SYSTEM IDENTIFICATION AND CONTROLLER DESIGN FOR HYDRAULIC ACTUATOR

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ABSTRACT

System Identification of Hydraulic Actuators is critical for analyzing their performance and designing a suitable Control System. Hydraulic actuators are extensively used in many applications, ranging from flight simulators, robotics, orthopaedic surgery, material testing, construction and many other industrial types of machinery. In the aviation industry, hydraulic actuators are currently being used in full flight simulators used for controlling the position and orientation of the motion platform. Every actuator has its characteristics, therefore, the choice of excitation signals for System Identification must take into account the dynamics of the actuator under consideration. This work proposes the selection of excitation signals based on the bandwidth of the hydraulic actuator. Validation of the proposed selection is done by performing system identification, obtaining a mathematical model and comparing it with a nonlinear hydraulic actuator model designed in Simscape. After validation, a nonlinear PID control has been tuned on the identified model and tested on the nonlinear model. Extensive simulations have been run and results show accurate mathematical modelling, as well as precise control, has been achieved through the proposed methodology.

Key Words: Black-box model; Controller Design; Electro-hydraulic Actuator (EHA); Flight Simulator; NPID; Hydraulic Actuator; System Identification.

1. INTRODUCTION

Electro-hydraulic servo actuator systems (EHSAS) find significant uses in several areas due to their reliability, maintainability and high-power efficiency. Consequently, they are integrated into many applications such as manipulators, vehicles, robots, and aircraft [1]. Therefore, precise control of EHSAS is an active research area and great effort has been done in the field of dynamic modelling and control of actuators to enhance performance and accuracy. An accurate mathematical model is required for analyzing the EHSAS dynamics and designing a control system. The mathematical model is obtained through the process of system identification which can be categorized as white box, black box, and grey box. The development of the white-box model is entirely derived from the first principles. This kind of modelling assumes complete knowledge of the process and is determined by theoretical modelling. When enough knowledge is not available then a general model structure can be used in black-box modelling. By using an estimation the procedure, parameters are estimated by providing custom excitation inputs/signals to the system and measuring the output. A combination of the black and white box model is the grey box model. In addition to the knowledge from the first principles and the information contained in the measurement data, other sources of knowledge such as qualitative knowledge formulated in the rules may also be used. However, such modelling is defined by the inclusion of various kinds of easily available information [2]. When an accurate mathematical model is available then the control scheme needs to be selected which enables precise manipulation of different performance parameters despite non-linearities, friction, noise, internal leakages, and delays. This research aims to investigate the relation of excitation signal with the system dynamics that

(a) Flight Simulator [3]

are further used in building the mathematical model of EHSAS with the help of system identification techniques. Although often ignored in the previous findings, this research determines the right excitation frequencies related to the system bandwidth and also

(b) Hydraulic Actuator [4]

Figure 1: Example of a flight simulator with individual hydraulic actuator.

defines the behaviour of the system. By considering the bandwidth of the system in the selection of excitation inputs, further improvements are achieved in the system identification resulting in a more accurate mathematical model. The model has been validated with the help of multiple test signals of varying amplitudes and frequencies. The proposed black-box modelling method can build and parametrize an accurate model of servo control hydraulic actuator with significant accuracy. The main contributions of this research paper are summarized below;

- The Realistic Nonlinear Dynamic Model of Hydraulic Actuator of Aircraft Flight Simulator has been designed.
- An appropriate selection of the excitation input based on system properties has been proposed.
- The selection of excitation input characteristics based on system dynamics has been proposed.
- Experimental validation has been performed in simula¬tion.

The remaining part of the paper is assembled as follows. Section 2 reviews existing literature in the area of system identification and control of hydraulic actuators. Section 3 presents the methodology portion that covers some of the basic concepts used for system identification and its different techniques and further illuminates the implementation of controller design. The paper is finally concluded in Section 4.

2. Literature Review

Due to their importance in industry, the control of servo-hydraulic systems has attracted a lot of attention from re¬searchers. To obtain a mathematical model of the system, a method of identifying an actuator needs to be chosen so that an optimal accuracy of the model can be attained. This section reviews the recent literature relevant to system identification and control of hydraulic actuators. A detailed analysis of system identification covering the excitation sig¬nal, model type, model order, and validation accuracy of these techniques has been performed. The literature review is summarized in Table 1.

In 2009 Wang et al. [6] proposed a model identification of the electro-hydraulic servo position system based on the Real-Time Workshop (RTW) hardware in the loop simulation framework, as well as the MATLAB toolbox for system identification. They obtained a 3rd order State Space and ARX model by feeding a sine wave signal as an excitation signal. The author was able to achieve very precise control through a nonlinear hybrid controller consisting of a proportional, fuzzy, and classic PID controller. However, their system identification techniques covered a limited amount of dynamic range due to the use of a single frequency. Kalyoncu et al. [5] suggested the Fuzzy logic controller and introduced a 3rd order transfer function. They considered the leakage flow in their mathematical modelling while most authors have ignored this phenomenon. They investigated the effects of internal leakage on the obtained mathematical

Table 1: Available Literature on System Identification And Controller Design Techniques.

No	Author	Excitation Signal	Model Type	Model Order	Validation Accuracy	Controller Design	Shortcomings
1	Kalyoncu et al. [5]	Mathematical Modelling	Transfer Function	3rd Order	----	Fuzzy Logic Controller	The model has not been acquired from a real system
2	Wang et al. [6]	Sine Wave	State Space, ARX	3rd Order	----	Proportion-Fuzzy PID Hybrid	The model could not cover all the dynamics through a single input frequency
3	Rahmat et al. [7]	Multisine	ARX	4th Order	92.8%	PID	Selection of excitation signal has not been related to its dynamics and randomly selected its frequencies
4	Izzuddin et al. [8]	Multisine, step	ARX	3rd Order	95.86% 94.67%	Predictive Functional Control. PID	The selection of the excitation signal and their frequencies have not been related to its dynamics

No	Author	Excitation Signal	Model Type	Model Order	Validation Accuracy	Controller Design	Shortcomings
5	Ishak et al. [9]	Multisine	ARX	3rd Order	91.16%	Pole Placement Method	Selection of excitation signal has not been related to its dynamics and selection on trial-and -error base method
6	Ren G et al. [10]	Chirp	Transfer Function	4th Order	----	Adaptive Controller	The full capability of actuators has not been tested
7	Ghazali et al. [11], Saeed	Load and Pressure Values	ARX	3rd Order	----	Hybrid Fuzzy PID	The model has not been validated on whole dynamics
8	Liang et al. [13]	3 Types of Signal	ARX	3rd Order	----	Predictive Controller	Validation has not been done on their mathematical model either through a test signals or best-fit criteria
9	Proposed Technique	Multisine, Chirp	Transfer Function, ARX	3rd Order	99.17% 98.79%	NPID	----

model and the efficiency of the position control system even on the small spool displacement. Rahmat et al. [7] have also formulated a related work to model the electro-hydraulic actuator. The author used a multisine signal and obtained the 4th order ARX model with validation of 92.8% by using system identification techniques and further designed a PID controller for the model through simulation. The work proposed a mathematical model based on best-fit criteria, residual analysis of autocorrelation and cross-correlation. Although good results were achieved, the parameters of the multisine excitation signal were selected randomly and not related to the physical characteristics of the hydraulic actuator. Ishak et al. [9] designed a feedback controller with a pole placement method to achieve better system performance with more accuracy. The model was acquired by system identification based on the ARX model by introducing trial and error-based frequencies of multisine signals. Therefore, the actual model is close to the obtained 3rd order model with 91.16% best-fit validation accuracy. Izzuddin et al. [8] presented a system identification approach by using two types of excitation signals, the identification of the EHA system has been performed and the 3rd order ARX model was chosen. Multisine signal exhibit 95.86% best-fit criteria whereas the step input signal showed 94.67% fit. Other than the best-fit criteria, these models were also selected based on final prediction error (FPE) and mean square error (MSE). For position tracking, this research outlined the modelling and designing of the predictive functional control (PFC) algorithm and then compared it with the PID controller by using PSO tuning method. Ren G et al. [10] developed a controller with low bandwidth based on an offline parametric linear identification technique. It was observed that the internal actuator leakage altered the model type and significantly reduced the open-loop gain that is constrained to motion. To design a controller, the mathematical model is generally obtained first by using system identification techniques. They obtained the 4th order transfer function based on the chirp input signal, but the full capability of the actuator has not been tested for validation purposes. In 2019, Liang et al. [13] applied the technique of Model Predictive Control (MPC) by using the optimization and constraint handling problem. This technique was validated through predictive functional control (PFC) and the results were evaluated for position control EHA system with and without disturbances in both MATLAB simulation and real-time experiments. On the other hand, the dynamic characteristics of the system gain through system identification based on the 3rd order ARX model by using three different types of input signals. However, validation has not been done on their mathematical model either through test signals or best-fit criteria. Li et al. [14] introduced a methodology by integrating black and grey box model identification for deriving a mathematical model of an electro-hydraulic servo system. A white-box model of the entire system was built and the unknown parameters were calculated approximately as per prior experience. In this research, to enhance the model of a white box, the identification of the black box model was applied to change certain parameters of the model. Finally, the identification of the grey box model has been done using the improved model as a new initial model. Therefore, simulation results and their comparison with measurement data showed an accurate model of the system. Ghazali et al. [11] dealt with system identification using recursive or offline techniques and proposed a 3rd order ARX model by varying load and pressure values. As the significant effect in model parameters have been improved, despite that, the model has not been validated on whole dynamics. In 2019, Liyang et al. [15] presented a double-layered network scheme identification, a combination of the black and grey box method. However, a precise model is obtained by adding the two layers separately. Based on the validation tests, the obtained model is highly compatible with the actual model. Moreover, disturbance, stability, and speed are some dynamics of the system, that were being used to improve the system by adding controllers to the existing system. In this regard, Zhong proposed an algorithm [16] that is the combination of fuzzy logic and neural network techniques, to suppress the non-linearities and disturbances for such systems. Wonohadidjojo et al. proposed a Fuzzy logic controller to overcome the non-linearities and Particle Swarm Optimization (PSO) method used in his research to obtain the best value for tuning its parameters [17]. Saeed et al. [12] introduced a hybrid fuzzy PID tracking methodology for the electro-hydraulic servo system from the perspective of heavy manufacturing processes. The aim was to build a nonlinear hybrid controller comprising of a classical PID controller, fuzzy logic controller, and a fuzzy-PID controller based on the self-adjusting modifying factor that significantly improves the robustness of the system and its dynamic and static properties. Researchers have introduced a variety of other controllers as well to overcome the non-linearities of the system, such as linear, nonlinear controller, and artificial intelligence approaches such as PID [18], model predictive control (MPC) [19], sliding mode control (SMC) [20], and adaptive control [21]. After reviewing the state-of-the-art relevant literature, it has been determined that a methodology for relating excitation signals with dynamics of the system to be identified, has not been presented. Therefore, in this research, the primary focus is to present a framework for the selection of correct parameters of excitation signals. Our work improves upon the existing research in this field by characterizing the excitation signal concerning the dynamics of the system to be identified. As a first step, a realistic nonlinear dynamic model of EHSAS has been developed in Simulink. The effects of compressibility, friction, internal servo valve leakage, actuator leakage, and inertia have been included to make the model more accurate. Once the mathematical model is obtained through system identification, a nonlinear PID controller has been used to implement the precise position control of an electro-hydraulic servo system.

3. Methodology and Experimental Validation

Firstly, the following section explains the dynamics of the system. Then based on dynamics, the nonlinear hydraulic actuator system has been modelled by using the Simscape physical system toolbox where all components of the hydraulic actuator have been provided, which are particularly applied to control the displacement of the hydraulic actuator. Furthermore, system identification techniques have been done to acquire an accurate model and for that, a suitable selection of excitation signal and model have been identified. Consequently, after the EHSAS model as shown in Fig. 2 is acquired, both the simulation and the position control of EHSAS experiments

have been performed based on the obtained model. Moreover, a nonlinear PID controller has been implemented on the nonlinear model and the identified model.

3.1. Dynamics of the Plant

The EHSAS to be studied here in this paper is a Moog MCR-M-1002 hydraulic actuator that is commonly used in the motion platform of flight simulators. The plant is also composed of a servo amplifier, servo valve by Moog 725-106, and the load. The whole system is operated by

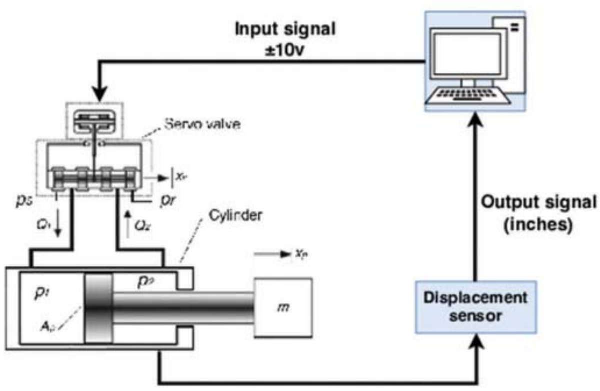


Figure 2: Basic Flow of EHSAS

a hydraulic pump equipped with safety valves. To make the system more efficient, the system also incorporates the following sensors: 1 linear variable differential transducer (LVDT) that governs the position of each cylinder, two pressure transducers; one for piston side and second for rod side chamber pressure, and two limit switches to interpret the feedback of full extension and retraction of the cylinder.

In this study, the EHSAS under consideration consists of two major components: the valve and the cylinder. The cylinder has been modelled along with a double actuator with load mounted at the end of the rod. The servo valve and actuator are depicted in Fig. 2. The control signal is represented by u, the displacement of the cylinder is represented by X_p, A_p is the area of the hydraulic cylinder, the fluid flow to and from the cylinder is Q_1 and Q_2, respectively. The fluid pressure within chamber 1 of the cylinder is P_1 and chamber 2 of the cylinder is P_2. On both sides, the pressurized areas are A_1 and A_2, respectively. When there is a pressure difference between P_1 and P_2 the cylinder will extend or retract in its position. The servo valve controls the fluid flow Q in each chamber. The basic fluid flow is expressed by Equation 1.

$$Q = K_v X_v \sqrt{\Delta P_v} \quad (1)$$

where K_v is servo valve gain, X_v denotes spool valve displacement that is controlled by input signal u and P_v is the pressure difference. The fluid flow towards the cylinder and back to the cylinder is represented by Equations 2 and 3 [25].

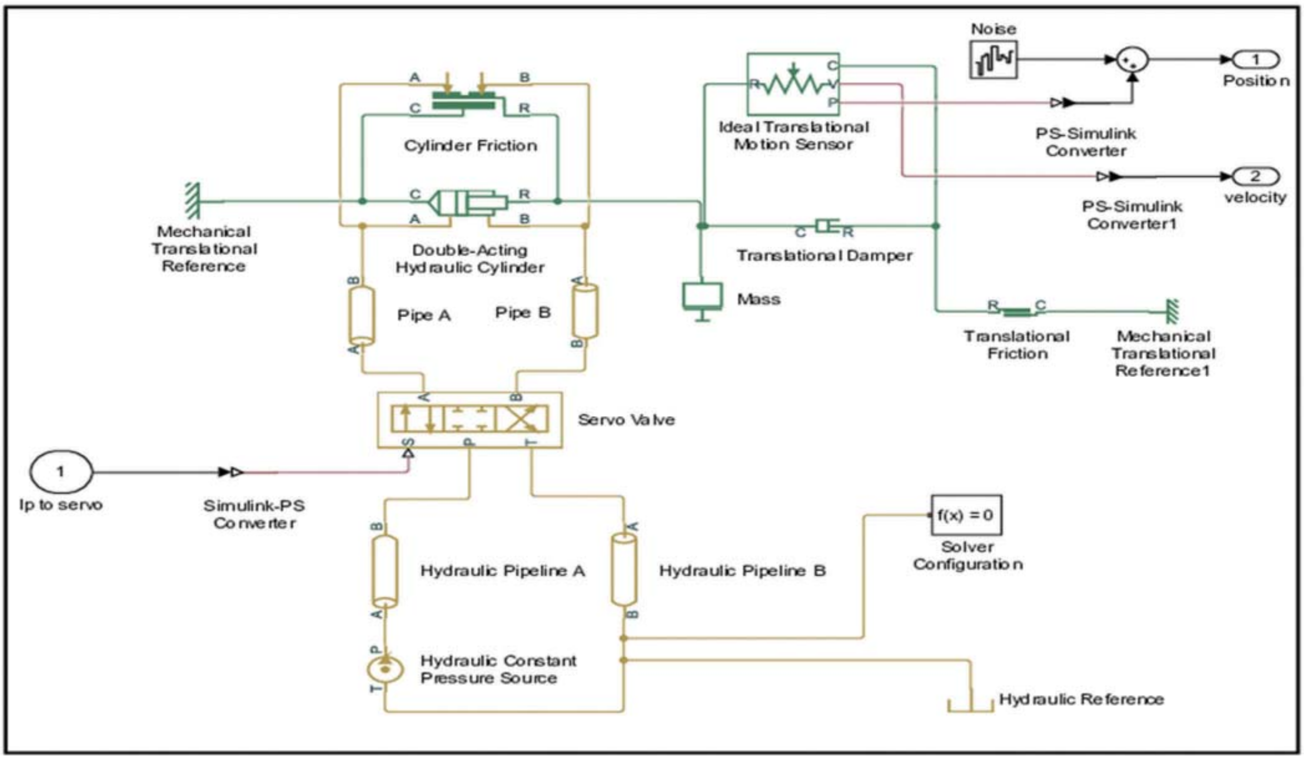


Figure 3: Nonlinear Model of EHSAS.

$$Q_1 = \begin{cases} K_1 X_v \sqrt{P_s - P_1} \ ; & X_v \geq 0 \\ K_1 X_v \sqrt{P_1 - P_r} \ ; & X_v < 0 \end{cases} \quad (2)$$

$$Q_2 = \begin{cases} -K_2 X_v \sqrt{P_2 - P_r} \ ; & X_v \geq 0 \\ -K_2 X_v \sqrt{P_s - P_2} \ ; & X_v < 0 \end{cases} \quad (3)$$

Therefore, pressure can be obtained for each chamber by specifying the relation between the bulk modulus, volume, and flow rate. The fluid pressure P_1 and P_2 can be written as:

$$P_1 = \frac{\beta}{V_1} \int \left(Q_1 - \frac{dv_1}{dt}\right) dt \quad (4)$$

$$P_2 = \frac{\beta}{V_2} \int \left(\frac{dv_2}{dt} - Q_2\right) dt \quad (5)$$

Now, Equation 6 presents a relation between the spool valve displacement X_v, and the input voltage signal u, where the servo valve gain K_v acts as the constant of proportionality.

$$X_v = K_v u \quad (6)$$

Hence, the hydraulic system dynamics for fluid flow Q_L has been obtained from a Tailor Series Linearization.

$$Q_L = K_q X_v - K_c P_L \quad (7)$$

Because of the fluid flow Q_L, the load pressure P_L can be defined as the pressure across the servo actuator and the first derivative equation of the load pressure is defined by the division of the total flow through the fluid capacitance and hydraulic actuator. Here, K_q represents the flow gain coefficient and K_c shows the flow pressure coefficient. So, the first derivative of the load pressure in the form of a mathematical equation is given by [8].

$$\dot{P}_L = \frac{4\beta}{V_t}\left(Q_L - C_{tp} P_L - A_p \dot{X}_p\right) \quad (8)$$

Here, β defines the bulk modulus, C_{tp} represents the total leakage coefficient, and V_t is the total volume of the fluid. Then, after adding and substituting the above equations, the displacement in terms of derivative becomes:

$$\dddot{X}_p = A_p^2 \frac{4\beta}{V_t M} \frac{K_q K_v}{A_p} u - \frac{4\beta}{V_t}(K_c + C_{tp}) \ddot{X}_p -$$

$$A_p^2 \frac{4\beta}{V_t M} \dot{X}_p \quad (9)$$

By rearranging the above equations, we get:

$$\dddot{X}_p + \frac{4\beta}{V_t}(K_c + C_{tp})\ddot{X}_p + A_p^2 \frac{4\beta}{V_t M}\dot{X}_p =$$

$$A_p^2 \frac{4\beta}{V_t M}\frac{K_q K_v}{A_p} u \qquad (10)$$

From Equation 10, the continuous-time transfer function is given as:

$$\frac{X_p(s)}{U(s)} = \frac{A_p^2 \frac{4\beta}{V_t M}\frac{K_q K_v}{A_p}}{s^3 + s^2 \frac{4\beta}{V_t}(K_c + C_{tp}) + s A_p^2 \frac{4\beta}{V_t M}} \qquad (11)$$

Therefore, transfer function equation 11 can be written in terms of constant values that are:

$$\frac{X_p(s)}{U(s)} = \frac{\omega_a K_a}{s^3 + 2\zeta_a \omega_a s^2 + \omega_a s} \qquad (12)$$

In equation 12, actuator gain K_a, natural frequency ω_a, and servo valve damping coefficient ζ_a can be defined as:

$$K_a = \frac{K_q K_v}{A_p}$$

$$\omega_a = A_p \sqrt{\frac{4\beta}{V_t M}}$$

$$\zeta_a = \frac{\sqrt{\frac{4\beta}{V_t}(K_c + C_{tp})}}{2A_p}$$

Therefore, after reviewing the generic mathematical model in Equation 12, it has been proposed that the transfer function of EHSAS can be suitably presented as a third-order transfer function. The basic structure of the proposed continuous-time transfer function is as shown in Equation 13.

$$G(s) = \frac{X_p(s)}{U(s)} = \frac{b_1 s^2 + b_2 s + b_3}{s^3 + a_1 s^2 + a_2 s + a_3} \qquad (13)$$

3.2. Nonlinear Modelling Based on Actual Parameters

This section discusses the dynamic modelling of the hydraulic servo system. The system has been modelled as a nonlinear system in Simscape. After such parameter identification, the nonlinear model has been modified into a mathematical form in which the physical structure is represented in a nonlinear generalized model. To develop a mathematical model of the system, different dynamic parameters have been used. Each of the Simscape model components has been configured with parameters of the real hydraulic actuator taken from its technical manuals and also shown in Table 2. This nonlinear model as shown in Fig. 3 has been generated as a replacement of the real actuator, so that system identification and experimentation techniques would be applied without any damage to the hydraulic actuator.

3.3. System Identification

Although hydraulic actuator can be fully defined by its physical laws as shown in Subsection 3.1 However, with repeated usage, the system develops leaks or the performance of its components deteriorates and many uncertainties occur in the system. System identification techniques use measured experimental data to obtain frequency responses with the intent that, system uncertainties are observed, and the models obtained are more precise.

3.3.1 Selection of Input Excitation Signal

Based on the dynamics of the system and the requirements of modelling, researchers have presented various excitation signals. The most commonly used excitation signal is Pseudo Random Binary Sequences (PRBS) which is a periodic and deterministic signal with the replacement of noise. An integer number of periods in PRBS should be used to enjoy its good properties that limit the choice of the length of the experiment [25]. For the identification of linear systems, the PRBS signal is widely used. Therefore, it cannot be used for nonlinear systems as they also require the judicious choice of excitation amplitude to cover the entire operating range of the system to identify.

Another commonly used excitation signal is a step signal, which can give the different response parameters which are very helpful in

Table 2: Parameters of EHSAS [24].

Components	Parameters	Symbols	Values
Servo Valve (Moog 725-106)	Input Signal	u	± 10 v
	Flow Discharging Coefficient	C_f	0.6
	Leakage Area	K_a	1e-12 m^2
	Maximum Opening	O_m	0.0178 m
	Servo Valve Area	A_s	0.0002318 m^2
	Servo Valve Gain	K_v	2.2e-6 $m/$v
Hydraulic Actuator (Moog MCR-M-1002)	Piston Stroke	X_s	60 in
	Contact Stiffness	C_s	6.14e8 N/m
	Contact Damping	C_d	200 $N/(m/s)$
	Piston Area	A_p	12.5 in^2
	Flow Gain Coefficient	K_q	1.8e-6 m/V
	Actuator Gain	K_a	491.04e-12
	Dead Volume	V_d	0.0003048 m^3
	Specific Heat	h	1.4
	Ratio Bulk Modulus	β	22e4 psi
	Load	M	500 kg
	Damping Coefficient	B_s	100 $N/(m/s)$
	Spring Stiffness	K_s	20 Nm
	Coulomb Friction Force	α1	450 N
	Viscous Friction Coefficient	α2	64 $N/(m/s)$

system identification. However, the step signal does not cover the full dynamics of the system as it contains low information content in data [26]. Therefore, it is not considered for this research. Sinusoidal is another useful signal, which covers the given frequency with different possible amplitudes. However, to cover the full dynamic range of the system, the sinusoidal signal is given as a chirp or multisine signal so that more frequencies can be captured. After an extensive literature review of system identification of similar hydraulic actuators, it has been determined that the most suitable excitation signals for black-box identification of EHSAS are multisine and chirp signal as presented in Table 1.

The chirp excitation signal is a frequency sweep signal, with increasing frequencies exponentially over a certain period. Chirp signal has the same crest factor as sinusoid and the excited frequency band is well controlled. The chirp excitation signal is designed according to [27], as shown in Equation 14.

$$X_{chirp}(t) = A\cos(\phi(t)) \qquad (14)$$

In equation 14, A represents the amplitude of the signal and φ(t) shows the phase of the signal.

$$\phi(t) = \phi_0(t) + 2\pi(\frac{k}{2}t^2 + f_0(t))$$

$$k = \frac{f_1 - f_0}{T}$$

f_0 is the starting frequency at $t = 0$, f_1 is the final frequency and T is the time that is taken to sweep from starting to final frequency.

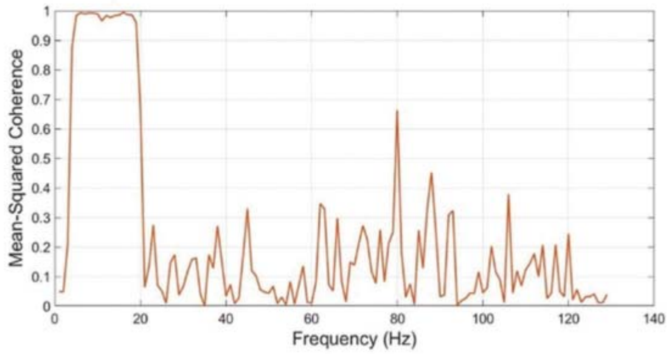
3.3.2 Selection of Parameters of Excitation Signal

Formation of the selected excitation signals requires the determination of amplitude and frequency. However, the reviewed literature has used hit and trial to select the excitation signal parameters and then perform experimental validation to check the required accuracy of the mathematical model has been achieved. Therefore, in this research, the parameters of excitation signals have been proposed according to the actuator dynamics. A reference has been obtained from system identification of complex nonlinear systems such as aircraft and rotorcraft [28]. There is no need for higher frequency inputs. To obtain a good identification model for flight mechanics and control applications, the maximum chirp signal frequency for aircraft and rotorcraft is limited to almost 2 Hz. For forming a chirp signal, the minimum ω_min and maximum ω_max frequencies are required to ensure that the excitation signal covers the full range of dynamics of the system. However, the excitation signal must also be related to the dynamics of the system. Therefore, a range of frequencies has been proposed in relation to the bandwidth of the system. The range of frequency for the chirp signal is 0.1ω_Bw≤ω≤2ω_Bw. Finally, the maximum amplitude has been selected which avoids the actuator saturation to excite the system and to improve the signal-to-noise ratio (SNR) [2].

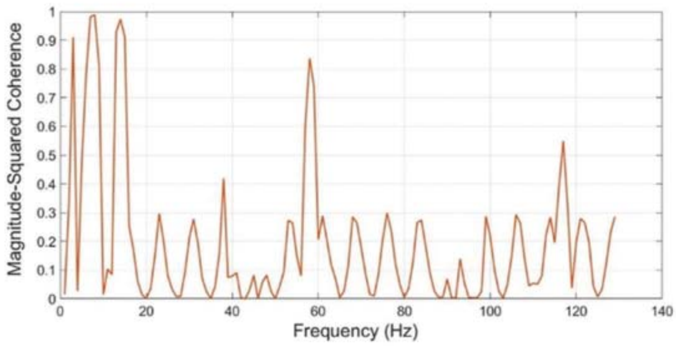
Similarly, a multisine excitation signal has also been used for capturing the whole dynamics of the system. The combination of three different frequencies with relation to its system behaviour has been proposed instead of distribution over a range of frequencies. Equation 15 shows the proposed multisine equation with selected parameters.

$$X_{multisine}(t) = A[sin[0.1\omega_{Bw}(t)] + sin[0.5\omega_{Bw}(t)] + sin[2\omega_{Bw}(t)]] \quad (15)$$

So, at this stage, input versus output data has been chosen, there is a sanity check through



(a) Chirp Excitation Signal



(b) Multisine Excitation Signal

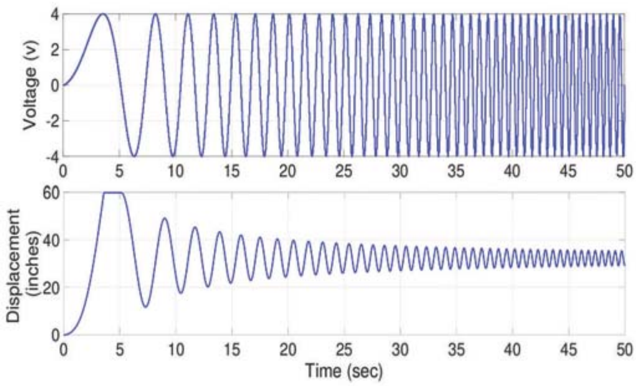
Figure 4: Coherence Function Estimation of Input-Output Data

coherence function to find out whether this data is rich enough to give better results of system Identification. The coherence function calculates how well a system can be predicted based on input-output frequencies. In Fig. 4, it has been observed that the value of coherence reaches 1 at the selected frequency range.

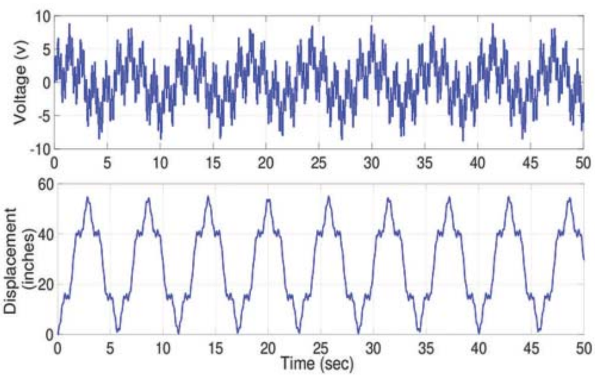
3.3.3 Model Identification

A linear model is used as the identification of EHSAS to approximate a nonlinear model. Since this is the discrete-time model that can describe the relationship between $u(t)$ and $X_p(t)$. The linear model is preferred over the nonlinear model as it is a more popular model among different estimation methods to identify the EHSAS, while at the same time, it can represent the real system with high accuracy [15]. Different researchers have preferred that will result in a 3rd order transfer successfully modelled the hydraulic actuator as a linear system. Therefore, a 3rd order transfer function model and ARX model have been selected, as discussed in Section 2.

To estimate the unknown parameters of the system based on the ARX model, the least square method is used. Furthermore, it also has been experimentally validated. The general



(a) Chirp Excitation Signal



(b) Multisine Excitation Signal

Figure 5: Data Collection for Model Identification.

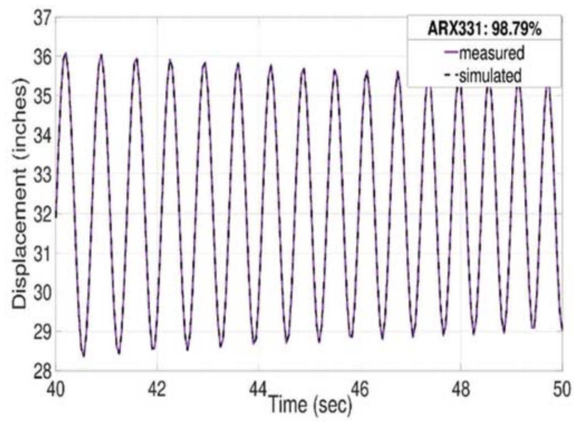
equation of ARX model is as shown in Equation 16, where A and B represents the polynomials, input $u(t)$, output $y(t)$, u_i shows the ith input, $n_u$is the total number of inputs, nk_i presents ith input delay and e(t) is the white noise respectively. Both time and frequency domain data has been used to estimate the transfer function models. The continuous time model has been obtained by direct convertion of discrete time function $(c2d)$.

$$A(q)y(t) = \sum_{i=1}^{nu} B_i(q)u_i(t - nk_i) + e(t) \tag{16}$$

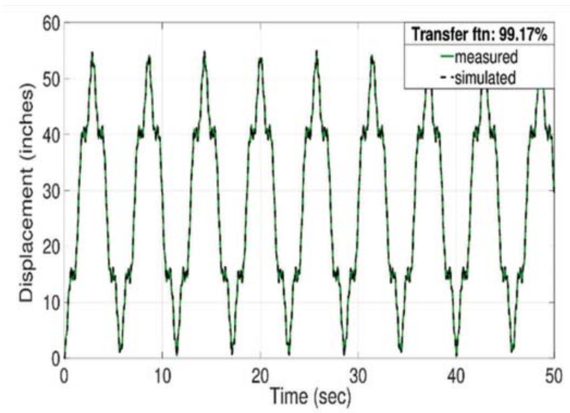
The first step in the identification of the model is to get system input and output signals. The chirp excitation signal and the corresponding output as shown in Fig. 5a is divided into two sets within the 50s; the 80% set is used for estimation and the remaining 20% is used for validation.

Model ARX-331 obtained from one of the sets of data as a result of the highest best-fit value with 50ms sampling time, that is known as

3.3.4 Model Validation



(a) Chirp Excitation Signal

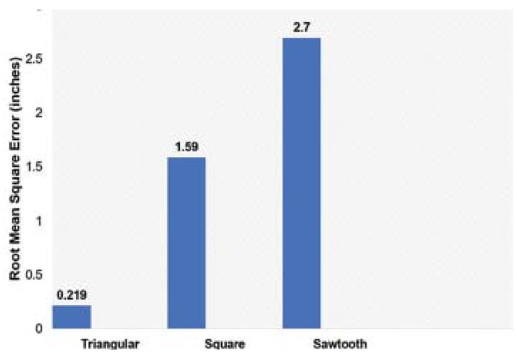


(b) Multisine Excitation Signal

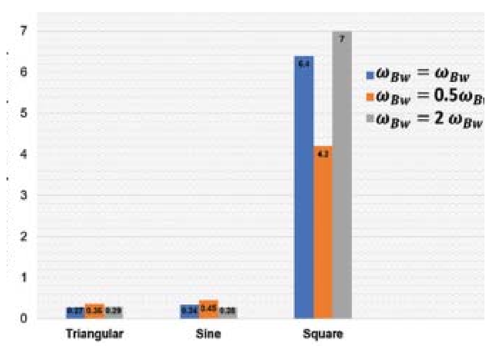
Figure 6: Measured and Simulated Output Data. $G_{chirp}(s)$.

Multisine signal is the second type of excitation signal used to get the EHSAS model. Fig. 5b displays the estimation and validation obtained data, respectively. The first half of the obtained data has been used for estimation and the second for validation. The 3rd order transfer function, G_multisine (s) has been chosen to represent the multisine excitation model since it has the highest best-fit value.

The model validation has been done by evaluating the best fit between the measured and simulated data. The model with a higher percentage of best fit indicates that the model can represent a model close to the nonlinear model. In addition to the best-fit, mean square error (MSE) and final prediction error (FPE) has been observed for model identification as tabulated in Table 3. In Fig. 6, it is shown that the model obtained through multisine and chirp excitation signals provides an accurate measured and simulated output.



(a) Chirp Model



(b) Multisine Model

Figure 7: Experimental Analysis Through RMSE.

Besides the best-fit percentage, FPE and MSE of multisine and chirp excitation signal, the validation has been done. For the evaluation of the identified model, different test signals including triangular, square, sine, and sawtooth have been fed to the model of chirp and multisine. Therefore, to draw a comparison between the nonlinear model and identified model, the root means square error (RMSE) has been calculated as shown in Fig. 7, respectively. It is depicted that the lowest error calculated by chirp excitation signal responded

Table 3: Model Selection Criteria.

Model Parameters	Multisine	Chirp
Best-Fit Percentage	99.17%	98.79%
MSE	0.002918	0.00301
FPE	0.00304	0.00311

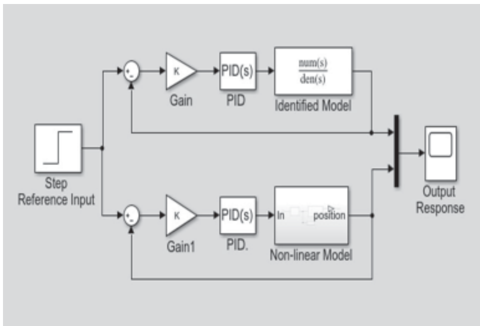


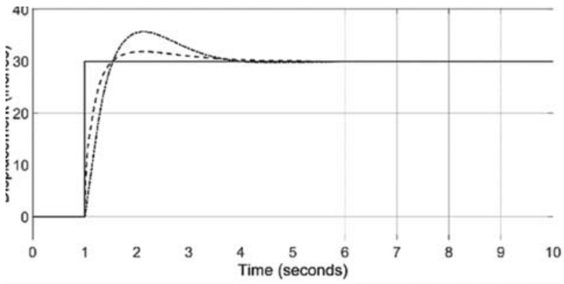
Figure 8: Simulink Model with NPID Controller.

to different test signals are triangular, followed by square signal and sawtooth signal. Similarly, in multisine excitation signal by varying amplitude and frequency of test signals, it has been noted that there is the minimum error obtained from the triangular test signal then sine signal followed by a square signal. Thus, if the comparison has been drawn between chirp and multisine excitation signals then it has been claimed that the chirp excitation signal shows better performance with minimum RMSE.

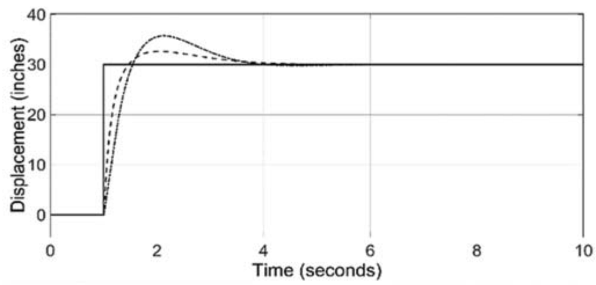
3.4 Controller Design

After the system identification has been completed with reasonable accuracy, the nonlinear PID controller has been selected for control. The most widely used control scheme in various applications is PID. The PID controller has been used very effectively for better position tracking performance, and fast response time [29]. Since it has a basic structure having different types of tunning methods available that are more efficient as well. By tuning the PID gain K_p, K_i and K_d values, system performance such as rise time, overshoot, settling time, and steady-state error can be significantly improved. The conventional type of controller is often difficult to acquire optimum performance because of the presence of nonlinearities in the system. As the dynamic model of the hydraulic actuator system incorporates major non-linearities, achieving reasonable performance for these systems is difficult for PID controllers. Therefore, the PID controller combines with nonlinear gain called the NPID controller, which is designed to control the EHSAS position tracking [31,43]. The nonlinear gain is used to enhance system efficiency and minimize overshoot by using a relatively higher gain [24]. Equation 17 represents the NPID controller.

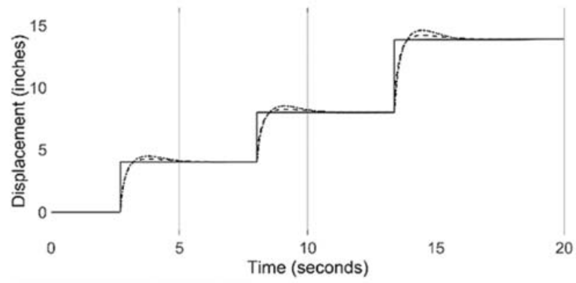
$$u(t) = K_p k(e) e(t) + K_i k(e) \int_0^t e(t)dt + K_d k(e) \frac{d}{dt} e(t) \tag{17}$$



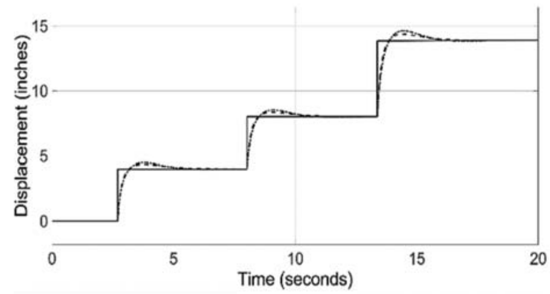
(a) Step Response Comparison for Chirp Identified Model



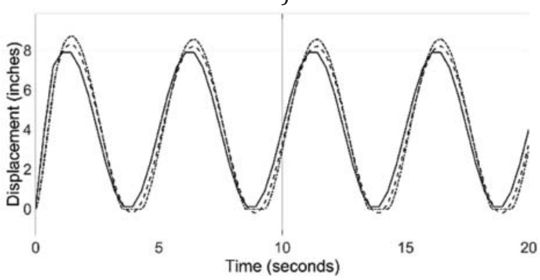
(b) Step Response Comparison for Multisine Identified Model



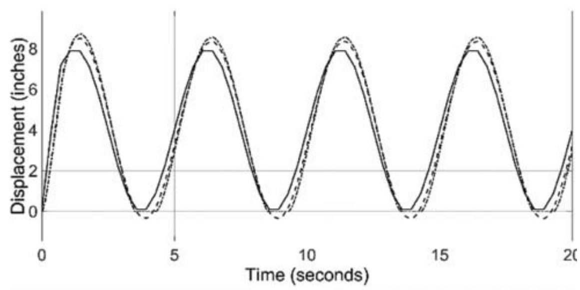
(c) Staircase Response Comparison for Chirp Identified Model



(d) Staircase Response Comparison for Multisine Identified Model.



(e) Sinusoidal Response Comparison for Chirp Identified Model



(f) Sinusoidal Response Comparison for Multisine Identified Model

Figure 9: Comparative Results of Controller Performance Between Identified Model and Nonlinear Model by Using Different Reference Signals (Left hand side shows the obtained model through chirp excitation signal whereas, right hand side shows the obtained model through multisine excitation signal). Represents The Reference Signal, -- - -- - -- Shows The Nonlinear Model, - - - - - - Shows An Identified Model.

A wide variety of options are available for the nonlinear gain k. Here, as a function of error e, nonlinear gain k has been used as the hyperbolic function [24].

$$k = k_0 + k_1[1 - sech(k_2 e)] \quad (18)$$

$$k = k_0 + k_1\left[1 - \frac{2}{\exp(k_2 e) + exp(-k_2 e)}\right] \quad (19)$$

$$k_{max} = k_0 + k_1 \ ; \qquad e = \pm\infty$$

$$k_{min} = k_0 \ ; \qquad e = 0$$

where k_0, k_1, k_2 represents the constant values fed by the user, that has been selected through experimentation. However, k_0 shows the minimum value, the range of variation defined by k_1, and the rate of variation of k specified by k_2. The experiment is repeated with k as a hyperbolic function of e, with the effect of the nonlinear gain k on the system performance, as shown:

$$k = 4 - 3sech(0.05e) \quad (20)$$

The nonlinear gain k varies with respect to the error. The gain is automatically minimized as the time continues and the error is reduced, then eventually settles to the final value of one, with zero steady-state error.

Although the output of the device needs to achieve zero steady-state error with this controller, proportional controller K_p is used to improve the speed of response so that it can track the position of a hydraulic actuator. The system is given an integral controller K_i to get the steady-state error zero or very low. Derivative controller K_d will improve system speed performance [23]. The derivative action may not be appropriate at times because the proportional and integral action already provides a reasonable response to the output. Ziegler-Nichols tuning method is used to determine the tuning value of K_p, K_i, and K_d. Before the tuning process, the critical gain, K_{cr} and critical oscillation period, T_{cr} needs to be determined. Based on these two parameters, the value of K_p, K_i, and K_d are adjusted. Ziegler-Nichols tuning rules and these values might be modified to obtain the best output response.

Stability of the ARX model has been ensured by setting the model order equal to order of the identified system. Linear and non linear PID gains have also been set within designated limits [31] to ensure a stable closed loop system. Experimental validations also indicate that the proposed method results in a stable closed loop system.

Table 4: Transient Response Analysis.

Models		T_r (s)	T_s (s)	OS (%)
Model 1 *Chirp*	Identified Model	0.25	2.1	4.5
	Nonlinear Model	0.28	2.2	4.8
Model 2 *Multisine*	Identified Model	0.1	2.8	3.2
	Nonlinear Model	0.3	3.0	4.3

The nonlinear PID controller has been applied to improve the position performance of the system. Fig. 8 illustrates the Simulink model composed of the NPID controller. The tracking performance of the controller has been verified by feeding different types of reference signals like step, staircase, and sine. These reference signals have been given to both; the nonlinear model and the identified model for position tracking capability analysis. Fig. 9 clearly shows that both inherited output signals from the chirp and multisine excitation signal followed the nearest path to the reference signal. The performance of the controller has been investigated with the transient response analysis, including the rise time T_r, settling time T_s and over-shoot OS, as presented in Table. 4.

4. Conclusion

In this research, the selection of suitable excitation signals for system identification of hydraulic actuator has been presented. A proposed methodology for the selection of excitation signal parameters with actuator dynamics has been validated in simulation by comparing performance with a nonlinear model of the actuator. After that, a nonlinear PID controller is configured to control the electro-hydraulic servo actuator system, based on the model acquired from the identification process. The results show an accurate tracking performance. Future work includes experimental verification of the proposed techniques and implementation on a hydraulic actuator.

References

[1] Choi, J. (2013). Robust position control of electro-hydrostatic actuator systems with radial basis function neural networks. Journal of Advanced Mechanical Design, Systems, and Manufacturing, 7(2), 257-267.

[2]. Nelles, O. (2020). Nonlinear System Identification: From Classical Approaches to Neural Networks, Fuzzy Models, and Gaussian Processes. Springer Nature.

[3]. Koblen, I., & Kovácová, J. (2012). Selected information on flight simulators-main requirements, categories and their development, production and using for flight crew training in the both Slovak Republic and Czech Republic conditions. Incas Bulletin, 4(3), 73.

[4]. "Electrohydraulic," East Aurora, NY, August 2013. [Online].Available: www.moog.com/products/actuators-servoactuators/actuation-technologies.

[5]. Kalyoncu, M., & Haydim, M. (2009). Mathematical modelling and fuzzy logic based position control of an electrohydraulic servosystem with internal leakage. Mechatronics, 19(6), 847-858.

[6]. Wang, Z., Shao, J., Lin, J., & Han, G. (2009, August). Research on controller design and simulation of electro-hydraulic servo system. In 2009 International Conference on Mechatronics and Automation (pp. 380-385). IEEE.

[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]. N. Izzuddin, M. R. Johari, K. Osman. (2015). System identification and predictive functional control for electro-hydraulic actuator system. In 2015 IEEE International Symposium on Robotics and Intelligent Sensors (pp. 138–143). IEEE.

[9]. Ishak, N., Tajjudin, M., Ismail, H., & Adnan, R. (2006). System identification and model validation of electro-hydraulic actuator for quarter car system.

[10]. Ren, G., Song, J., & Sepehri, N. (2018). Design of a low-bandwidth position controller based on system identification for an electro-hydrostatic actuator. Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, 232(2), 149-160.

[11]. Ghazali, R., Soon, C. C., Jaafar, H. I., Sam, Y. M., & Rahmat, M. F. (2014, November). System identification of electro-hydraulic actuator system with pressure and load effects. In 2014 IEEE International Conference on Control System, Computing and Engineering (ICCSCE 2014) (pp. 256-260). IEEE.

[12]. Mohammed, S., Soon, C. C., Ghazali, R., Yusof, A. A., Sam, Y. M., & Shern, C. M. (2018). An Electro-Hydraulic Servo with Intelligent Control Strategy. In MATEC Web of Conferences (Vol. 150, p. 01016). EDP Sciences.

[13]. 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).

[14]. Li, L., & Thurner, T. (2013). Accurate modeling and identification of servo-hydraulic cylinder systems in multi-axial test applications. Ventil, 19(6), 462-470.

[15]. Jin, L., & Wang, Q. (2019). Accurate model identification of the inertial mass dynamic of hydraulic cylinder with model uncertainty. Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, 233(5), 501-510.

[16]. Yao, J., Jiang, G., Gao, S., Yan, H., & Di, D. (2014). Particle swarm optimization-based neural network control for an electro-hydraulic servo system. Journal of Vibration and Control, 20(9), 1369–1377.

[17]. Wonohadidjojo, D. M., Kothapalli, G., & Hassan, M. Y. (2013). Position control of electro-hydraulic actuator system using fuzzy logic controller optimized by particle swarm optimization. International Journal of Automation and Computing, 10(3), 181-193.

[18]. 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.

[19]. Richalet, J., & O'Donovan, D. (2011, May). Elementary predictive functional control: A tutorial. In 2011 International Symposium on Advanced Control of Industrial Processes (ADCONIP) (pp. 306-313). IEEE.

[20]. Cho, S. H., & Edge, K. A. (2000). Adaptive sliding mode tracking control of hydraulic servosystems with unknown non-linear friction and modelling error. Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, 214(4), 247-257.

[21]. Ghazali, R. (2013). Adaptive Discrete Sliding Mode Control of an Electro-hydraulic Actuator System (Doctoral dissertation, Universiti Teknologi Malaysia).

[22]. Shern, C. M., Ghazali, R., Horng, C. S., Jaafar, H. I., & Soon, C. C. (2019). Performance Analysis of Position Tracking Control with PID Controller using an Improved Optimization Technique. Evolution (DE), 11, 12.

[23]. Salleh, S. & Rahmat, Mohd & Othman, Siti & A. Danapalasingam, Kumeresan. (2015). Review on Modeling and Controller Design of Hydraulic Actuator Systems. International Journal on Smart Sensing and Intelligent Systems. 8. 338-367.

[24]. “Actuators-servoactuators,” East Aurora, NY, 2013. [Online]. Available: www.moog.com/products/actuators-servoactuators

[25]. Ljung, L. (2007). Practical issues of system identification. Linköping University Electronic Press.

[26]. Barenthin, M. (2006). On input design in system identification for control (Doctoral dissertation, Signaler, sensorer och system).

[27]. P. Flandrin. Chirps everywhere. CNRS-Lyon, 2002.

[28]. Carnduff, S. (2007). Aircraft and Rotorcraft System Identification: Engineering Methods with Flight Test Examples MB Tischler and RK Remple American Institute of Aeronautics and Astronautics, 1801 Alexander Bell Drive, Suite 500, Reston, VA 20191-4344, USA. 2006. 523pp. Illustrated. 119.95 (non-members). ISBN 1-56347-837-4. The Aeronautical Journal, 111(1123), 601-601.

[29]. Ling, T. G., Rahmat, M. F., Husain, A. R., & Ghazali, R. (2011, May). System identification of electro-hydraulic actuator servo system. In 2011 4th International Conference on Mechatronics (ICOM) (pp. 1-7). IEEE.

[30]. Zuo, X., Liu, J. W., Wang, X., & Liang, H. Q. (2017). Adaptive PID and model reference adaptive control switch controller for nonlinear hydraulic actuator. Mathematical Problems in Engineering, 2017.

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

[32]. De Silva, C. W. (1989). Control sensors and actuators. Prentice Hall.

[33]. Ghazali, R., Sam, Y. M., Rahmat, M. F., & Hashim, A. W. I. M. (2010). Zulfatman," Sliding mode control with PID sliding surface of an electro-hydraulic servo system for position tracking control,". Australian Journal of Basic and Applied Sciences, 4(10), 4749-4759.

[34]. Li, B., Yan, J., Guo, G., Wang, H., & Zhang, M. (2012, July). Identification of dynamic parameters and friction coefficients for a heavy-duty hydraulic manipulator. In Proceedings of the 10th World Congress on Intelligent Control and Automation (pp. 3102-3106). IEEE.

[35]. Maier, C. C., Schröders, S., Ebner, W., Köster, M., Fidlin, A., & Hametner, C. (2019). Modeling and nonlinear parameter identification for hydraulic servo-systems with switching properties. Mechatronics, 61, 83-95.

[36]. Novak, A., Simon, L., Kadlec, F., & Lotton, P. (2009). Nonlinear system identification using exponential swept-sine signal. IEEE Transactions on Instrumentation and Measurement, 59(8), 2220-2229.

[37]. Xavier, T. S., Barbosa, E. C. G., & Góes, L. C. (2018, December). Predictive Control Design Based on System Identification of an Electro-hydraulic Actuator Applied to Brazilian Sounding Rockets and Microsatellite Launchers. In WIEFP2018–4th Workshop on Innovative Engineering for Fluid Power, November 28-30, Sao Paulo, Brazil (No. 156, pp. 63-68). Linköping University Electronic Press.

[38]. R. Adnan, M. Tajjudin, N. Ishak, H. Ismail, and M. H. Fazalul Rahiman. Self-tuning fuzzy pid controller for electro-hydraulic cylinder. In 2011 IEEE 7th International Colloquium on Signal Processing and its Applications. (pp. 395–398).

[39]. Ahmed, Mohammed & Halilu, Borskghinchin & Idi, usa & Mohammed, B.. (2015). System identification and control of a hydraulic actuator. 10. 9043-9047.

[40]. Rydberg, K. E. (2016). Hydraulic Servo Systems: Dynamic Properties and Control.

[41]. Van den Hof, P., Bombois, X., & Course, L. N. D. (2004). System identification for control. Delft Center for Systems and Control, TU-Delft. Lecture notes, Dutch Institute for Systems and Control (DISC).

[42]. Sastry, D. V. L. N., & Naidu, M. S. R. (2012). An implementation of different non linear PID controllers on a single tank level control using MATLAB. Int. J. Comput. Appl, 54(1), 6-8.

[43]. G. Zaidner, S. Korotkin, E. Shteimberg, A. Ellenbogen, M. Arad, and Y. Cohen. Non linear pid and its application in process control. In 2010 IEEE 26-th Convention of Electrical and Electronics Engineers in Israel (pp. 000 574–000 577). IEEE.

[44]. Wang, Z., Shao, J., Lin, J., & Han, G. (2009, August). Research on controller design and simulation of electro-hydraulic servo system. In 2009 International Conference on Mechatronics and Automation (pp. 380-385). IEEE.

[45]. Jahid Hasan , Tanmoy Karmaker , Mazid Ishtique Ahmed, 2019, Mathematical Modeling and Simulation based System Identification of Non-Minimum Phase Electro-Hydraulic Servo (EHS) System, INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH & TECHNOLOGY (IJERT) Volume 08, Issue 09 (September 2019).

[46]. Pencelli, M., Villa, R., Argiolas, A., Ferretti, G., Niccolini, M., Ragaglia, M., ... & Zanchettin, A. M. (2019, March). Accurate dynamic modelling of hydraulic servomechanisms. In 2019 Design, Automation & Test in Europe Conference & Exhibition (DATE) (pp. 1257-1260). IEEE.

[47]. Maier, C. C., Schröders, S., Ebner, W., Köster, M., Fidlin, A., & Hametner, C. (2019). Modeling and nonlinear parameter identification for hydraulic servo-systems with switching properties. Mechatronics, 61, 83-95.

[48]. Annus, P., Land, R., Min, M., & Ojarand, J. (2012). Simple signals for system identification. Fourier Transform-Signal Processing. InTech: Rijeka, 257-276.

[49]. H. Peng, T. Ozaki, K. Nakano, V. Haggan-Ozaki and Y. Toyoda, "Stability analysis of the RBF-ARX model based nonlinear predictive control," 2003 European Control Conference (ECC), 2003, pp. 3129-3134, doi: 10.23919/ECC.2003.7086520.