Dynamic Performance Analysis of PID and Fuzzy Logic Controllers Applicable in Electrohydraulic Servo Actuator

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***Abstract*—Electrohydraulic servo actuators (EHSAs) are the main element of many hydraulic systems used for variety of applications. They are usually preferred because of their unique and flexible characteristics. However, to optimise their performance, these systems are usually accompanied with sophisticated control systems. Generally, there are different types of control systems or algorithms, and the choice of the suitable one is subjective and based on a trade-off between different system parameters. This paper presents a critical appraisal of two types of control algorithms, PID and Fuzzy logic, and investigates the relative performance of them when applied to EHSAs using the Moog 760 servo valve. The PID controller was design using Trial and Error and Ziegler-Nichols methods. It was concluded that a proportional P controller is suitable for controlling the system. The response of the P controller is fast, but it contains oscillation and this makes it nonsuitable for some aspects of applications. The Fuzzy controller was separated into Sugeno and Mamadani. Sugeno is more preferred than Mamdani to control EHSAs systems because it produces a faster response. The Fuzzy controller response has no oscillations and this is suitable for many important/high precision applications such as robotics and military systems.**

1. Introduction

Currently the demand to efficiently control the power of pressurise fluid systems is increasing because they can achieve high power to wait ratio. Since their creation, they have been through many stages of development reading to the discovery of electro-hydraulic-servo systems [1]. EHSAs applications are wide ranging and divers. This is due to their many advantages such as high accurate control, high stiffness, zero backlashes, and rapid response [1] and [2]. In aerospace, EHSAs are used to control aircraft surfaces such as rudders, elevators, slats and undercarriage [3]. Regarding to military applications, EHSAs has been used for Antenna elevation, point actuation, level actuation and missile steering and turret stabilisation. Also, they are heavily used in automotive industries, transportation, mining, construction, agriculture, four-wheel driving and modern driving and flight or driving simulator [4]. Other applications are in material handling, metal and plastic forming, robotics and CNC machines [1]and [5]. Figure 1 shows the main components of EHSAs. The servo electronics is used to control a power modulator that controls the direction and amount of fluid. This servo electronics is designed based on a control system with different types and procedures. Generally, control systems for EHSAs can be divided into feedforward and feedback. Position feedback is the most preferred because it has a direct effect on the overall system stability [6]. The criteria for the stable EHSAs shouldnt exceed amplitude ratio of 1.3, overshoot 23%, amplitude margin 45 and damping ratio 0.45. Different types of position feedback control systems are used and they are classified between traditional and intelligent control systems. Firstly, traditional controllers, such as PID controllers, are widely used in different industrial applications because of its simplicity and easy online tuning. It was used to design a magnesium alloy rolling machine [7].

Moreover, a high speed linearized PD controller was designed to control a mini press machine [8]. The performance of the linear PD controller using an ITEA technique was better than the performance of nonlinear control strategies, and the latter is also more complicated in design [9]. On the other hand, the effect of state feedback controllers incorporating a feedback linearization compensator was discussed in [9]. As a result of this research, the linearized system can be largely affected by external disturbances. Feed-forward compensation by the pole-zero placement theory can be used to improve the position tracking and increase the system bandwidth that required in specific application such as shaking table which requires about 100 Hz bandwidth [10]. Finally, the adaptive inverse controllers can be used to overcome the nonlinearity of the system and the disturbances during operation using parameter estimation. This is used to diminish the nonlinearity effects by age [11].

Secondly, intelligent controller such as a neural network and a fuzzy logic controller are used to control the EHSAs system. The neural network approach relies on many factors such as number of model layers, training and experience of the system performance. These factors make the neural network more complicated than other controllers, but it gives a better performance especially after long training [12].

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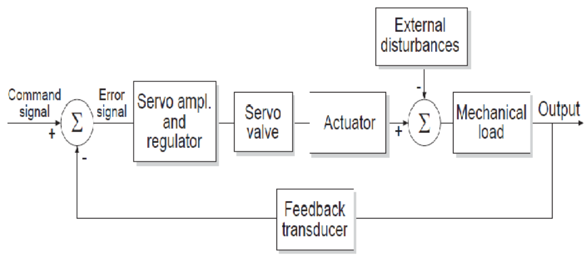

Figure 1 Main components of electrohydraulic servo system.

Similarly, fuzzy logic control produces more accurate positioning and a better performance as a whole depending on the experience of the system [13]. A fuzzy logic controller demonstrated a better performance comparing to traditional controller, PID, as it had diminished the response oscillation [14]. Many techniques are used to design fuzzy controllers such as trial and error and particle swarm optimization [14], which was used to design PID controller for a reusable launch vehicle that is used to carry a payload from earth surface to outer space [15]. With regard to the speed, fuzzy controllers are a bit slower than PID controller, and this depends on the number of fuzzy parameter and the type of a fuzzy controller: Mamdani or Sugeno. However, in EHSAs systems, Sugeno is more preferable because of its quicker response [16]. Some applications use the fuzzy PID technique such as maintenance processes in the China Fusion Engineering Test Reactor (CFETR) blanket remote handling (RH) [17]. Fuzzy PID is one of hybrid controllers that are being improved in these days to take advantages of both controllers [18]. Finally, some of iterations to improve the performance of EHSAs are based on the mechanical design such as changing the piston size [19]. Based on the previous literature review, this research will focus on investigation the performance of Fuzzy logic controller in EHSAs comparing with PID. It explores how the Fuzzy controller can improve the response performance such as speed, response oscillation and Bandwidth for Moog 760 valve model.

2. CONTROL SYSTEMS

2.1. PID CONTROLLER

The PID (Proportional, Integral and Derivative) controller is the most famous controller used in industry due to its simple construction and easy online tuning [20]. This controller is split into two main types which are series and parallel. The series model is not as commonly implemented as the parallel model which is represented in Equation 1, [20]. Table 1 summarizes the parameters effect on the system response.

$$PID = K_p * e(t) + K_i * \int_0^t e(t)dt + K_d * \frac{de}{de} \quad (1)$$

PID controller design methods can be classified into two main types, Classical and Computational techniques [22].

TABLE 1 Relation betweeb parameter and closed loop response [21]

Response	Rise time	Overshoot	Settling time	Steady state error	Stability
Increasing Kp	Decrease	Increase	Small Increase	Decrease	Degrade
Increasing Ki	Small decrease	Increase	Increase	Large decrease	Degrade
Increasing Kd	Small decrease	Decrease	Decrease	Minor change	Improve

The classical is based on Trial and Error, Ziegler-Nichols Method and Cohen-Coon Method [21]. The computational methods are such as Immune algorithm, Ant colony optimization, Bacteria forage technique, Genetic algorithm and Artificial neural network, [21]. This paper focuses on Trial and Error and Ziegler-Nichols as they help to better explain the system itself.

In fact, step response analysis is a suitable method to evaluate the performance of the controller as the frequency response is used to evaluate the system stability. Based on table1, the Trial and Error technique is to reach one-quarter peak ratio [21]. Similarly, Ziegler-Nichols technique is performed by disconnecting the integration and derivative parameter then increasing the proportional gain until the periodic oscillation appears. This gain is called ultimate gain Ku and the oscillation period is called ultimate period Pu and then follows the procedure shown in Table 2 Ku and the oscillation period is called ultimate period Pu and then follows the procedure shown in Table 2.

TABLE 2 controller parameter using Ziegler nichols [21]

Type	Kp	Ki	Kd	Stability
P	Ku/2		Small Increase	
PI	Ku/22	1.2Ku/Pu	Increase	
PID	0.6Ku	2Ku/Pu	Decrease	KuPu/8

2.2. FUZZY LOGIC CONTROLLER

The use of Fuzzy logic controllers has already been successfully in different areas. The combined use of Fuzzy control systems and microelectronic is seen to constitute as a major leap in electrohydraulic servo systems because of many favourable characteristics listed below.

1) The nonlinear relation between the input and the output.
2) The fuzzy logic controller can be multi input multi output (MIMO) controller.
3) It is suitable for adaptive controlling design.
4) Fuzzy logic control technique is based on qualitative study [22]. It evaluates parameters and control signals using if statement as following: If (antecedents) Then (consequences).

The antecedents are called premise and they express the value of error which is the difference between the desired and output values, and the consequence represents the action should be taken to reach the desired. The main construction of fuzzy logic controller is shown in Figure 2.

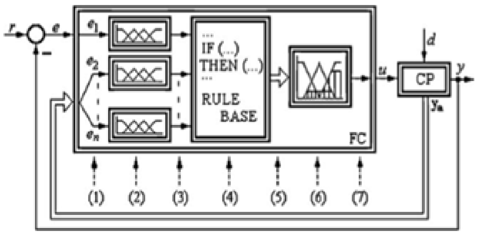

Figure 2 Main construction of fuzzy logic controller [23]

The two main parts of fuzzy logic controller are rule base and inference engine. The rule base is a collection of IF-THEN statements that can be MIMO or single input SISO. The inference engine contains three steps which are aggregation, activation, accumulation. Input signals are usually prepared for the next stage by removing noises, scaling. After that the controlling parts which are as follows:

1) Fuzzification: It is the process of converting classical variables into fuzzy variables [23].
2) Inference engine: This block contains control signal operations and has the following stages:
    a) Aggregation: This stage is to determine the degree of fulfilment of every rule in the memberships and this can be determined by the min relation between the premise memberships.
    b) Activation: This stage is to determine the conclusion based on every rule.
    c) Accumulation: In this stage, the final conclusion based on every rule result obtained.
3) Defuzzification: This process is to convert the output from fuzzy to a crisp. Defuzzification techniques are Mean of the maximum method, Centre of gravity method and weighted average method. The most popular and trustful technique is centre of gravity implemented by Equation 2.

$$GOC = \frac{\int \mu(x_i) x_i dx}{\int \mu(x_i) dx} \tag{2}$$

As indicated before, there are two main types of fuzzy controllers which are Mamdani and Sugeno. The main difference between them is the output calculation method. The Mamdani is based on finding an amount of the output in the memberships relying on the firing value of the input and also it uses membership function for result analysis [24] . With regard to the Sugeno controller, it is more preferred to Mamdani in industrial applications because it produces higher quality numerical prediction [6]. The main difference between this and Mamdani is that the conclusion is a linear function of the input.

3. VALVE MODEL DESIGN

The model used in this research is Moog 760 servo valve with 10 cm stroke symmetrical double actuator. Servo valves have different types according to positions and ports number, but the most famous one, and which is mainly used in load position controlling is 4/3 valve. On the other hand, another classification is based on the number of stages one, two or three stages. The most famous type is a 2 stages servo valve. This part is separated into three main types, two spool valve, jet pipe and flapper jet servo. Figure 3 shows the flapper jet servo. The working principle of this type that flapper movement produced by electrical motor controls the fluid pressure on the both sides of the main spool by opening and closing the nozzles around the flapper. The feedback wire is used to produce more precise control. The actuator used in this model is double acting cylinder.

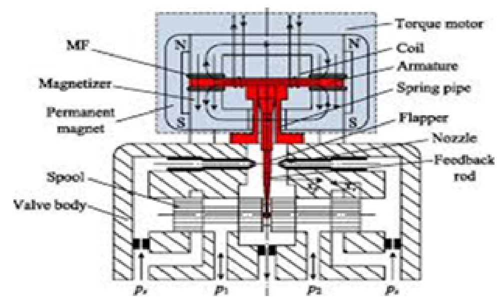

Figure 3 flapper Jet servo valve [2]

A mathematical model to represent each part of the system is necessary to develop the simulation using Matlab. The first part is the servo valve which splits into three parts. The mathematical model of the electrical torque motor which is represented by Equation (3) [2].

$$\frac{I(s)}{V(s)} = \frac{1}{sL_c + R_c} \tag{3}$$

The spool dynamic modeling is the most complicated one because of the inherent nonlinearity [2]. Moog Company in their technical bulletin concluded that it is impossible to find a transfer function which can govern all the operation of the servo in spite of increasing the order of the differential equation to 8 [25]. The suitable equation can be used to model this part is Equation (4)and the parameters of this equation can are listed in valve data sheet [26].

$$\ddot{X}_v + 2\omega_n \zeta \dot{X}_v + {\omega_n}^2 X_v = I * {\omega_n}^2. \tag{4}$$

The valve flow pressure that is represented by Equation(5).

$$Q = A_o C_d = \sqrt{\frac{2}{\rho}(p_1 - p_2)} \tag{5}$$

Based on Equation(5) and Figure(4) the equations that represent the flow are as follows:

$$Q_A = A_a(X_v)C_d\sqrt{\frac{2}{\rho}(P_s - P_A)}$$
$$Q_b = A_a(X_v)C_d\sqrt{\frac{2}{\rho}(P_A - P_r)}$$
$$Q_c = A_a(X_v)C_d\sqrt{\frac{2}{\rho}(P_B - P_r)}$$
$$Q_d = A_a(X_v)C_d\sqrt{\frac{2}{\rho}(P_s - P_B)} \quad (6)$$

The flow into and from the cylinder indicatedas follows:

$$Q_A = Q_a - Q_b$$
$$Q_B = Q_c - Q_d \quad (7)$$

The change of restriction area is indicated in the following equations:

$$A_a = A_c = \omega\sqrt{(X_v)^2 + C^2} \quad \forall X_v > 0$$
$$A_a = A_c = \omega C \quad \forall X_v < 0$$
$$A_b = A_d = \omega C \forall X_v > 0$$
$$A_b = A_d = \omega\sqrt{((X_v)^2 + C^2)} \forall X_v < 0 \quad (8)$$

The output pressure can be determined using the following equations:

$$PA = \int \frac{\beta}{V_c + A_p X_p}(Q_A - A_p\dot{X}_p - QL_i - QLe)dt$$
$$PB = \int \frac{\beta}{V_c - A_p X_p}(-Q_B + A_p\dot{X}_p - QL_i - QLe)dt$$

QLi: Internal leakage

QLe: External leakage (9)

The dynamic operation of the hydraulic actuator is represented using following equations:

$$F_p = A_p(PA - PB)$$
$$F = M_p\ddot{X}_p + B_l\dot{X}_p + K_l X_p \quad (10)$$

The parameters of the system are included in Table 3. All the previous equation will be used to design a model for simulation using Matlab Simulink

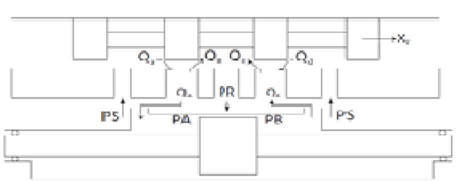

Figure 4 Valve and cylinder flow paths

4. SIMULATION AND ANALYSIS

4.1. PID CONTROLLER

The two methods will be applied are Trial and Error and Ziegler Nichols methods. The first method response is

TABLE 3 Parameter, Symbol and value

Piston mass	M	$9Kg$
Initial chamber volume	v_c	$32.25 * 10^-6m^3$
Piston Area t	A_p	$30 * 10^-4m^2$
Resistance to internal leakage	R_i	$10^{20}Pas/m^3$
Resistance to external leakage	R_e	$10^{20}Pas/m^3$
Ration of peaking servo valve	M_v	$1.5dB$
Servo valve damping ratio	ζ	0.48
Servo valve natural frequency	ω_n	$534rad/s$
Coil inductance	L_c	$0.59H$
Coil resistance	R_c	100Ω
saturation current	I_{sat}	$0.02A$
Spool radial clearance	C	$1 * e^-6m$
Spool port width	ω	$0.002m$
Discharge coefficient	c_d	0.611
Fluid density	ρ	$867kg/m^3$
Bulk modulus	β	$1.5e9Pa$
Supply pressure	P_s	$2e7P_a$
Return pressure	P_r	$0P_a$
Viscous damping	B_l	2000
Spring stiffness	K_l	$2N/m$

shown in Figure(5), and this is using gain factor 300 for P controller. The obtained rise time is 5.2ms and settling time is 15ms. These results are very close to the response criteria of Moog 760 valve spool which can be obtained from the natural frequency and damping ratio in Table 3. Adding integration parameter starts to introduce steady state error that results in in the increased overshoot. However, the integration effect is usually inherited in servomechanism positioning system and due to that integration part isnt required. In this system the PD controller produce a close result to the P controller, but its very sensitive to noises and due to that the controller is left as Proportional part only.On the same manner, Ziegler Nichols method design indicated that the best design is P =407 as shown in the response marked PID in Figure(5), and usually Ziegler-Nichols method need to be modified by Trial and Error so it will be again about 300.

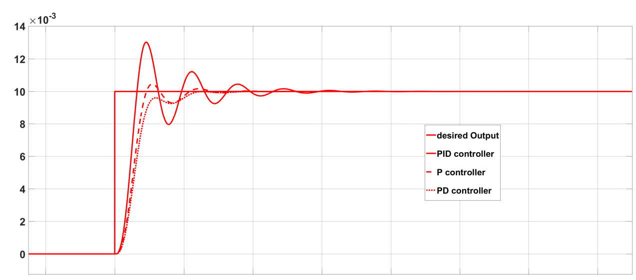

Figure 5 P,PD and PID controller responses. PID is using Zigeler Nichols method

4.2. FUZZY LOGIC CONTROLLER

This section explores the ability of fuzzy controller and it will be based on the Matlab toolbox. Many researches were performed in this topic. For example, the number of memberships was 7, triangle memberships without gaps and Mamdani type in [27]. A comparison between the Mamdani and Sugeno types controllers using 7 membership functions for input and output to determine which produces a faster response , the faster response was by Sugeno and the number of output memberships were less than Mamadni which means a simpler controller may require. The membership function shapes used were triangular and trapezoidal. The arrangement of membership functions was based on using trial and error to get the best response without oscillation [28]. This paper proved that the response of Sugeno controller was better than that of Mamdani. Finally, and based on this review with some iterations, the best and simplest form that satisfies the stability is a 7 memberships 5 triangular and two trapezoidal without gap and 50% intersection for both types of controller Sugeno and Mamdani.

4.2.1. MAMDANI CONTROLLER . The chosen range as input for this controller is [-0.01 to 0.01] to give movement of 10 mm and the output range is [-0.8 to 0.8] based on Trial and Error as shown in Figure (6)and (7) . The input range consists of 7 memberships which are Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Big (PB), the output has the same configuration also. All of these memberships are triangular except NB and PM are trapezoidal to produce better and more stable results [24]. The defuzzification for this output is based on Centre of gravity. The response for 10 mm response is shown in Figure (9). The rise time is 47.5 and the overshoot is 0.4% and this is not suitable for many applications because it is too slow. As results of oscillated sine input, the maximum frequency bandwidth within which the system can track the input signal is 50 Hz.

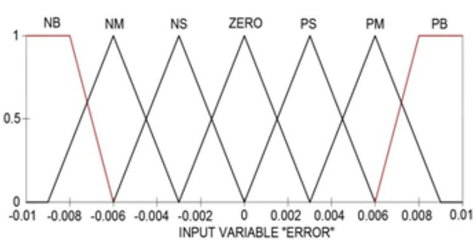

Figure 6 Input memberships for Fuzzy controllers

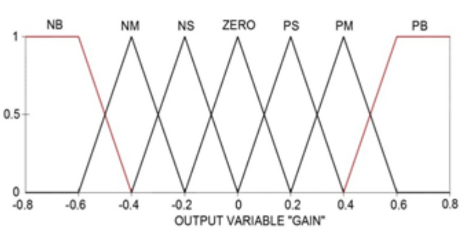

Figure 7 Output memberships for Mamdani controller

4.2.2. SUGENO (E) CONTROLLER . It has the same input and output ranges of Mamdani (E) as illustrated in Figure (6)and Figure (8). But, the gains were designed based on zero order function which means that every membership has one value of the output gain values. The relation between the input and the output are presented in Table (4) which is called the lookup table. The step response for 1 cm is shown in Figure 19 which indicates that the rise time is 24.35 ms, the settling time is 33 ms and the overshoot is 0.45%. As results of many iterations were performed on the system the maximum allowable frequency bandwidth for the system is 90 Hz.

TABLE 4 Sugeno memberships relations

Error	BN	MN	NS	ZERO	PS	PM	PB
Gain	BN	MN	NS	ZERO	PS	PM	PB

4.2.3. SUGENO (E,CE) CONTROLLER. Adding the change of error helps to predict the future error and modifies the signal based on the response. The inputs for the controller are the error and differentiation of it as mapped by the lookup table 5. Using the same memberships values of previous controller, Sugeno (E) controller produces a little bit faster response, Figure (9). As concluded from iterations that changing error values has a good effect system performance. The response of the system with these parameters is rising time and settling time 10 ms and this is faster than all the previous controllers without oscillations. This controller produces a bandwidth about 120 Hz and this is very suitable for many systems such as shaking table.

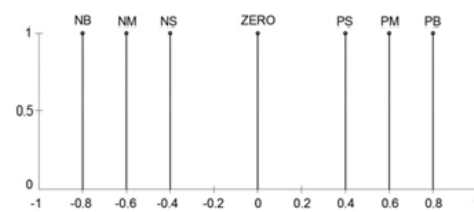

Figure 8 Main components of electrohydraulic servo system.

TABLE 5 Sugeno (E.CE) rules map

E \ CE	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

5. CONCLUSION

A critical appraisal of the differences in performance PID and Fuzzy logic controller for EHSAs was conducted when applied to control a Moog 760 servo valve with 10 cm stroke actuator. This was to evaluate the performance of modern intelligent controller Fuzzy logic, especially on Moog 760 model. As a result it can be concluded from this paper that PID controller is simpler in construction and produces good results that satisfy the requirements and criteria of a stable control system. PID can be used as general purpose and simple control systems that allow for

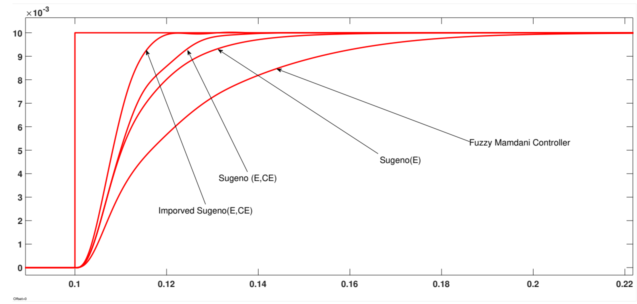

Figure 9 Fuzzy logic controllers responses

high tolerance in the response such as industrial application. The main disadvantage of this controller is its response oscillation. This makes it non suitable for sensitive applications such as robotics that are used in production lines and nuclear planets. On the other hand, the performance of fuzzy logic controller was better using Sugeno (E,CE). It produces a fast response without oscillation, and this is very suitable for high precision applications such as microelectronics, robotics, military and nuclear applications. With regard to the system bandwidth, PID controller produced a better response which is about 400 Hz while the maximum bandwidth achieved by Fuzzy controller is 120 Hz and this is due to the conditions processing (Pre and post). Finally, a designer has to trade-off between different control methods and procedure according to the system requirements.

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