Comparison Study between Open-Loop and Closed-Loop Identification for Industrial Hydraulics Actuator System

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***Abstract*—In control applications involving motion control, precise control of the Industrial Hydraulics Actuator (IHA) is necessary to accurately assess the position of the actuator rod. Non-recursive identification is used to model the system with an open-loop and closed-loop approach for this paper. The grey box approach is used to estimate the continuous model and parameter estimation for the system. The System Identification toolbox in MATLAB is used for the model estimation. The process starts by obtaining the input-output data from the experimental work. The input-output data validation outcome reveals a best-fit percentage for open-loop 88.91% and closed-loop 95.43%, as well as a small Root Mean Square Error (RMSE). This indicates a successful validation between the estimated model and the actual system due to a high degree of agreement. The open-loop and closed-loop identification have proven successful as there is no noteworthy disparity in the outcomes. The closed-loop system can be applied to unstable systems and any potential system.**

***Keywords*—industrial hydraulics actuator, system identification, grey box, open-loop, closed-loop, root mean square error**

I. INTRODUCTION

Industrial Hydraulics Actuators (IHA) are widely used in manufacturing applications. They are commonly found in industrial fields such as aircraft, rolling mills, and mobile lifts, where there is a need for high torque [1–5] and accurate response control. The increasing demand for force and position control performance in various applications has led to a rise in the use of IHA systems. These systems are applicable in situations that require precise and reliable control, thanks to their ability to generate significant forces while maintaining fast response times and good durability [6–10]. Due to their capacity for position tracking, IHA has become popular research topic for several decades, particularly in industrial applications, where optimal performance and efficiency are sought.

The natural behavior of IHA systems is characterized by nonlinearity, uncertainties, and disturbances, which present challenges in system handling [11−19]. The main causes of nonlinearity include fluid compressibility and fluctuations in fluid temperature and viscosity, all of which impact the performance of position tracking in nonlinear IHA systems. Before designing any controller for position tracking control, a precise model is required to gain a deeper understanding of system dynamics. Therefore, a system model can be achieved through system identification methods.

System identification can be used to characterize the dynamic behavior of the hydraulic actuator system. It requires input and output data to obtain the system model. It is a technique that can structure the model based on known physical principles with unknown parameters. The model can be estimated using the “grey box” model approach under open-loop and closed-loop structures. For example, Jin and Wang [10] used a double-layered network method for system identification that can obtain an accurate model instead of a grey box or black box method. Furthermore, Ghani *et al.* [18] worked on a third-order model with grey box system identification for an Electro-Hydraulic Actuator (EHA) system with an open loop configuration.

This paper will explore both open-loop and closed-loop identification approaches. Ghazali *et al.* [13] have worked on recursive identification with a discrete model in open-loop and closed-loop configurations. Initially, a mathematical model comprising a hydraulic actuator and a

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proportional valve is developed, focusing on a fixed supply load and pressure. Open-loop and closed-loop identification are two fundamental approaches used in this process. Open-loop identification typically involves applying known input signals to the system and measuring the corresponding output responses without any feedback control. This method is often used when the system can be easily excited and when a high level of accuracy is not required. It provides valuable insights into the system's behavior and dynamics. On the other hand, closed-loop identification involves applying input signals to the system while using feedback control to maintain the system at a desired operating point. This method is more complex but can provide more accurate models, especially in cases where the system dynamics are nonlinear or where disturbances are present. The comparison study between open-loop and closed-loop identification for industrial hydraulic actuator systems aims to investigate the strengths and limitations of each approach. It may consider factors such as the accuracy of the identified models, the complexity of the identification process, and the robustness of the models to disturbances and uncertainties of the system.

The expected result of these studies is the creation of a model that can effectively depict the dynamic behavior of the Industrial Hydraulics Actuator (IHA). Furthermore, it is expected that both the open-loop and closed-loop identification methods will produce consistent outcomes for the estimated parameters, achieving a best-fit percentage of above 80%. In addition, the statistical analysis should exhibit low Root Mean Square Error (RMSE) values, while a graphical histogram analysis shows a symmetrical bell-shaped distribution that is uniformly centered around zero. It indicates that the assumption of normality is likely to be true.

This paper is organized as follows: Section II explains the literature review on the working principle of the IHA system and system identification. Section III presents the system identification process with the experimental setup. Section IV discusses the results and findings from the experimental work. Finally, Section V provides the conclusion.

II. LITERATURE REVIEW

A. IHA System Working Principle

The IHA system converts electrical energy into hydraulic power for controlling motion. It comprises two signal sections: the power signal and the control signal. The power signal involves supplying electrical input from a power source or control system to the IHA system, which drives an electric motor connected to a hydraulic pump. The mechanical motion generated by the motor is utilized by the pump to pressurize hydraulic fluid, creating a flow of pressurized fluid within the IHA system. This pressurized fluid is then directed to a hydraulic cylinder containing a piston and cylinder, resulting in linear motion.

The signal section of an IHA system is responsible for receiving control commands and transmitting them to the actuator. It serves as the interface between the control system and the IHA system, facilitating the communication of instructions for desired motion. The control signal can originate from diverse sources, including a control system, sensors, or manual input devices [11–13]. It is within the signal section that these control signals are received and transmitted appropriately to the IHA system, enabling precise control over its operation.

B. System Identification

System identification is the procedure used to estimate or ascertain the mathematical model that portrays the behavior of a dynamic system, relying on input-output data. By examining the system's response to known inputs and employing statistical and mathematical methodologies, system identification enables the estimation of the system's parameters, structure, or dynamics.

1) Parameter estimation

There are a few parameter estimations in the field of system identification. This paper focuses on open-loop and closed-loop parameter estimation. Open-loop identification involves the estimation of system parameters or model structure without incorporating feedback or control actions. It is necessary to design the input signals used to cover a broad range of operating conditions and excite the system dynamics. The advantage of open-loop identification lies in its simplicity and ease of implementation. On the other hand, closed-loop identification has various methods for identification, including direct, indirect, and joint input-output identification [14–19]. Direct identification is simple and does not require consideration of feedback controllers, making it suitable for systems with nonlinearity.

2) System identification model

The system identification model involves three methods: white box, grey box, and black box. The white box model typically incorporates known physical properties, equations, and relationships, making it highly interpretable but not suitable for uncertainties in the model. The grey box model has both data and physiological knowledge but lacks specific details about the system. However, it is flexible enough to capture complexities and uncertainties in the system. Lastly, the black box model is the most popular model used in system identification. It focuses solely on the relationship between input and output data from the system. Despite its lack of interpretability, the black box model can capture system behaviors and is flexible in handling nonlinear or time-varying systems.

3) Model validation

Model validation is the process of evaluating the performance, accuracy, and reliability of a mathematical or computational model by comparing its predictions with real-world data or observations, as mentioned in [20–25]. This is typically done by splitting the available data into two sets: one for model estimation and another for validation. There are several methods used to validate the estimated model, which is a graphical approach to selecting a satisfactory model and producing statistically acceptable results. Through the graphical approach, one can observe the best fits produced, the histogram of analysis, and correlation analysis. One such graphical approach involves examining the quality of the model fit [16, 26–30]. This analysis can be done by visually comparing the predicted values of the model to the actual observed data. A satisfactory model will exhibit a close alignment between the predicted values and the observed data points.

III. MODELLING AND EXPERIMENTAL SETUP

A mathematical model of the IHA system in Fig. 1 has been developed using the principal method, which consists of parameters such as mass, damping, and stiffness. The derivation is as follows:

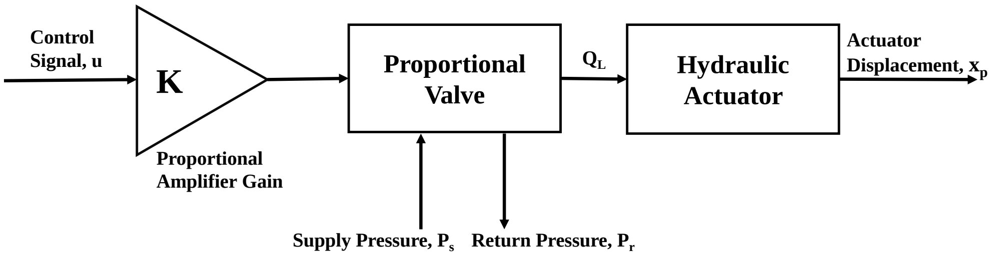

Fig. 1. Block diagram of IHA system.

Defining Q_L as movement of the cylinder and the leakage oil flow, this factor represented in Eq. (1), where V_t, A_p, $\dot{x}_p$, β_e and $f(P_L)$ are the total compressed oil volume, cylinder piston surface area, cylinder piston velocity, effective bulk modulus coefficient, and the nonlinear function of internal and external oil leakage, respectively.

$$Q_L = A_p\dot{x}_p + \frac{V_t}{4\beta_e}\dot{P}_L + f(P_L) \tag{1}$$

$$\dot{P}_L = \frac{M_t\ddot{x}_p}{A_p} \tag{2}$$

Thus, Eq. (3) represents the combination of Eqs. (1) and (2).

$$\frac{M_t\ddot{x}_p}{A_p} = \frac{4\beta_e}{V_t}\left(Q_L - A_p\dot{x}_p - C_{tp}P_L\right) \tag{3}$$

After going through the process of Laplace transform, the transfer function in Eq. (4) for $\frac{X_p(s)}{U(s)}$ is developed. The transfer function is used in constructing the parameter estimation during system identification.

$$\frac{X_p(s)}{U(s)} = \frac{b_1}{s^3+a_1s^2+a_0s} \tag{4}$$

The experimental setup of the IHA system consists of a few main parts: a computer, a data acquisition system, a hydraulic actuator, a hydraulic power jack, a proportional valve, and wire displacement sensor, as shown in Fig. 2. The hydraulic cylinder has a 40 mm bore and a 25 mm rod diameter, with a maximum flow rate of 80 L/min and a peak supply pressure of 31.5 MPa. (see Table I).

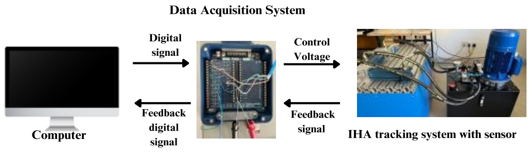

Fig. 2. Control schematic diagram of IHA workbench.

TABLE I. IHA SYSTEM WORKBENCH SPECIFICATIONS

Description	Value
Cylinder Bore	40 mm
Rod Diameter	25 mm
Cylinder Stroke	200 mm
Supply Pressure	3 MPa

The input signal is generated from a computer using MATLAB, which has been used to create the system model for both open-loop and closed-loop configurations. The data acquisition system employs a PCIe-6321 card to transmit the signal to the proportional valve. The control of the hydraulic cylinder is managed by the proportional valve, while the position of the rod in the double-acting cylinder is captured by a wire displacement sensor during extension or retraction, converting the mechanical movement into an electrical signal. To ensure proper functionality when the input signal is applied, the rod must be positioned at the midpoint before the start of the experiment.

Fig. 2 illustrates the interface between the computer and the PCIe-6321 card, serving as the operator interface. MATLAB/Simulink is employed to run the developed model, collect experimental data, and subsequently analyze and compare it to the simulation data in the time domain. During the experiment, the Data Acquisition (DAQ) system, as detailed in Table II, receives digital signals from the computer and generates corresponding voltage signals. These signals are then directed to the Industrial Hydraulics Actuator (IHA) working bench, specifically to the proportional valve, as detailed in Table III. The regulated piston displacement is achieved by controlling the pressurized fluid flow to the hydraulic actuator via the proportional valve. The feedback output signal is then sent back to the DAQ system and transmitted to the computer after digital conversion.

TABLE II. PCIe-6321 CARD SPECIFICATIONS

Description	Value
Number of analog input channels	16 single-ended or 8 differentials
Number of analog output channels	2 with output range of ± 10 V
Resolution	16 bits
Sample rate	250 kHz/s sample per second
Input range	± 0.2 V, ± 0.1 V, ± 5 V, ± 10 V

TABLE III. PROPORTIONAL VALVE BOSCH REXROTH 4WREE6

Description	Value
Command value signal	± 0 V
Supply voltage	24 V
Maximum operating pressure	3.15×10^7 Pa
Maximum flow	80 Liter per minute

IV. RESULT AND DISCUSSION

A. *Model from System Identification Toolbox*

The system identification process was carried out using the grey box model approach with 3 zeros and 2 poles used for the simulated transfer function for both open-loop and closed-loop structures. MATLAB was utilized for the System Identification Toolbox to guide the procedure. Data, comprising input and output information, was gathered for both model estimation and validation. The input and output data align with the specification, where the input signal varies based on the specified pressure setting. The experiment was conducted over a duration of 50 s, with a sampling time of 1 ms. Data acquisition for system identification was performed during this period. This model is executed at varying pressures specifically at 3×10^6 Pa.

Figs. 3 and 4 present the input-output data that was generated from the IHA system with configurations of open-loop and closed-loop respectively. Furthermore, Table IV displays the parameter values for both open-loop and closed-loop scenarios aligned with the designated pressure. However, the values show consistency between the scenarios but there is a slight difference for some coefficients but still within the acceptable range (see Table IV).

TABLE IV. ESTIMATED PARAMETER FOR OPEN-LOOP AND CLOSED-LOOP

Identification Structure	a_1	a_2	a_3	b_1	b_2	b_3
Open-Loop	1.70	9.16	0.28	9.04	14.11	93.04
Closed-Loop	2.58	23.28	0.35	11.85	24.28	301.50

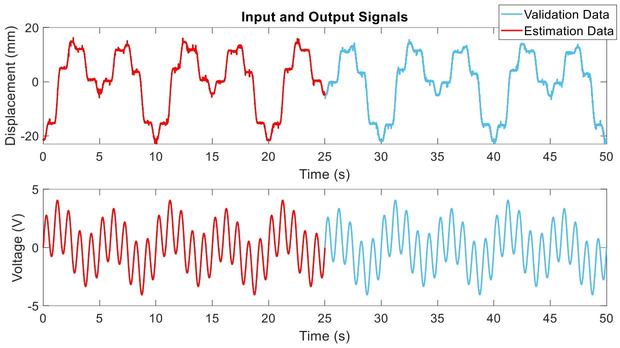

Fig. 3. Input-output data for open-loop.

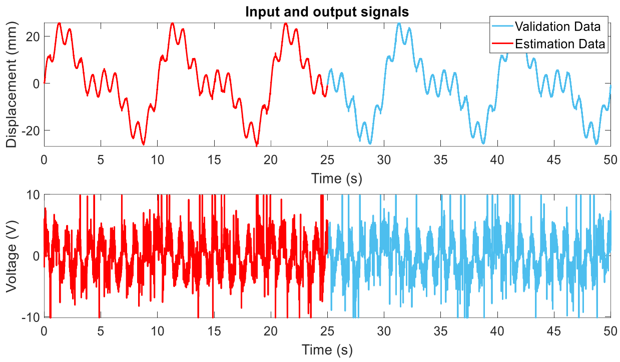

Fig. 4. Input-output data for closed-loop.

$$\frac{y(s)}{u(s)} = \frac{9.04s^2+14.11s+93.04}{s^3+1.70s^2+9.16s+0.28} \tag{5}$$

$$\frac{y(s)}{u(s)} = \frac{11.85s^2+24.28s+301.50}{s^3+2.58s^2+23.28s+0.35} \tag{6}$$

B. *Model Validation*

The generated estimated model from system identification has undergone validation to assess the accuracy of the measured data and the degree of agreement as shown in Figs. 5 and 6. The primary emphasis during the validation process will be on techniques that measure the percentage of best fit and histogram analysis.

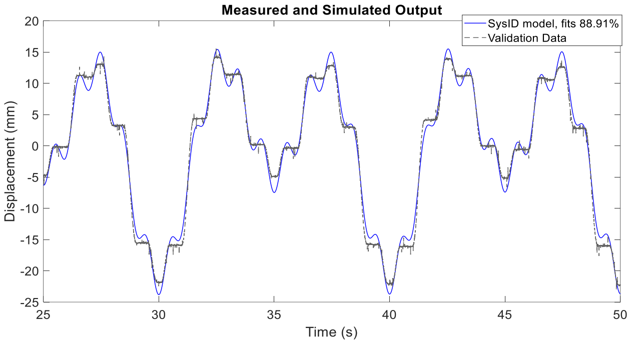

Fig. 5. Best fit validation for open-loop.

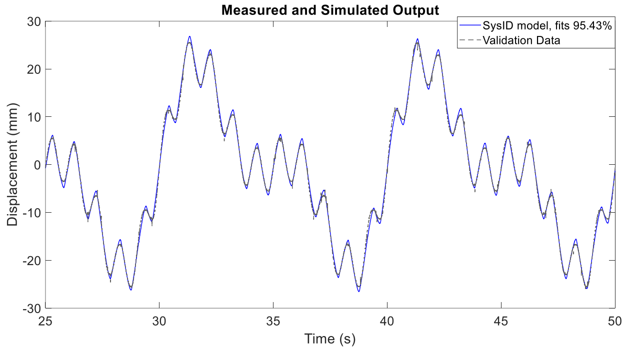

Fig. 6. Best fit validation for closed-loop.

The percentage of best fit generated by the MATLAB System Identification Toolbox indicates a nearly accurate agreement between the estimated model and the actual IHA system. Through the conducted analysis, the data set yielded a percentage of best fit exceeding 80%, demonstrating a significant level of similarity between the estimated model and the real system. In Ref. [18], the model achieved a best fit of 89.1%, demonstrating a high level of accuracy and capability in representing the system model for an open-loop configuration with a supply pressure of 8 MPa. In contrast, this research presents both open-loop and closed-loop configurations with supply pressure 3 MPa. The remaining percentage accounts for uncertainties within the IHA system. It is essential to recognize that the estimated model may not encompass all aspects of the IHA system, and the existence of uncertainties in the system should be duly acknowledged.

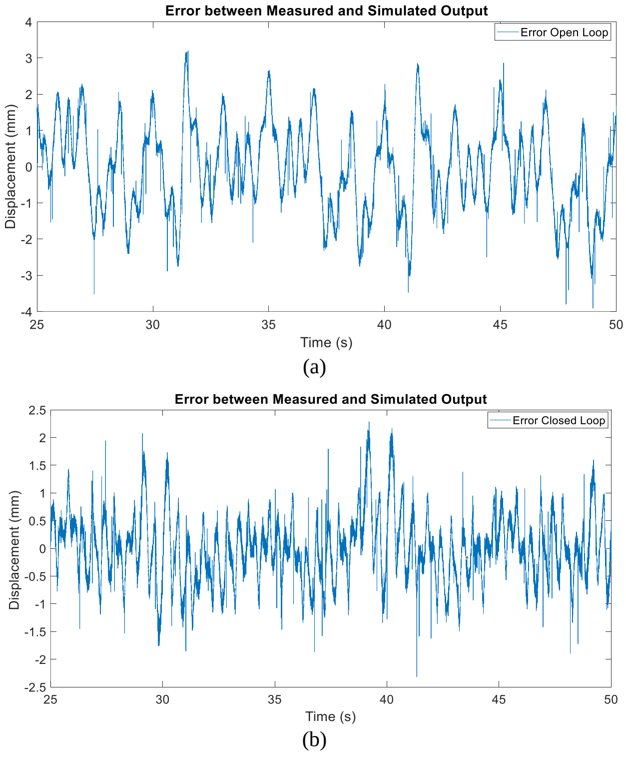

Fig. 7. Error between measured and simulated output, (a) Open-loop identification, (b) Closed-loop identification.

Fig. 7 shows the error plot between simulated and measured output based on the best-fit validation graph. It shows that the smaller error both for open-loop and closed-loop structures present the presence of a small RMSE value which is 0.1102 for open-loop and 0.0952 for closed-loop. This indicates a high level of agreement between the measured data and the actual model. The consistent small RMSE values enhance the accuracy of the validation for the estimated model.

The histogram of residuals is shown in Figs. 8 and 9 reveals Gaussian distributions, suggesting that the estimated model is generally acceptable and aligns with good modeling practices. The presence of residuals determined to resemble white noise further supports the quality of the estimated model. Additionally, the existence of uncorrelated and constant residual variance enables the estimated model to effectively capture the unpredictable behavior of the IHA system.

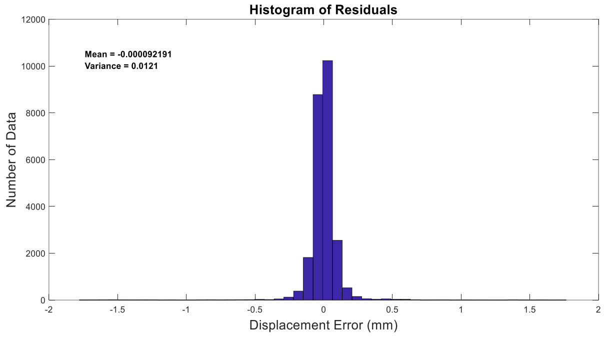

Fig. 8. Residuals histogram for open-loop.

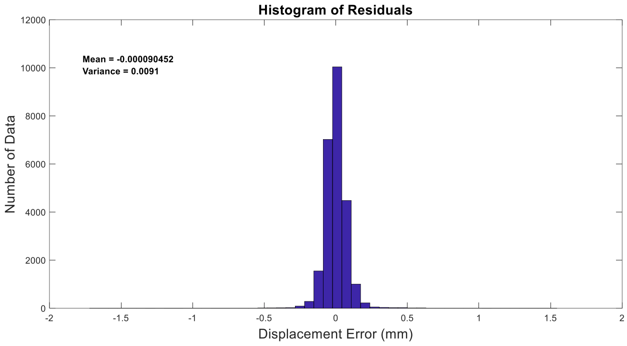

Fig. 9. Residual histogram for closed-loop

V. CONCLUSION

As a conclusion, the Industrial Hydraulics Actuator (IHA) system has successfully estimated the system model and its parameters through a grey box model. This model considers both open-loop and closed-loop structures. The validation of the model, through graphical and fit analysis, has provided an 88.91% accuracy for the open-loop and 95.34% accuracy for the closed-loop. These results meet the requirement of percentage best fits, with no statistical difference observed. Therefore, an effective model for the IHA system has been established, which is suitable for various analytical purposes. The advantage of these methods is that closed-loop identification can be effectively applied to unstable systems for identifying dynamic behavior and uncertain parameters. However, a limitation of this approach is the necessity to linearize a highly nonlinear system, which may result in suboptimal outputs that require further improvement. This method needs to be adapted according to the specifications of the hydraulic actuator to enable its implementation in real industrial applications. In the future, the closed-loop system identification can be conducted using an indirect method, or by incorporating various input signals such as Pseudo Random Binary Signals (PRBS) and Pseudo Random Multi-Level Signals (PRMS).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

N. H. M. Ali and R. Ghazali conducted the research, analyzed the data, and wrote the paper. H. I. Jaafar, M.F. Ghani, Z. Has review the manuscript. All authors had approved the final version manuscript.

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