predictive Controller for Positioning Control of Electro-Hydraulic Actuator (EHA) System

Abstract. *An Electro-Hydraulic Actuator (EHA) is a hydraulic system that is commonly used in applications that require high power concentrations, efficient energy dissipation, or exceptionally high forces. The crucial part of this system is to control the position of its cylinder stroke at the desired position. Failure to properly control the position will cause the cylinder stroke position to be inaccurate. This study is proposed for this reason. The scope of this study consists of modeling and controlling the EHA positioning system. In this study, the system identification technique is used to model the EHA system, while predictive controller specifically Predictive Functional Controller (PFC) is proposed as a new strategy to control the position of the EHA system. Both modeling and controlling processes in this study fully utilise MATLAB software. To evaluate the effectiveness of the proposed PFC, the positioning performance of the PFC was compared with the basic controller (Proportional-Integral-Derivative (PID)) in terms of transient response performance. Comparison between the proposed PFC and the classical PID controller based on MATLAB Simulink showed that PFC can be used to control the EHA positioning system, however, the speed response of the system can be improved through certain modifications in the PFC algorithm.*

Streszczenie. *Siłownik elektrohydrauliczny (EHA) to układ hydrauliczny, który jest powszechnie stosowany w aplikacjach wymagających dużej koncentracji mocy, wydajnego rozpraszania energii lub wyjątkowo dużych sił. Kluczową częścią tego systemu jest sterowanie położeniem skoku cylindra w żądanej pozycji. Brak właściwej kontroli pozycji spowoduje, że pozycja skoku cylindra będzie niedokładna. To badanie jest proponowane z tego powodu. Zakres tego badania obejmuje modelowanie i sterowanie systemem pozycjonowania EHA. W tym badaniu do modelowania systemu EHA wykorzystano technikę identyfikacji systemu, podczas gdy sterownik predyktywny, w szczególności Predictive Functional Controller (PFC), został zaproponowany jako nowa strategia kontrolowania pozycji systemu EHA. Zarówno procesy modelowania, jak i sterowania w tym badaniu w pełni wykorzystują oprogramowanie MATLAB. Aby ocenić skuteczność proponowanego PFC, wydajność pozycjonowania PFC została porównana z podstawowym regulatorem (proporcjonalno-całkująco-różniczkującym (PID)) pod względem wydajności odpowiedzi na stany przejściowe. Porównanie proponowanego PFC z klasycznym regulatorem PID opartym na MATLAB Simulink wykazało, że PFC może być wykorzystany do sterowania systemem pozycjonowania EHA, jednak odpowiedź prędkościowa układu może zostać poprawiona poprzez pewne modyfikacje algorytmu PFC. (**Modelowanie i rozwój sterownika predykcyjnego do sterowania pozycjonowaniem układu siłownika elektrohydraulicznego (EHA)**.)*

Keywords: Hydraulic, System Identification, Predictive Controller, PID Controller
Słowa kluczowe: Hydrauliczny, Identyfikacja Systemu, Kontroler Predykcyjny, Kontroler PID

Introduction

A. Electro-Hydraulic Actuator (EHA) System

An Electro-Hydraulic Actuator (EHA) system is one of the most common basic drive systems used in industrial processes and engineering practice. EHA system uses fluid pressure to facilitate mechanical movement. EHA can be used for various applications, such as material testing, machine tools, and many other types of industrial machinery. Furthermore, EHA systems are found to be widely used in the industry where the main operation is to control the position.

EHA system (as shown in Figure 1) integrates various components such as hydraulic cylinders, valves, and sensors in a single system. EHA system uses hydraulic power to facilitate mechanical operation, and the mechanical motion gives an output in terms of linear, rotary, and oscillatory motion.

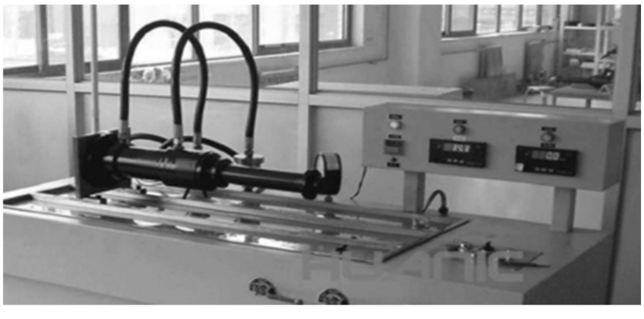

Fig.1. EHA system

However, the most difficult part when dealing with the EHA system is to accurately control the position of its cylinder stroke at the desired position. Controlling the EHA positioning system at the desired position is very challenging and difficult due to the issues of nonlinearities and uncertainties in the system itself [1]. Controlling the EHA positioning system also becomes more complicated with the need to simultaneously consider the accuracy of the system and other factors, such as the response time and stability of the system [2]. Apart from the control aspect, the modeling aspect is also an aspect that should be paid considered when dealing with the EHA system. Improper modeling will result in inaccurate characteristics and dynamics of the EHA system [3]; hence, affecting the positioning performance of the developed controller [4].

Therefore, this study proposes the system identification technique to determine the mathematical model of the EHA system, meanwhile, the predictive controller is proposed as the main controller to control the position of the cylinder stroke of the EHA system. MATLAB software will be used for both modeling and controlling processes. In order to evaluate the effectiveness of the proposed predictive controller, the positioning performance of the proposed predictive controller will be compared with the classical Proportional-Integral-Derivative (PID) controller in terms of transient response. Finally, a comparative study based on simulation tests will be analysed and discussed to identify which controller delivers better positioning performance in terms of transient response.

B. Modeling of EHA System using System Identification Technique

System modeling can be divided into two approaches: 1) theoretical (physical law), and 2) experimental. The theoretical approach, which requires expert and thorough knowledge of the system, is hard to apply [5]. The experimental approach, in contrast, requires only input and output data pairs to obtain a system model and is more often applied due to its ease of application [6]. The experimental approach is also known as system identification. Identification is the exercise of developing a mathematical relationship (model) between the causes (inputs) and the effects (outputs) of a system (process) based on observed or measured data. Stated otherwise, identification establishes a mathematical map between the input and output spaces as determined by the data [4]. In the study, the use of the experimental will be considered.

Most researchers used the experimental approach due to its simplicity and effectively saves more time compared to the theoretical approach. Rahmat et al. (2010) reported using the system identification technique to model the EHA system [7]. Rahmat et al. (2010) have modeled the EHA system in their study by using the fourth-order linear Auto-Regressive with eXogenous input (ARX) model. According to Rahmat et al. (2010), the model is acceptable to represent the real EHA system used in their study since the model successfully achieved 92.8% of fitting based on model validation.

Ling et al. (2012) also focused on modeling the EHA system based system identification approach. In the study, the linear ARX model was chosen as the model structure for the EHA system [2]. According to Ling et al. (2012), the linear model is preferred to be chosen as the model in the study since it is much simpler and can represent the real EHA system with high precision. Moreover, the system identification approach is also easy to apply as it requires only stimulus-response data pairs of the system. As a result, the third-order linear ARX is chosen as the model for the EHA system used in the study by Ling et al. (2012).

Apart from Rahmat et al. (2010) and Ling et al. (2012), Parvaresh and Mardani (2019) in [3] also reported applying the system identification technique to model the EHA system. Parvaresh and Mardani (2019) argue that the second-order ARX model is adequate to represent the EHA system used in their study. The identified ARX model was then used as a plant model for the Model Predictive Controller (MPC) to control the EHA positioning system.

C. Controlling of EHA Positioning System using Proportional-Integral-Derivative (PID) Controller

Proportional-Integral-Derivative (PID) controller is considered the most popular control method in the industry [8]. Reportedly in [9], over 90% of the controllers used in the industry today are PID controllers. PID controllers are preferable to be used in the industry due to their simplicity, understandability, reliability, and robustness [10].

Zulfatman and Rahmat (2009) are among the researchers who designed a PID controller to control the position of an industrial hydraulic actuator system [11]. They developed a self-tuning fuzzy PID controller to improve the performance of the electro-hydraulic actuator. Simulation results using MATLAB revealed that the performance of the hydraulic system controlled using the proposed self-tuning fuzzy PID controller was improved and satisfied compared to the conventional PID controller.

In 2010, Rozali et al. in [12] are reported proposed a Ziegler-Nichols as a tuning method for the PID controller. The aim is the same as the study done by Zulfatman and Rahmat (2009) in [11], which is to control the position of industrial hydraulic systems. However, compared to the study by Zulfatman and Rahmat (2009) in [11], Rozali et al. (2010) also verified the functionality of the developed controller through real-time experiments. At the end of the study, they prove that the simulation and experimental results are almost similar. The proposed controller successfully controls the position of the industrial hydraulic systems. The output of the system is also able to track the reference input signal.

Many other studies have been done to control the position of the EHA system using a PID controller. Among them such as the study by Alqadasi et al. (2019) in [13], Shern et al. (2020) in [14], and Ghani et al. (2022) in [15]. All of them managed to prove that the PID controller with a little modification can control the EHA system well.

D. Controlling of EHA Positioning System using Predictive Controller

Compared to the PID controller, EHA system position control using a predictive controller is not much reported.

Liang and Ismail (2019) have proposed a CVXGEN-Model Predictive Controller (MPC) to control the position of the EHA system [16]. Third-order Auto-Regressive with eXogenous input (ARX) model was chosen as the model structure for the EHA system used. To verify the functionality of the developed CVXGEN-MPC, Liang and Ismail (2019) have compared the positioning control performance of the EHA system using CVXGEN-MPC with another predictive controller, namely Predictive Functional Controller (PFC). Simulation and experimental works revealed that PFC has a slightly better rise time over CVXGEN-MPC. However, overall, Liang and Ismail (2019) claimed that CVXGEN-MPC gives better performance than PFC in settling time, steady-state error, and control effort.

In the same year, Parvaresh and Mardani (2019) propose Dynamic Matrix Control (DMC)-MPC to control the EHA position system, which is used in helicopter gearboxes [3]. The controller was evaluated in two conditions; the normal condition and in the presence of disturbance. The study concludes that the proposed DMC-MPC successfully provides superior performance in controlling the EHA system.

Methodology

A. System Modeling

The system identification technique was applied to acquire the real-time model that represents the dynamics of the Electro-Hydraulic Actuator (EHA) system used in this study. Figure 2 shows the real EHA system used in this study. The EHA system shown in Figure 2 is a bidirectional hydraulic cylinder type and has a stroke length of 400mm, piston diameter of 25mm, and piston rod diameter of 25mm.

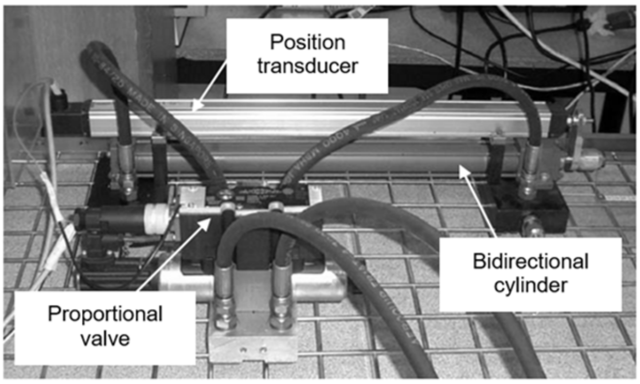

Fig.2. The real EHA system used in the study

Figure 3 illustrates the step-by-step procedure for modeling the EHA system using the system identification approach.

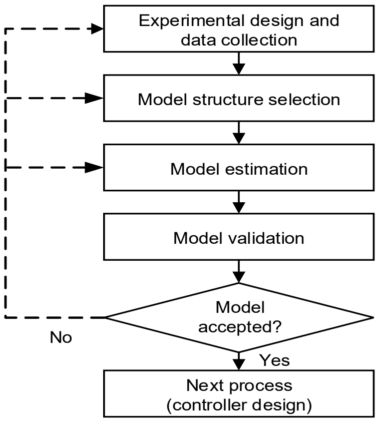

Fig.3. System identification procedures

Figure 4 shows the plot of data of measured input and output acquired from open-loop test. 1200 measurements of input and output data were collected from an open-loop test using a sampling time *(T_s)* of 50ms. In this study, 'voltage' is considered as the input data, while 'displacement' is the output data.

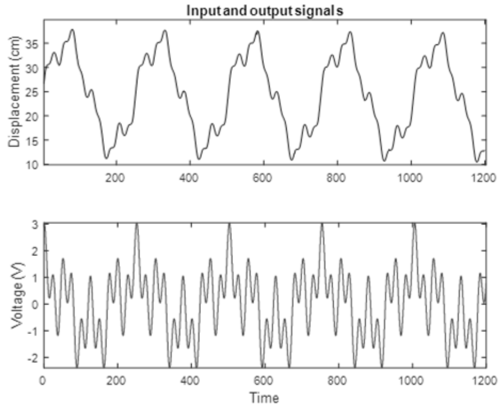

Fig.4. Plot of measured input and output data of the EHA system

For modeling using the system identification technique, the data of input and output were divided into two sets; one set for training (estimation) and the other set for the validation of the identified model. Figure 5 illustrates the estimation and validation process carried out using MATLAB System Identification Tool.

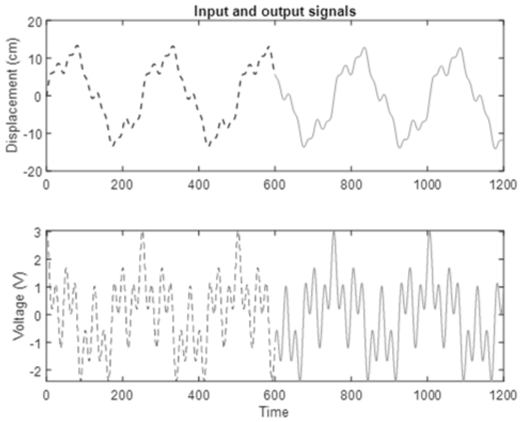

Fig.5. Estimation and validation process of measured data using MATLAB System Identification Tool

Based on the plots as illustrated in Figure 5, 50% of the first data set contained 600 data of input and output (dash line plot: sample 1-600) collected from real-time experiments were used for model training (estimation), meanwhile, the remaining 50% of the second data sets (solid line plot: sample 601-1200) was used for testing (validation). In this study, the second-order Auto-Regressive Moving Average with eXogenous input (ARMAX) system (AMX2131) was selected as the model structure of the EHA system.

Figure 6 shows the general block diagram of the ARMAX model, while Equation (1) expressed the general mathematical equation of the ARMAX model.

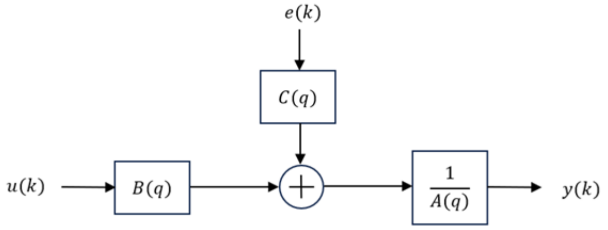

Fig.6. General block diagram of the ARMAX model

(1) $A(q)y(k) = B(q)u(k) + C(q)e(k)$

where: $A(q) = 1 + a_1q^{-1} + \cdots + a_{n_a}q^{-n_a}$, $B(q) = b_1q^{-1} + \cdots + b_{n_b}q^{-n_b}$, $C(q) = 1 + c_1q^{-1} + \cdots + c_{n_c}q^{-n_c}$, $y(k)$ is the output,
$u(k)$ is the input, $e(k)$ is the white-noise error, and, q^{-1} is the backshift operator

Equation (2) expresses the discrete-time transfer function of the EHA system dynamics based on the second-order ARMAX (AMX2131) model structure, which was estimated using MATLAB System Identification Tool.

(2) $EHA = \frac{0.1912z^{-1}}{1-1.286z^{-1}+0.2867z^{-2}}$

A predictive Functional Controller (PFC) is a type of controller that is designed based on a mathematical model of the plant. Since this study will use PFC as the controller, Equation (2) must be first converted to state-space form to facilitate the work of designing the PFC controller. Equation (3) expresses its discrete-time state-space model.

$$A = \begin{bmatrix} 1.2860 & -0.5734 \\ 0.5000 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0.5000 \\ 0 \end{bmatrix}, \tag{3}$$
$$C = [0.3824 \quad 0], \quad D = [0]$$

where $A, B, C,$ and D are the EHA system matrices.

B. Controller System Design

(i) Predictive Functional Controller (PFC)

Like any other predictive controller (i.e. Model Predictive Controller (MPC)), Predictive Functional Controller (PFC) predicts the future outputs and calculates the manipulated variables for optimal control. Figure 7 shows the basic block diagram of PFC. In Figure 7, PFC uses a plant model (EHA system) to predict future output. In this study, a state estimator or observer is applied in the design of PFC with the assumption that not all the state variables ($x(k)$) of the EHA system are available at time k. Hence, the future state variable is calculated using the estimated state variables.

As mentioned in the previous sub-section, this study used state-space form for the purpose of designing PFC. Thus, the discrete-time state-space model of the EHA system in Equation (3) was used for this purpose. Equation (4) expressed the PFC control law used in this study:

(4) $u_{PFC}(k) = -H^{-1}\left[Px(k) + (r(k) - (r(k) - y(k))\Psi^i\right]$

$$u_{PFC}(k) = -K_C x(k) + P_C r(k)$$

where $K_C = -H^{-1}[P - \Psi^i y(k)]$ and $P_C = -H^{-1}[1 - \Psi^i]$

Ψ in Equation (4) is a tuning parameter that represents the system's closed-loop pole. In order to ensure the stability of the closed-loop system of this study, the value of Ψ must be within the following range: $0 \leq \Psi < 1$. In this study, Ψ is set to be 0.4.

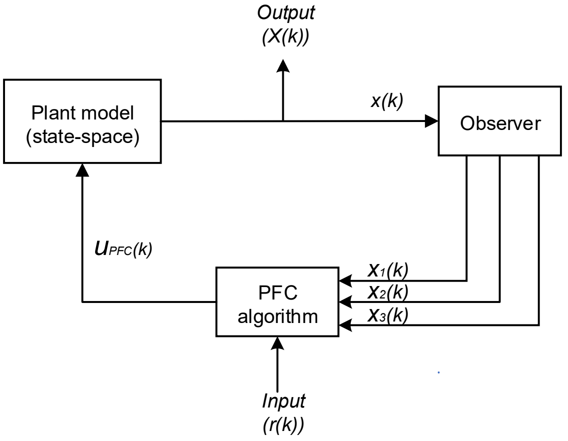

Fig.7. PFC block diagram

(ii) Proportional-Integral-Derivative (PID) controller

A PID controller consists of three basic parameters: Proportional (P), Integral (I), and Derivative (D). Each parameter has its own function, and these three parameters also affect the performance of the PID controller. Figure 8 illustrates the block diagram of a classical PID controller.

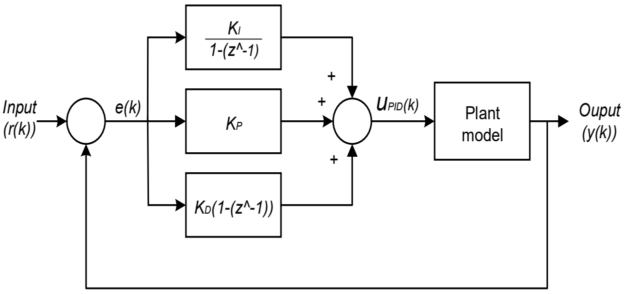

Fig.8. Classical PID controller block diagram

Equation (5) describes the basic equation of the PID controller used in this study.

(5) $$u_{PID}(k) = \left[K_P + \left[\frac{K_I}{1-z^{-1}}\right] + K_D[1 - z^{-1}]\right] e(k)$$

In this study, the PID controller gains K_P, K_I, and K_D were set at 3.5, 3.0, and 0.01, respectively.

Results, Analysis, and Discussion

A. System Modeling

As described earlier, this study uses the system identification technique to model the Electro-Hydraulic Actuator (EHA) system. In this study, the second-order Auto-Regressive Moving Average with eXogenous input (ARMAX) (AMX2131) model is considered acceptable to be used as a model to represent the dynamics of the EHA system used. The AMX2131 successfully provides a satisfying output fitting (80.29% of fitting) to the measured output obtained from the real-time experiments. Figure 9 displays the validation results on the AMX2131 model based on the best fit that has been carried out using the MATLAB System Identification Tool.

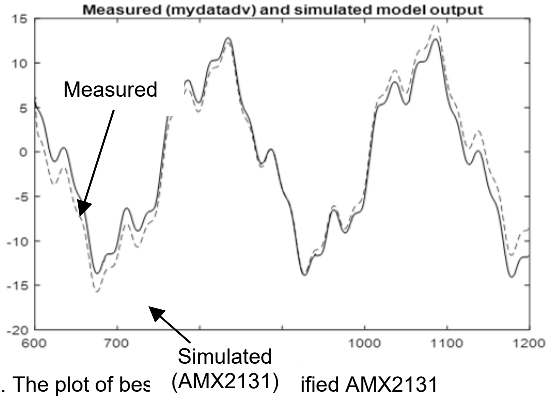

Fig.9. The plot of bes ified AMX2131

The identified model is also stable since it successfully provides all the system's poles inside the unit circle (0.9994 and 0.2868). Table 1 tabulates the model validation results on the AMX2131 model that has been done to confirm the acceptance of the model to be used as an EHA system model.

Table 1. Summary of the model validation performance of the AMX2131 model based on system identification criteria

Criteria	**AMX2131**
Best fit (%)	80.29
Final Prediction Error (FPE)	0.002673
Mean Square Error (MSE)	0.002633
Pole(s) location	0.9994 0.2868
Stability	Stable

Based on the model validation data as tabulated in Table 1, modeling the EHA system using AMX2131 is considered sufficient to represent the real EHA system utilised in this study.

B. Controller System

This section presents the performances of the proposed controller (Predictive Functional Controller (PFC)) in controlling the positioning system of the EHA through simulation tests using MATLAB Simulink. For comparison purposes, a classical Proportional-Integral-Derivative (PID) controller has been used.

Figure 10 shows a performance comparison of the EHA positioning control system using PFC and PID for 100cm (1/4) displacement. In this analysis, the step signal was applied as the input signal, and the simulation test was conducted for 10s.

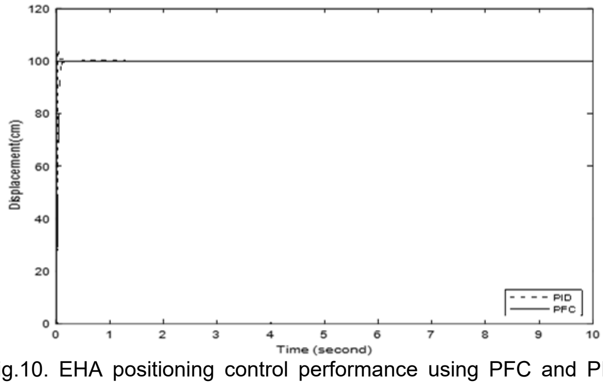

Fig.10. EHA positioning control performance using PFC and PID control strategies for 100cm displacement

Table 2 summarised the performances of the system's transient (i.e. rise time (t_r) settling time (t_s), percentage of overshoot (*%OS*), and steady-state error (e_{ss})) between the PFC and PID controller.

Table 2. Summary of transient response performance for EHA positioning system using PFC and PID controller

Response characteristic	Controller	
	PFC	PID
Rise time (t_r)	0.0497s	0.0170s
Settling time (t_s)	0.0773s	0.0385s
Percentage of overshoot *(%OS)*	0	4.4330%
Steady-state error (e_{ss})	0.0001296cm	0.0001469cm

Based on the plot in Figure 10 and tabulated data in Table 2, it can be seen that the proposed PFC was capable of controlling the EHA positioning system. Comparison with the classical PID controller shows that the EHA positioning system controlled by the proposed PFC strategy was unable to control the positioning system as fast as PID. In terms of overshoot, PFC provided 0% of the percentage of overshoot *(%OS)*, compared to PID controller which provides 4.4330% at the beginning of the simulation. The PID controller, as expected, is very fast in response, but at the same time will produce overshoot at the beginning of its operation. Thus, it can be said that the results obtained in Figure 10 and Table 2 were in line with the findings by Seraji in [17] which indicated that it is somewhat challenging to simultaneously achieve a fast response and no overshoot simultaneously, especially in the case of linear controllers. In terms of the steady-state error (e_{ss}) performance, both controllers provide good positioning accuracy when controlling the position of the EHA cylinder stroke at 100cm displacement.

Conclusion

In this study, a Predictive Functional Controller (PFC) was proposed as a new strategy to control the Electro-Hydraulic Actuator (EHA) positioning system. This study primarily focused to evaluate the capability of the proposed PFC to control the EHA positioning system as well as to improve the transient response performance of the system. Before the development of the controller is made, firstly, system modeling using system identification techniques has been done to obtain a mathematical model that can be used to represent the real EHA system. In this study, the second-order Auto-Regressive Moving Average with eXogenous input (ARMAX) (AMX2131) model was accepted to be used to represent the EHA system used. The performance of the PFC was analysed and compared with the classical Proportional-Integral-Derivative (PID) controller. The results based on the simulation test using MATLAB Simulink show that the proposed PFC was proven to be capable of providing 0% of overshoot during the simulation and higher accuracy in the position control of the EHA cylinder stroke. Even though the PFC was able to provide 0% of overshoot and accurate positioning control of the EHA system, however, PFC is unable to give a fast response to the positioning system as PID did. For wider applications, the EHA system must have the capability to attain fast speed response with high accuracy. Therefore, for future work, this study considered that the speed response of the system can be improved through certain modifications in the PFC algorithm.

Acknowledgement

The authors would like to thank the Centre for Research and Innovation Management (CRIM), Universiti Teknikal Malaysia Melaka (UTeM) for sponsoring this project.

***Authors**: Siti Fatimah Sulaiman, Centre for Telecommunication Research and Innovation (CeTRI), Fakulti Teknologi dan Kejuruteraan Elektronik dan Komputer, Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia, E-mail: sitifatimahsulaiman@utem.edu.my; Nurul Aini Ngateni, Centre for Telecommunication Research and Innovation (CeTRI), Fakulti Teknologi dan Kejuruteraan Elektronik dan Komputer, Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia, E-mail: b021920027@student.utem.edu.my; Khairuddin Osman, Centre for Telecommunication Research and Innovation (CeTRI), Fakulti Teknologi dan Kejuruteraan Elektronik dan Komputer, Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia, E-mail: khairuddin.osman@utem.edu.my; Sharatul Izah Samsudin, Centre for Telecommunication Research and Innovation (CeTRI), Fakulti Teknologi dan Kejuruteraan Elektronik dan Komputer, Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia, E-mail: sharatul@utem.edu.my; Noor Asyikin Sulaiman, Centre for Telecommunication Research and Innovation (CeTRI), Fakulti Teknologi dan Kejuruteraan Elektronik dan Komputer, Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia, E-mail: noor_asyikin@utem.edu.my; Noorhazirah Sunar, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia, E-mail: noorhazirah@utm.my.*

REFERENCES

[1] Ishak, N., Kamarudin, A. Z., & Adnan, R. (2021). Tracking control of an electro-hydraulic actuator system using LQR controller. *ELEKTRIKA - Journal of Electrical Engineering*, *20*(2), 8-13.

[2] Ling, T. G., Rahmat, M. F., & Husain, A. R. (2012, March). System identification and control of an Electro-Hydraulic Actuator system. In *2012 IEEE 8th International Colloquium on Signal Processing and its Applications* (pp. 85-88). IEEE.

[3] Parvaresh, A., & Mardani, M. (2019). Model predictive control of a hydraulic actuator in torque applying system of a mechanically closed-loop test rig for the helicopter gearbox. *Aviation*, *23*(4), 143-153.

[4] Ling, T. G., Rahmat, M. F., & Husain, A. R. (2014). A comparative study of linear ARX and nonlinear ANFIS modeling of an electro-hydraulic actuator system. *Jurnal Teknologi*, *5*, 1-8.

[5] Ghazali, R., Sam, Y. M., & Rahmat, M. F. A. (2009, November). On-line identification of an electro-hydraulic system using recursive least square. In *2009 IEEE Student Conference on Research and Development (SCOReD)* (pp. 471-474). IEEE.

[6] Rahmat, M. F., Ling, T. G., Husain, A. R., & Jusoff, K. (2011). Accuracy comparison of ARX and ANFIS model of an electro-hydraulic actuator system. *International Journal on Smart Sensing and Intelligent Systems*, *4*(3), 440-453.

[7] Rahmat, M. F. A., Rozali, S. M., Wahab, N. A., & Jusoff, K. (2010). Modeling and controller design of an electro-hydraulic actuator system. *American Journal of Applied Sciences*, *7*(8), 1100.

[8] AKCA, T. B., ULU, C., & OBUT, S. (2023). ANFIS Based Inverse Controller Design for Liquid Level Control of a Spherical Tank. *Przeglad Elektrotechniczny*, *99*(2).

[9] Åström, K. J., & Hägglund, T. (2001). The future of PID control. *Control Engineering Practice*, *9*(11), 1163-1175.

[10] Essa, M. E. S. M., Aboelela, M. A., & Hassan, M. A. M. (2016). Position control of hydraulic servo system using proportional-integral-derivative controller tuned by some evolutionary techniques. *Journal of Vibration and Control*, *22*(12), 2946-2957.

[11] Zulfatman & Rahmat, M. F. (2009). Application of self-tuning fuzzy PID controller on industrial hydraulic actuator using system identification approach. *International Journal on Smart Sensing and Intelligent Systems*, *2*(2), 246-261.

[12] Rozali, S. M., Rahmat, M. F., Wahab, N. A., & Ghazali, R. (2010, December). PID controller design for an industrial hydraulic actuator with servo system. In *2010 IEEE Student Conference on Research and Development (SCOReD)* (pp. 218-223). IEEE.

[13] Alqadasi, M. M. A., Othman, S. M., Rahmat, M. F., & Abdullah, F. (2019). Optimization of PID for industrial electro-hydraulic actuator using PSOGSA. *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, *17*(5), 2625-2635.

[14] Shern, C. M., Ghazali, R., Horng, C. S., Soon, C. C., Too, J., & Sam, Y. M. (2020). Performance Evaluation of EHA System using Weight Aggregation Strategy in MOPSO-PID. *Journal of Advanced Research in Applied Mechanics*, *73*(1), 1-10.

[15] Ghani, M. F., Ghazali, R., Jaafar, H. I., Soon, C. C., Sam, Y. M., & Has, Z. (2022). Improved third order PID sliding mode controller for electrohydraulic actuator tracking control. *Journal of Robotics and Control (JRC)*, *3*(2), 219-226.

[16] Liang, X. W., & Ismail, Z. H. (2019). System identification and model predictive control using CVXGEN for electro-hydraulic actuator. *International Journal of Integrated Engineering*, *11*(4).

[17] Seraji, H. (1998). A new class of nonlinear PID controllers with robotic applications. *Journal of Robotic Systems*, *15*(3), 161-181.