SEPTEMBER 2017   M. Sc. in Mechanical Engineering   MEHMET ÖKSÜZ

UNIVERSITY OF GAZİANTEP

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MOTION CONTROL OF AC CRANK SERVO PRESS: FUZZY LOGIC APPROACH

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IN

MECHANICAL ENGINEERING

BY

MEHMET ÖKSÜZ

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Motion Control of AC Crank Servo Press:

Fuzzy Logic Approach

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Supervisor

Prof. Dr. L. Canan DÜLGER

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Mehmet ÖKSÜZ

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This is to certify that we have read this thesis and that in our consensus opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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Mehmet ÖKSÜZ

ABSTRACT

MOTION CONTROL OF AC CRANK SERVO PRESS: FUZZY LOGIC APPROACH

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M. Sc. in Mechanical Engineering
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Servo presses have provided an alternative to conventional and hydraulic presses in recent years. They offer flexibility, accuracy and reliability in industrial applications. Servo motor can perform free motion concepts for presses with operational advantages. Fuzzy logic control techniques have been applied to a wide range of engineering systems. The structure of fuzzy logic consists of three functional blocks; fuzzification, interface, and defuzzification. In fuzzy controllers, the control rules are not described analytically. They are expressed in linguistic rules describing the relation between the inputs and the outputs providing flexibility.

A cascade fuzzy-PID controller is proposed for an AC servo crank press in this thesis. The system; servo crank press, cascade fuzzy-PID controller and AC servo motor dynamics are modeled by using MATLAB Toolboxes (Simulink and Fuzzy Logic). Theoretical and experimental studies are performed on servo press control. Deep drawing implementations are performed as case studies. Simulation and experimental results are supported validity of the cascade fuzzy-PID controller proposed.

Key Words: Crank servo press, AC servo press, fuzzy-PID controller, cascade fuzzy-PID controller, metal shaping-deep drawing

ÖZET

AA KRANK SERVO PRESTE HAREKET DENETİMİ: BULANIK MANTIK YAKLAŞIMI

ÖKSÜZ Mehmet

Yüksek Lisans Tezi, Makine Müh. Bölümü

Tez Yöneticisi: Prof. Dr. L. Canan DÜLGER

Eylül 2017

74 sayfa

Servo presler son yıllarda geleneksel ve hidrolik preslere alternatif olarak kullanılmaktadır. Servo presler endüstriyel uygulamalarda esneklik, doğruluk ve güvenilirlikle birlikte operasyonel avantaj sağlamaktadır. Bulanık mantık denetim teknikleri birçok mühendislik sistemlerinde uygulanmaktadır. Bulanık mantık yapısı üç işlevsel bloktan oluşur; bulanıklaştırma, üyelik derecesi ve durulaştırma. Bulanık denetleyicilerde denetim kuralları analitik olarak belirtilmez. Giriş ve çıkışlar dilsel olarak belirtilerek esneklik sağlanmaktadır.

Tezde kaskat bulanık-PID denetleyicileri AA servo presin hareket denetiminde kullanılmıştır. Servo krank pres, AA servo motor ve kaskat bulanık-PID denetleyiciden oluşan sistemin matematik modeli çıkarılarak, Matlab’ta araç kutuları kullanılmış, çözümlenmiştir (Simulink ve Bulanık Mantık). Kuramsal ve deneyler çalışmalar birlikte yürütülmüş, servo presin denetimi sağlanmıştır. Tasarlanan koç hareketleri uygulanmıştır. Derin çekme hareketleri uygulanmıştır. Benzetim ve deneysel sonuçlar kaskat bulanık-PID denetleyicinin uygunluğunu ve başarımını göstermiştir.

Anahtar Kelimeler: krank servo pres, AA servo pres, bulanık-PID denetleyici, kaskat bulanık-PID denetleyici, metal şekillendirme, derin çekme

To My Mother...

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I would like to express my sincere gratitude to Prof. Dr. L. Canan DÜLGER without her guidance, motivation, and encouragement this thesis would not have become a reality. She motivated me to pursue my studies in all stages of the thesis.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

In the last years the artificial intelligence techniques have been used to perform intelligent control. Modeling and simulation of human intelligence is taken the highest interest in research studies. Intelligent systems are described by means of analogies taken by existing biological systems. However, making decisions is always not easy task during control. Fuzzy logic makes machines more intelligent by using approximate reasoning. It has been a powerful tool in many fields showing successful implementations. The following steps are available; fuzzification, knowledge base, fuzzy reasoning mechanism and defuzzification unit. The most important parts are to design of membership functions and fuzzy rules in applications.

1.2 Background on Fuzzy Logic and Applications

Fuzzy Logic is proposed by Lotfy Zadeh in 1965. He described the idea as 'Attempt to mimic human control logic'. So, the idea is introduced as a logical system which is closer to human thinking than traditional ones. This method is then used in different application areas including engineering [1]. Successful applications on fuzzy theory has been grown in the 1990s. Some applications can include areas; physics, chemistry, biology, geology, nuclear engineering, and others. Fuzzy logic idea is the most commonly seen in electrical engineering; image processing, electronic circuits or robotics. Among the other engineering disciplines; civil, mechanical, industrial, and computer have recognized importance of idea in the 1970 and mid 1980's respectively. In the 2000's, it has been a standard technology; it is then applied to data and signal analysis.

1.3 Applications in Engineering and Control

Primary interest has been seen especially use of fuzzy controllers in manufacturing and human machine interaction in recent studies. Fuzzy logic is applied to different fields as defense systems; detection, identification, tracking of aerial targets (37%), geo-science (17%), robotics and intelligent vehicles; navigation, tracking trajectory (14%), medicine (7%), industrial engineering (6%) and others (19%) [2]. The application in control engineering has taken the major role with embedded control (28%), industrial automation (62%) and process control (10%). In the past two decades; many non-engineering applications are also seen in medicine, social sciences and economics [3]. Additional areas are noticed in optimization, cognitive mapping and agent-based models [4].

Hybrid applications are very effective designing intelligent control systems. By taking advantage of one method and eliminating drawbacks, hybrid approaches are seen. Fuzzy logic has been a good alternative in artificial intelligence (AI) applications. The idea can also be used together with conventional control techniques or heuristic approaches. Fuzzy controllers utilize heuristic information for developing methodologies for system control. Hybrid fuzzy logic applications refer the techniques fuzzy logic with other techniques and/or cascaded manner. Fuzzy-PID, Fuzzy-PI, fuzzy-PD, DSP based Fuzzy, model reference fuzzy cascade (MRFC) controller, model reference fuzzy adaptive PI (MRFA-PI) controller are seen in literature [5]. Similarly, evolutionary fuzzy systems represent hybrid fuzzy systems were evolutionary algorithms are used with fuzzy like fuzzy-GA. Especially GA-fuzzy systems are commonly seen as evolution based fuzzy system. The integration of neural network (NN) and fuzzy logic (FL) can be applied as neuro-fuzzy systems (NF), fuzzy neural network (FNN) and fuzzy-neural hybrid systems for example [6].

1.4 Organization of Thesis

Although an extensive literature is available in fuzzy logics and its applications, here our main concern is to reveal and apply idea of fuzzy logic as fuzzy-PID and cascade fuzzy PID in the system of interest. Thus, this thesis consists of five chapters. Chapter 2 is introduced a literature review on Fuzzy Logic for AC servo systems and servo presses. The aim of this thesis is to develop a fuzzy-PID controller for position control of an AC servo press system using MATLAB/Simulink. Fuzzy Logic toolbox is given in Chapter 3 with designed fuzzy-PID controller and cascade fuzzy-PID controller. Fuzzy Logic and PID tuning are described. Membership functions are designed Cascade Fuzzy-PID is designed in Chapter 4. Chapter 5 is included the performance of the system with some metal stamping applications by using servo press. Two case studies are performed on the system; Soft motion and Coining motion which are preferred in deep drawing applications. Conclusions and discussions are given in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Fuzzy logic control design is different than traditional control design. The main idea is to model the human mind. Generally, speaking there are three methods for description of a system; experimental method, mathematical modelling, and heuristic method. This chapter includes three parts as; fuzzy control on AC servo systems, fuzzy control in servo press use especially on metal shaping industry and the statement of problem. So, the literature is summarized on research studies performed during last 2 decades, and also the ones going on recently.

2.2 Survey on Fuzzy Control on AC Servo Systems

Control problems have had the best success in fuzzy control; designing a controller, tuning PID parameters etc. Here the studies are summarized on AC servo systems in the following.

Kim et al. (2001) designed a neuro-fuzzy controller for speed control applied to AC servo motor system. Experimental results are presented for PID, fuzzy controller and Neuro-Fuzzy controller using AC servo motor with varying loads. Finally, Neuro-Fuzzy controller is given less error with quicker rising time and slower learning time, also more stable with fuzzy rule [7].

D. Lakovou (2002) has given thesis on helicopter aviation by using fuzzy control and MATLAB tools. GUI has been developed and implemented. Simulations are managed by using the mathematical model with Simulink and MATLAB/Fuzzy Toolbox. X-Cell 60 SE helicopter parameters are applied [8].

J.H.Pujar and S.F.Kodad (2009) have presented an application of fuzzy logic to control the speed of an AC servo system. Direct fuzzy control of SVPWM inverter-fed PMSM AC servo system has been described, and analysed. Direct Torque Fuzzy

Control (DTFC) is superior to Direct Torque Control (DTC). Simulation has been performed in MATLAB/Simulink. Conventional DTC is given quick response but considerable ripple in torque, flux and current. DFTC is given better performance, robustness, and tracking precision [9].

J. Yu et al. (2009) have improved PMSM motor performance by using fuzzy logic PID controller based on smooth switching. Numerical simulation and experiments (1.1 kW PMSM) are performed. Compared with fuzzy-PID only, rise time, settling time and overshoot are considerably reduced [10].

S.W. Vikas et al. (2010) performed a study on position control of the switched reluctance motor (SRM) by using fuzzy logic. Simulation studies are carried on MATLAB environment [11].

Choi and Jung (2011) have presented Takagi-Sugeno (T-S) fuzzy approach for a fuzzy speed control system for permanent magnet synchronous motor (PMSM). Simulation and experimental results are included together. Proposed control system is given better results under model parameter and load torque variations [12].

J.Xu et al (2011) have proposed position control of AC servo system by adopting fuzzy PID based on Stribeck friction disturbance model. The control performance of system position is simulated by using traditional PID and fuzzy PID. Tracking precision of servo system is improved by fuzzy-PID decreasing influence of friction. Better position tracking is achieved by adopting fuzzy PID [13].

C.X.Gang et al. (2013) have combined fuzzy adaptive control methods with PI. It is applied to PMSM servo system and fuzzy-PI controller is built. System simulation is performed in MATLAB/Simulink environment. Motor speed is controlled with shorter rising time, small overshoot, and robust dynamic performance [14].

R.H.Du et al (2013) have studied on an adaptive fuzzy speed controller in the permanent magnet synchronous motor servo system. Simulations and experiments have shown better adaptivity and robustness with PI controller [15].

Maamaun et al. (2013) have presented a fuzzy logic controller (FLC) for speed control of permanent magnet synchronous motor (PMSM) drive. PI controller is tuned with fuzzy logic for speed control. Simulation studies are performed with (0.95

kW, 3 phase, 3 Nm and 3000 rpm) advantages of FLC under transient conditions [16].

2.3 Survey on Fuzzy Control of Servo Press Systems

In recent studies, servo motor controlled presses have seen on many industrial applications for sheet metal forming, blanking, stamping, and coining. Studies on metal forming are summarized here to reveal the idea.

Huang et al. (2006) have proposed a fuzzy-PID controller to improve the performance of a CNC servo system. Simulation studies are presented. PID and fuzzy-PID controlled system results are compared. A simulation model is prepared in MATLAB/Simulink based on a high speed milling machine. Quicker response, shorter settling time and stronger disturbance rejection are observed [17].

D.Q.Troung et al. (2011) have presented online tuning fuzzy PID approach based on Kalman filter. High force control precision is performed in the press machines. A test press bench is suggested as electro hydraulic test machine. The press performances are tested using PID, fuzzy PID, and a comparison is made. So robust extended Kalman filter (REKF) has given better control performance during real-time experiments [18].

H. Zhongliang and W.Xingsong (2012) have studied a fuzzy PID controller to control the position of AC servo press. PID parameters are set by using Borland C++ Builder. The experimental results are shown reduced overshoot, reduced settling time with little steady state errors. Fuzzy PID has given better performance than traditional PID. Experiments are realized on 2 tonne mini-press [19].

N.J.Soufi et al. (2014) have presented the formulation based on parameter varying PD fuzzy servo controller. Simulation results showed that fuzzy-PD controller has given better performance than PID with inclusion of changed parameters and disturbance [20].

H.M.Chen et al. (2014) have designed a PC based force control for the electrohydraulic servo press system. A fuzzy controller is designed with LabVIEW. Precision force servo control is performed. Maximum overshoot is reduced [21].

Halicioglu (2015) has presented AC servo press design and implementation for 50 tonne industrial press. System is designed for metal stamping operations. Cascade feedback control is used for an AC PMSM motor with a gear reducer. Different motion scenarios are designed and applied for metal forming. Ram motion performances are seen experimentally and also theoretical studies deriving the system's mathematical model [22].

2.4 Problem Definition

Initially background on the study is given on fuzzy logic and its applications on metal forming industry previously. This research is focused on a prototype 50 t crank servo press which is manufactured on a research project (SANTEZ). The control structure used was cascade-PID in previous research in the experimental system [22].

The system mentioned is used for different deep drawing applications this time. Its control structure is revised by using cascade fuzzy-PID controller. Fuzzy advantages will be seen during implementations. Mathematical model including AC PMSM motor will be included. These results will be supported by deep drawing applications on the prototype servo press. So, this thesis will be complementing part on control issues for the previous project.

CHAPTER 3

AC SERVO CRANK PRESS SYSTEM

3.1 Introduction

This section describes the experimental setup, and the system technical properties. The following section presents mathematical modelling of the slider crank mechanism with the actuator dynamics (PMSM). After analyzing the mathematical model, the transfer function of the system is attained. Finally, the state-space matrices are calculated from the transfer function of the system to design a controller. The transfer function and the state-space representation of the system are given.

3.2 Experimental System

Servo presses have been used in sheet metal deep drawing, shearing, stamping, and bending as an alternative to hydraulic and conventional presses. Several advantages are seen by comparing them with respect to hydraulic and conventional presses. These advantages are summarized as: The desired slide motions can be modified to extend the working ranges. During press motion, the touching speed is controlled and loading by impact is definitely reduced. Optimum motion characteristics can be designed. So, the accuracy of product is improved by establishing the optimum motion characteristic and slide motion control. Structural size of a servo press is smaller than the other press types. AC Servo motor (PMSM) and a slider crank mechanism are assembled to each other to provide these advantages, designed and manufactured. It has $50\,ton$ and $200\,mm$ stroke capacity. It is available in Mechanical Engineering Laboratory, University of Gaziantep.

3.2.1 AC Servo Motor (PMSM) Model

PMSMs have two main types; DC and AC. DC motor with brushes have similar function with PMSM. DC motor in fixed magnetic field is designed by permanent magnets or coils of armor But PMSM has an inverse manner, PM to create fixed field in the rotor and stator coils in which voltage to control speed and torque are applied [23]. PMSM is also called AC servo motor. These motors are operated with feedback monitoring system by using position sensors. They are also being used in applications where reliability, smooth torque, low noise, and low vibration [24].

These motors are usually required where high performance needed. They also have small size and volume by introducing wider speed ranges. They are attractive to use in wide applications [25]. Because the PMSMs have low inertia, high power potential, low noise, high efficiency, low maintenance cost, robustness, low volume and weight, smooth torque, and low vibration. The applications are CNC machines, robots, textile industry, plastic industry, conveying technology, wood processing, machine tools etc. [12,26]. According to available information, 18.6 kW AC PMSM (Parker-M_2053090®) servomotor is selected by Halicioglu et al [22] used in the experimental setup. It is illustrated in Figure 3.1, the features of motor and its driver are written in Table 3.1 and Table 3.2 respectively.

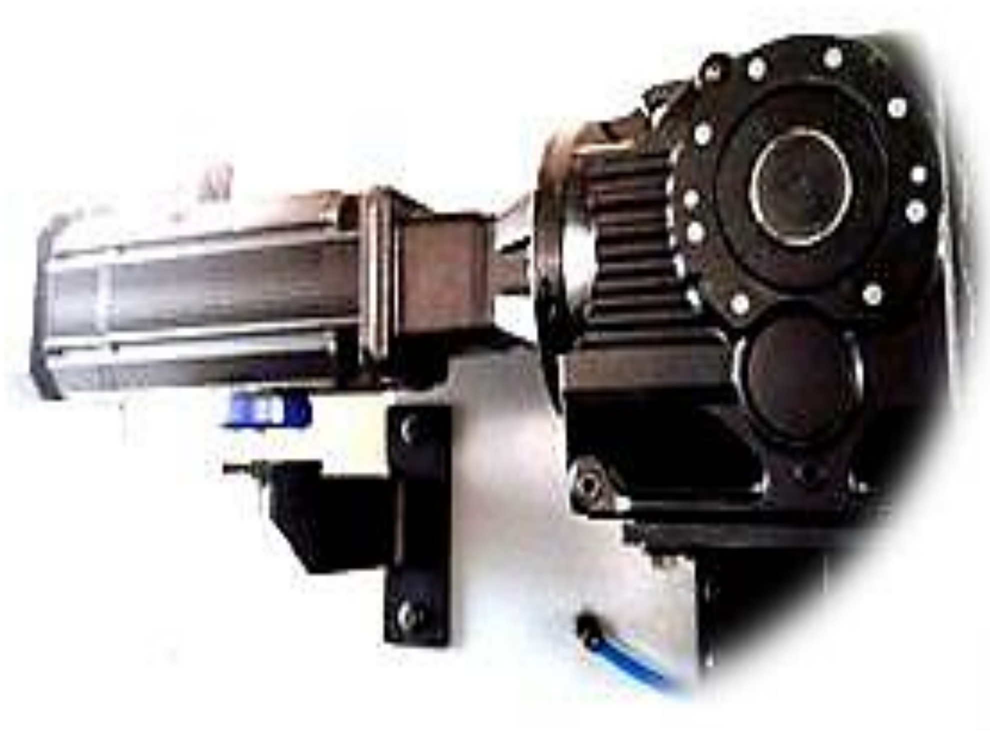


Figure 3.1 AC Permanent Magnet Synchronous Motor and Gearbox

Table 3.1 PMSM Technical Properties [27]

Features	**Units / Details**	**Values**
Nominal Power Capacity	kW	18,6
Nominal – Limit Torque	Nm	62-400
Nominal – Limit Speed	rpm	3000-3700
Working Voltage	V_{AC}	400
Inertia	*kgm*^{2}	0.0145
Ke (Electromotor Force Constant)	Vs	0,9
Kt (Torque Constant)	*Nm/A*	1,63
Poles	*Quantity*	8
Feedback		Absolute Encoder
Inductance	*mH*	1,30
Resistance	Ω	0,07

Table 3.2 Compax-3® H155 V4 Driver Technical Properties [27]

Drive Input Power	Voltage	350-528 V_{AC}
	Phase	3Ɵ
	Frequency	50/60 Hz
	24 VDC LP (Req')	24 VDC ±15%
Drive Output Power	PWM	8 kHz
	C. Current(RMS)	155 Amps @ 400 Vac
	P. Current(RMS)	232.5 Amps for 5 secs
	Communication	Sinusoidal
Internal Regeneration Capacity/ Storable Energy	**2.5000** / 1158 Ws	

3.2.2 Servo Press System

An advantage of the servo press over a conventional mechanical press, even when the press is not operating, energy is consumed for rotating the flywheel inertia to attain the inertia. So, the energy is only consumed when the press is in operation. Motor in conventional mechanical presses is mounted to pinion gear via flywheel, clutch, and brake. Motor in servo presses can be directly mounted to pinion as servo motors are controllable, providing any torque at any point. Structures of conventional mechanical press and servo press are illustrated in Figure 3.2.

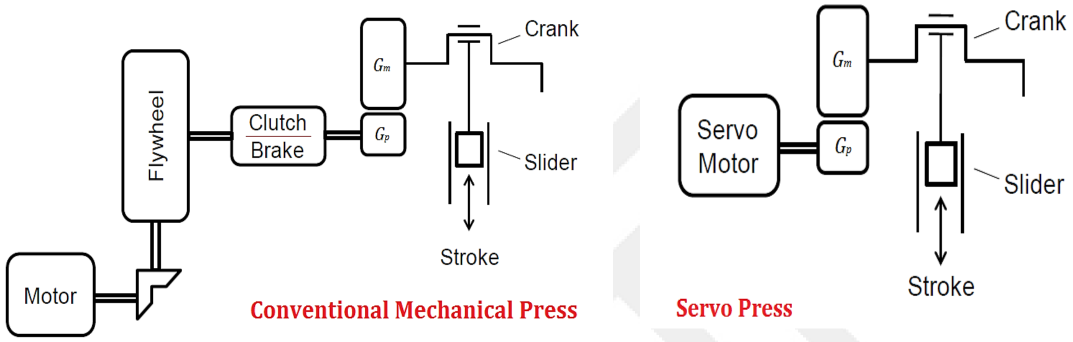
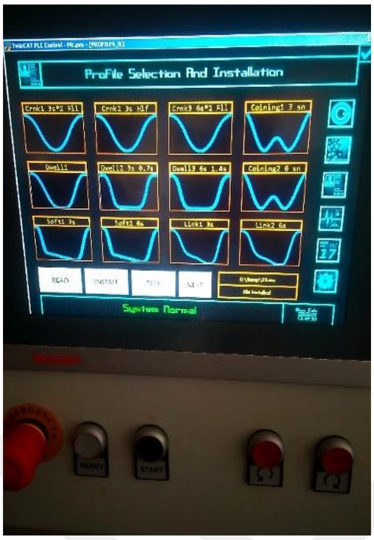


Figure 3.2 Structures of Conventional Mechanical Press and Servo Press [22]

In the control panel of the servo press, the system can be operated manually and the data is sent for some designed motion scenarios. Motor position velocity, acceleration and ram motion can be checked during the operation of system. Deformations at low velocities are needed to improve metal flow. Slow releasing periods are necessary for minimizing work piece spring back ensurance. Thus, stamping quality is improved by introducing smooth periods while the ram approaches. Dwell time results in uniform metal deformation. Metal forming operations using different motion scenarios (20 spm) are performed by applying 12 *ton* punching force on a Cr-Ni steel sheet having thickness of 1 mm [22]. Manufacturing performance of the press is definitely realized between the loads of 2-50 ton.

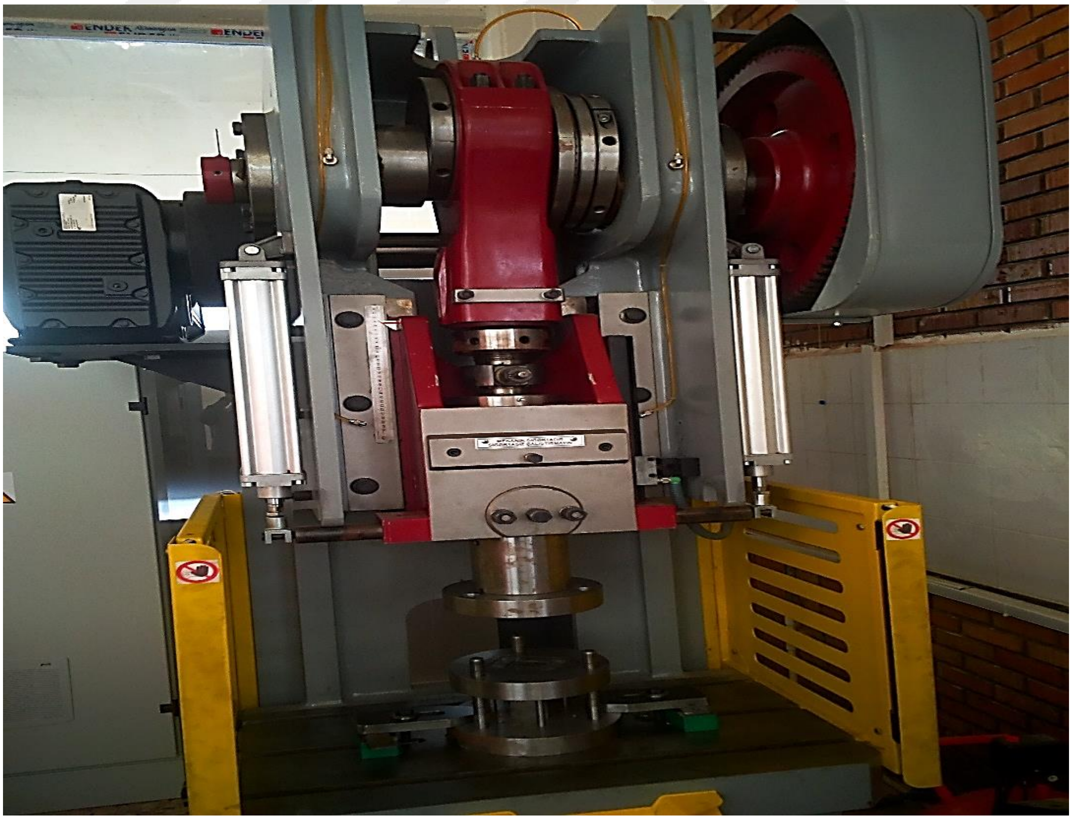
The control panel of the servo press and control cabinet are given in Figure 3.3(a) and Figure 3.3(b) respectively. Servo press consists of press mechanism, power supply, control panel, compressor, driver, computer, servo motor, gearbox, balance cylinder, safety barrier as shown in Figure 3.3(d). Its technical properties are given in Table 3.3.



(a) Control Panel

(b) Driver

(c) Press Die



(d) Servo Press System

Figure 3.3 The Servo Press Experiment Setup

Table 3.3 AC Servo Press Technical Properties [22]

Features	Units / Details	Values
Maximum Stroke Length for Nominal Load Capacity	mm	7 (for 50 ton)
Stroke Capacity	mm	200
Press Speed Capacity	spm	71
Press Speed Capacity (180-160-140-100 mm at Stroke)	spm	~80, ~90, ~100, ~130
Frame of Press		C Type
Platform Height	mm	300
Gear Ratio		1:52.05
Platform Size	mm^2	$800x500$

3.3 Mathematical Analysis of the System

The system is designed with slider crank mechanism which is coupled to motor using a crank. To determine the system characteristic, the system's mathematical model is formulated. Mathematical model of PMSM and slider crank mechanism is separately given in the following section.

3.3.1 Slider Crank Mechanism

There are great number of mechanisms used in servo press systems. Among all mechanisms which can be used in servo presses are classified according to advantages and disadvantages; cost analysis, required motion scenarios, forming sheet metal etc. The slider crank is selected in a previous study thesis called design, synthesis, and control of a mechanical servo press: an industrial application [22]. The slider crank mechanism is given schematically with its vector loop in Figure 3.4.

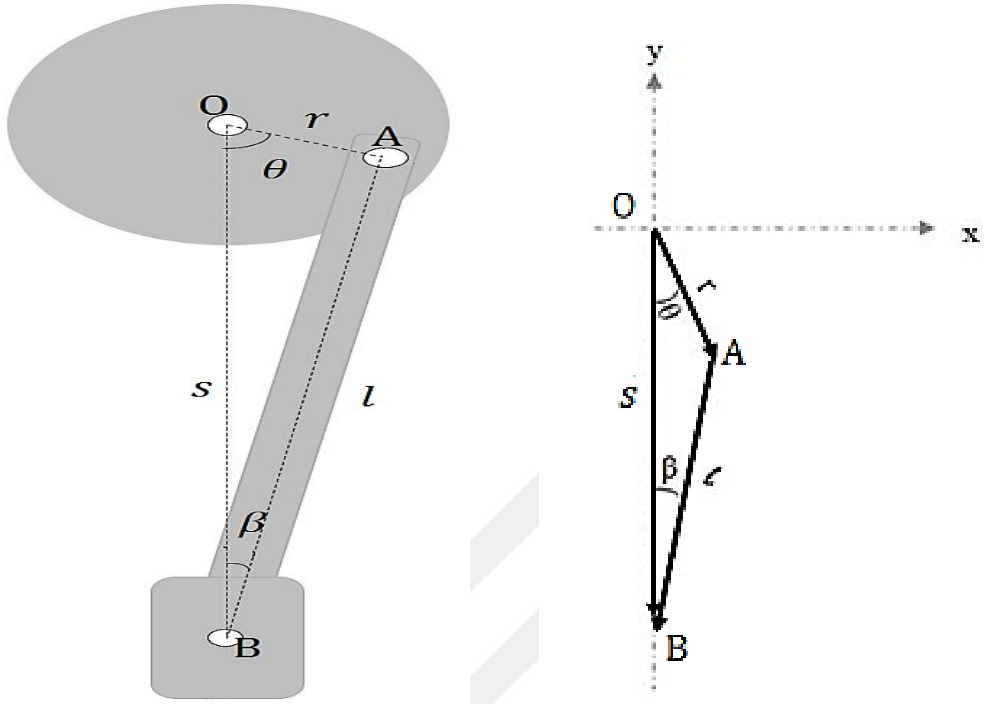


Figure 3.4 Slider Crank Mechanism and Its Vector Loop

The vector loop equation is presented in Equation (3.1). Derivation of position equations from the vector loop equation for the mechanism are given in the following Equations (3.2-3.4). Here, r, θ, l and β are the crank length, the crank angle, the stroke displacement, and the stroke angle, respectively [22].

$$\overrightarrow{OB} = \overrightarrow{OA} + \overrightarrow{AB} \tag{3.1}$$

$$0 = r\sin\theta - l\ \sin\beta \tag{3.2}$$

$$y = -r\cos\theta - l\cos\beta \tag{3.3}$$

$$s = (l + r) - y \tag{3.4}$$

In addition, the system simple dynamic model without load is given in the equation (3.5) where, J_m is the motor inertia, J_g is the gearbox inertia and J_s is the reflected inertia from system to the motor. Gear ratio and the motor mechanic friction coefficient are denoted by n and b respectively. Mechanism kinematics and dynamic equations are included in [22].

$$\tau_M(t) = n(J_M + J_g + J_s)\ddot{\theta}(t) + nb\dot{\theta} \quad (3.5)$$

3.3.2 PMSM Model

The electrical equivalent circuit of the PMSM per phase and its voltage vectors are illustrated in the following Figure 3.5. The electrical equivalent circuit of PMSM can be observed that it is similar with DC motor despite sinusoidal of the values of voltage and current [23].

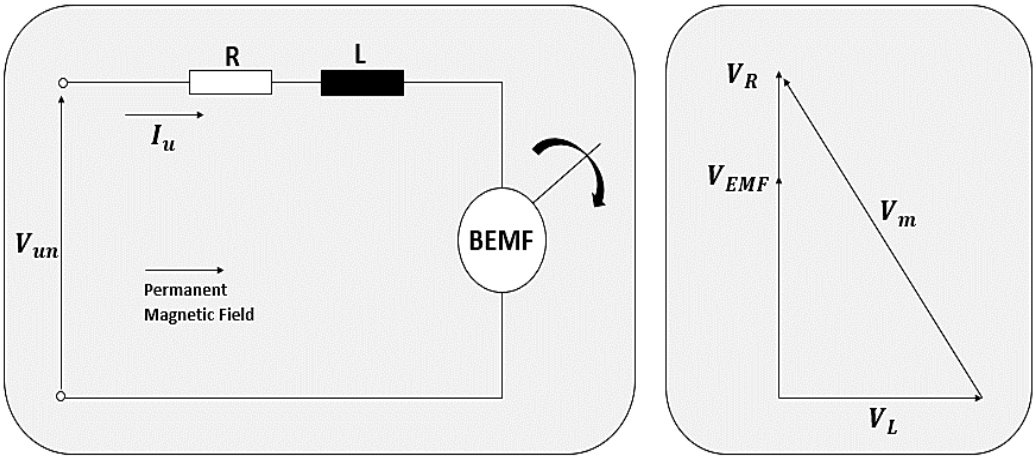


Figure 3.5 Electrical Circuit of PMSM per Phase and Its Voltage Vectors

The left side of Figure 3.5 illustrates the circuit, where R is the resistance per phase thus phase resistance is $2R$, L is the inductance per phase and it can be determined phase to phase as $\sqrt{3L}$. The voltage phase to phase which is symbolized by V_{un} equals to $\sqrt{3V_{un}}$. I_u is the current phase. The right side of Figure 3.5 shows the relationship of voltage vectors of the electric circuit, where V_R is the voltage drop of the phase resistance and it equals to I_uR. V_{EMF} is BEMF voltage and it is determined by $K_e n_m$ where K_e is a constant that depends on the constructive characteristic of the motor and n_m is the motor speed. V_L is the voltage dropped across inductance phase. It is formulated as $V_L = f_e L I_u$ where f_e is the frequency of the rotating field of rotor and V_m is the total natural voltage. Since the voltage vectors can be given in Equations (3.6) and (3.7);

$$V_{un} = \sqrt{(V_L)^2 + (V_{EMF} + V_R)^2} \quad (3.6)$$

$$V_{un} = \sqrt{(2\pi f_e L I_u)^2 + (K_e n_m + I_u R)^2} \quad (3.7)$$

The current cannot be isolated because of its nonlinear dependence parameters. Thus, it can be written as the following function for the current and the torque, Equations (3.8) and (3.9) are given;

$$I_u = f(V_{un}, n_m) \quad (3.8)$$

$$\tau = K_t I_u \quad (3.9)$$

The block diagram of PMSM is given in Figure 3.6. J_{total} is moment of inertia the mechanical system. The block diagram of PMSM is shown in Figure 3.6. K_t denotes the torque constant and B is the viscous friction.

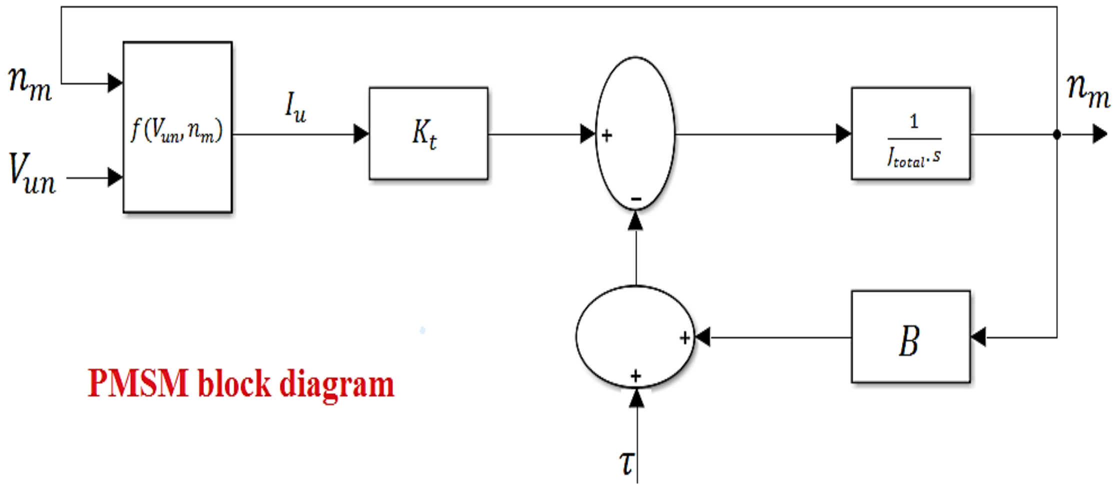


Figure 3.6 PMSM Block Diagram

3.4 Transfer Function of the System

Controllability of PMSMs is not easy due to the nonlinear characteristic. Therefore, linear control schemes such as P, PI or PID controls cannot ensure satisfactory performances [28]. PMSM transfer function can be thought as DC servomotors. There is similarity between PMSM and DC servomotors [23]. The transfer function of PMSM from transfer function of DC servo motor is derived. Figure 3.7 illustrates DC servo motor block diagram.

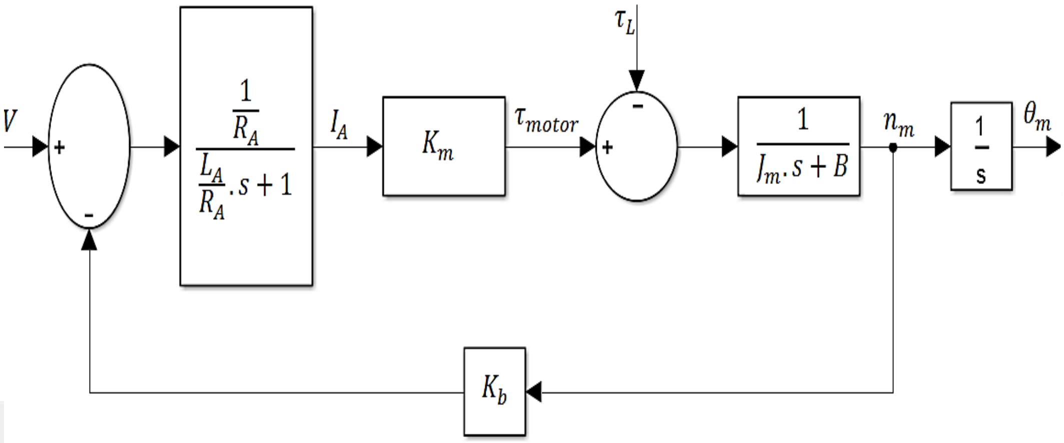


Figure 3.7 DC Servo Motor Block Diagram

According to the block diagram, the relationship between the input voltage and the motor angular velocity can be determined. The transfer function given in Equation (3.10) relates the input voltage with the velocity of PMSM, but without the external load.

$$\frac{n_m(s)}{V(s)} = \frac{K_m}{J_m L.s^2 + (J_m R + BL).s + (RB + K_m K_b)} \tag{3.10}$$

To obtain angular position of the motor shaft, the transfer function of the velocity should be multiplied to $1/s$. So, the angular position of PMSM relating with the input voltage is written in the following equation (3.11).

$$\frac{\theta(s)}{V(s)} = \frac{K_m}{J_m L.s^3 + (J_m R + BL).s^2 + (RB + K_m K_b).s} \tag{3.11}$$

Finally, the transfer function of the PMSM is determined by using parameters of the PMSM. Equation (3.12) is obtained as resulting transfer function of PMSM.

$$\frac{\theta(s)}{V(s)} = \frac{1.15}{0.0004s^3 + 0.02s^2 + 0.15s} \tag{3.12}$$

3.5 State Space Representation of the System

In this section; the state-space matrices are attained from the transfer function. There are three state variables which are specified by the angular position X_1, the angular velocity X_2, and the angular acceleration X_3. The general characteristic equation for three states system can be written as in Equation (3.13).

$$s^3 + a_2 s^2 + a_1 s + a_0 = 0 \tag{3.13}$$

The characteristic equation of the system shows denominator of the transfer function. Therefore, a general form for transfer function can be created in Equation (3.14).

$$\frac{\theta(s)}{V(s)} = \frac{K}{s^3 + a_2 s^2 + a_1 s + a_0} \tag{3.14}$$

After obtaining general form of transfer function, it is easy to have the general form of state-space matrices. State variables and derivative of these variables are given in Equations (3.16) and (3.17) respectively. Steps to attain the state-space matrices are shown in Equations (3.15-3.17). The general form for state-space representation is given in Equation (3.18).

$$\dddot{\theta} + a_2\ddot{\theta} + a_1\dot{\theta} + a_0\theta = Kv \tag{3.15}$$

$$X_1 = \theta,\ X_2 = \dot{\theta}\ \ and\ X_3 = \ddot{\theta} \tag{3.16}$$

$$\dot{X}_1 = X_2,\ \dot{X}_2 = X_3\ \ and\ \ \dot{X}_3 = -a_2X_3 + -a_1X_2 + -a_0X_1 + Kv \tag{3.17}$$

$$\begin{bmatrix}\dot{X}_1\\ \dot{X}_2\\ \dot{X}_3\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ -a_0 & -a_1 & -a_2\end{bmatrix}\begin{bmatrix}X_1\\ X_2\\ X_3\end{bmatrix} + \begin{bmatrix}0\\ 0\\ K\end{bmatrix}u \tag{3.18}$$

The transfer function which has already attained in Section 3.4 can be paralleled to the general transfer function form indicated in Equation (3.14). So, the coefficients a_0, a_1 and a_2 of the characteristic equation. The numerator of the transfer function K can be resulted;

$$a_0 = 0, \qquad a_1 = \frac{0.15}{0.0004} = 375,\ a_2 = \frac{0.02}{0.0004} = 50\ and\ K = \frac{1.15}{0.0004} = 2875$$

According to calculations, the state-space matrices of the system used in this study are given in Equation (3.19):

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -375 & -50 \end{bmatrix},\ B = \begin{bmatrix} 0 \\ 0 \\ 2875 \end{bmatrix},\ C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{ and } D = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{3.19}$$

Where, A is the state matrix, it gives information about characteristic of the system and B is the input-to-state matrix. On the other hand, C is the state-to-output matrix and D is the feed through matrix. These matrices will be used in Chapter 5; The simulation results will be taken after designing controllers.

CHAPTER 4

DESIGN OF FUZZY AND FUZZY CASCADE CONTROLLER

4.1 Introduction

This chapter includes four sections. The first section describes fuzzy logic, membership functions, rules, and defuzzification. Tuning parameters of PID controller are explained in the second section. Structure of fuzzy logic and structure of fuzzy logic approach for tuning of PID controller are given the next. Membership functions and fuzzy sets used for the system are then explained. Definition of fuzzy rules and fuzzy rules which are created to find tuning parameters of PID are included. The structures of Fuzzy-P and Fuzzy-PID cascade controller with inner and outer loops are given in detail.

4.2 Description of Fuzzy Logic and PID Tuning

Fuzzy logic is very effective method doing controller tuning. Fuzzy logic is being studied with membership functions and description of fuzzy rules [29]. PID parameters are tuned by an idea of fuzzy logic in system control. They are explained separately. They are then combined to each other to create an artificial intelligence control system.

4.2.1 Fuzzy Logic

Fuzzy logic is an approach used to calculate the degree of correctness rather than the choices from mathematically "1 and 0" or this is generally known as "true” or “false". Boolean logic represents the basis of modern computer. Fuzzy logic takes the values 0 and 1 as limit values and the degree of accuracy is set in this interval. If an example is given, the result of comparing two things cannot be “black” or “white”, they are given in “grey color”. Fuzzy logic implements a method that is close to the way the human brain works. The data are added to each other, edited and the degree of partial accuracy is determined. This means that the partial truth shows the truth. Certain thresholds that cause some motor reactions are exceeded. A similar process is used for artificial computers, neural network and specialized systems. Logic format and binary or Boolean logic can only help as a special case to the fuzzy logic [30].

4.2.1.1 Membership Functions for Controllers

A membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between “0” and “1” as shown in Figure 4.1. Sharp curve B has a higher resolution and control sensitivity other one smooth membership curve A has lower resolution, but the stability of system is better.

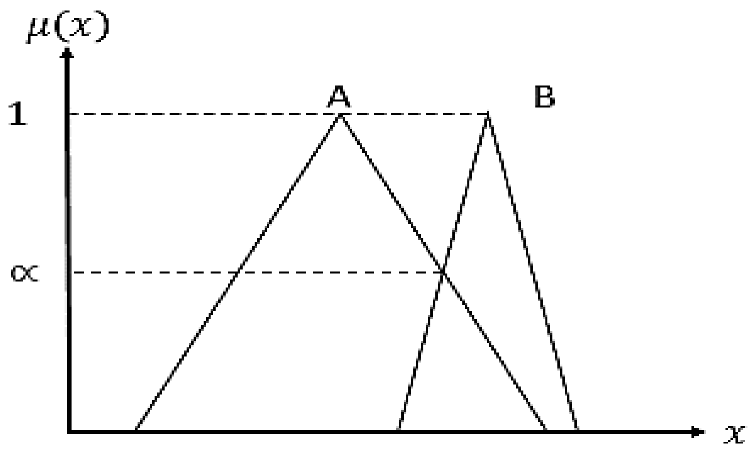


Figure 4.1 Two Membership Functions A and B [17]

Membership functions specify the characteristic of fuzzy sets. So, it is important to indicate membership functions. The following steps should be obeyed for creating the membership functions;

- When error is big, the membership function curve should be with low resolution, on the other hand high resolution for small error should be chosen.
- The degree of α is given between 0.4 and 0.8 usually. This value defines degree of interaction between two membership functions.
- The control sensitivity is high if α is small and strong robustness, good adaptability of the system will be occurred. However, if this value is extreme big or small, it can cause bad control [17].

The simplest membership functions are formed by using straight lines. The simplest is the *triangular* membership function, and it has the function name ‘*trimf*’ in MATLAB/Fuzzy Logic Toolbox. This function is collection of three points forming a triangle. The other simple function is *trapezoidal* membership function called '*trapmf*' in MATLAB/Fuzzy Logic Toolbox. It has a flat top and really is just a truncated triangle curve. These straight lines membership functions have the advantage of simplicity. Their graphs are shown in Figure 4.2. The other membership functions are explained in Appendix A. Parameters of 'a' and 'c' show the step coordinates, and 'b' shows the top point of triangular function in Equation (4.1). Parameters of a and d show the step coordinates, b and c show the top point of trapezoidal function in Equation (4.2).

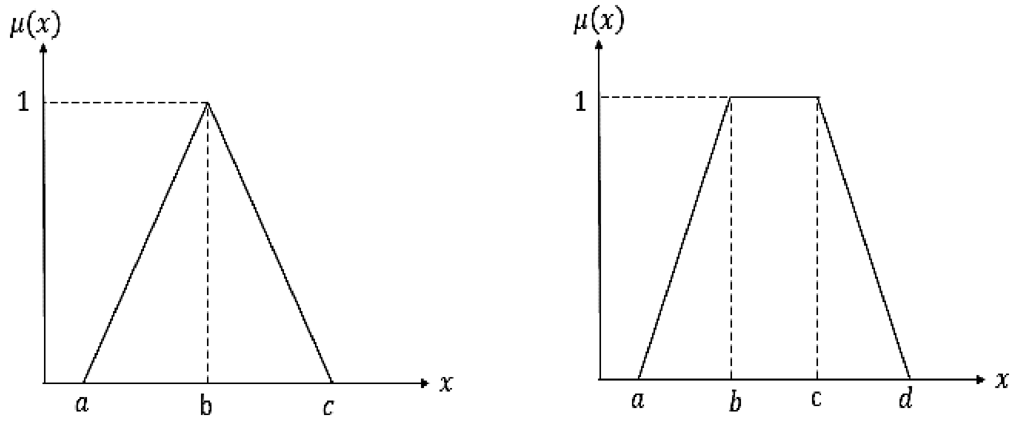


Figure 4.2 Triangular Function at Left Side and Trapezoidal at Right Side

$$\mu(x,a,b,c) = \begin{cases} 0, & x \le a \\ \frac{x-a}{b-a}, & a \le x \le b \\ \frac{c-x}{c-b}, & b \le x \le c \\ 0, & x \ge c \end{cases} \tag{4.1}$$

$$\mu(x,a,b,c,d) = \begin{cases} 0, & x \le a \\ \frac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \frac{d-x}{d-c}, & c \le x \le d \\ 0, & x \ge d \end{cases} \tag{4.2}$$

4.2.1.2 Definitions of Fuzzy Rules

Fuzzy sets and fuzzy operators are subjects and verbs of fuzzy logic. If-then rule states are used to formulate conditionals. A single fuzzy if-then rule supposes the form: 'If *x* is *MF1* then *y* is *MF2*' where *MF1* and *MF2* linguistic values which are defined by fuzzy sets on the ranges (universes of discourse) *x* and *y*, respectively. If part of the rule is "*x* is *MF1*" it is called the '*antecedent'* or premise; if 'then' part of the rule is "*y* is *MF2*", then it is called the '*consequent'* or conclusion.

In Binary Logic: p → q (both p and q are either correct, or both are incorrect).

Corresponding to fuzzy logic: 0.5 p → 0.5 q (partial premise provides partial results).

The pioneer of a rule is that 'if there is an overrun in the motor position control, if the sitting time is bad and if there is a permanent state error then ...' In this case all conditions of the premise are calculated at the same time. Then a single result is solved using the logical operators [30].

4.2.1.3 Defuzzification

The linguistic variables should be transformed to crisp output in the real-world requirements. Fuzzy quantity is changed into distinct quantity by defuzzification. This makes defuzzification as an important part of fuzzy control [19,20].

A fuzzy set is the input for the defuzzification process and the output is a single number. The final required output for each variable is generally a single number as much as fuzziness helps the rule consideration during the intermediate steps. However, the aggregate of a fuzzy set encompasses a range of output values, and so must be defuzzified to resolve a single output value from the set.

Perhaps the most popular defuzzification method is the centroid calculation. It is used in this thesis, which returns the center of area under the curve. There are five built-in methods supported: centroid, bisector, middle of maximum (the average of the maximum value of the output set), largest of maximum, and smallest of maximum [30].

4.2.2 PID Tuning

Proportional, Integral, Differential (PID) tuning is significant to have response for the system designed. If the dynamic behavior of the system under control is known, the tuning parameters of PID controller can be optimized by methods; Ziegler Nichols (ZN) tuning, Kappa tuning, pole placement, Nyquist based design, genetic algorithm (GA) etc. But these methods cannot be applied in some cases which parameters of dynamic conditions are alterable continuously [19,31]. It is difficult that the parameters of PID controllers can be calculated in some technical ways.

Nowadays, optimization of tuning parameters is provided by some computer software programs as MATLAB, Mathematica etc.

4.3 Structure of Fuzzy–PID Controller

Fuzzy logic is built on three units; fuzzification, fuzzy rules and defuzzification. It is based on fuzzy sets and fuzzy sub-sets. In traditional approach, a presence is existing or not for set. If it is expressed mathematically, "1" is existing for set and "0" is not. In fuzzy sets, every presence has a degree between '1'and '0'. It has linguistic structure and it can be adapted to the other controllers easily. The structure of fuzzy logic is shown in Figure 4.3.

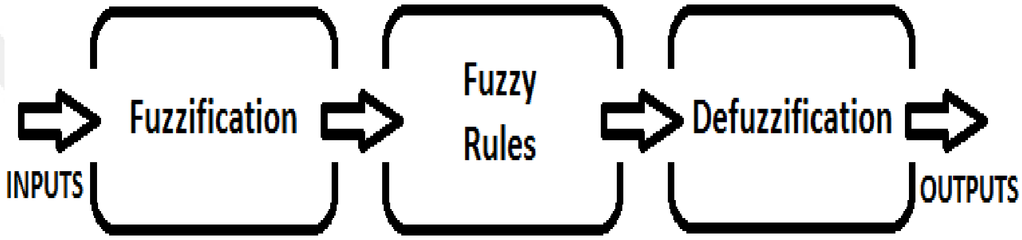


Figure 4.3 Structure of Fuzzy Logic

PID controller and fuzzy logic approach can be used to control alone. In this study, fuzzy logic approach is used to optimize tuning parameters of PID to control the system. It is used together as a hybrid controller to respond system with zero or minimum overshoot, faster response, more accurate and minimum steady state error. Additionally, tuning parameters of PID can be optimized by fuzzy logic (FL) approach. This provides adaptation of environmental conditions to increase performance of the system. The structure of the hybrid controller system is shown in Figure 4.4.

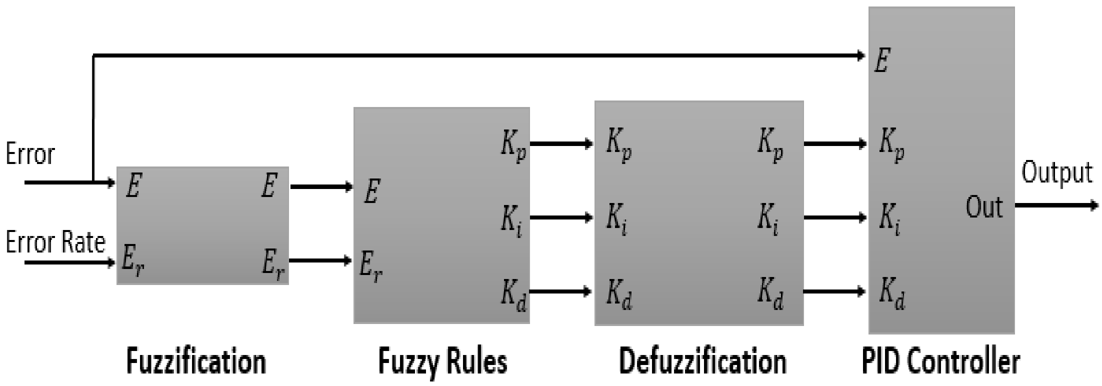


Figure 4.4 Structure of Fuzzy Logic (FL) – PID Controller

4.3.1 Initial Values of PID Tuning Parameters

Initial values for K_p, K_i and K_d can be calculated with using the transfer function given in Equation (3.12). But, the K_p, K_i and K_d parameters are previously tuned by using GA-PID controller by Halicioglu et al [32] and K_p has got value between 8 to 10 herein. In this study, the lower limit of K_p is reduced to 5, and it is optimized in the range of {5:10}. Halicioglu is used a range {4:10} for K_i and {0:1} for K_d. In this study, the range for K_i is reduced to {0.1:0.2} and K_d is enlarged to {0:2.5}. These ranges are explained in the following section.

4.3.2 Membership Functions for Linguistic Variable

Two inputs and three output sets are specified in relation to fuzzy structure. Two sets are called the error (E) and the error rate (E_r) for inputs. Three sets tuning parameters of PID controller are called the proportional gain (K_p), the integral gain (K_i) and the derivative gain (K_d) for the outputs.

The universe of discourse for fuzzy variable of error and the error rate is in areas (-3 3) or (-6 6) [17]. The ranges of fuzzy variable of proportional, integral and derivation parameters of fuzzy PID controller are defined in chapter 3 as (5 10), (0.1 0.2) and (0 0.25) respectively. Ranges for input and output fuzzy sets are shown in Table 4.1.

Every fuzzy set has membership functions. Input E_r has 5 membership functions {Big Negative (*BN*), Negative (*N*), Zero (*Z*), Positive (*P*), Big Positive (*BP*)}. The other input E sets on 6 membership functions {Big Negative (*BN*), Negative (*N*), Small Negative (*SN*), Small Positive (*SP*), Positive (*P*), Big Positive (*BP*)} because of zero membership function are divided by two functions as small negative and small positive for decreasing the steady state error [33].

Seven membership functions {Very Small (*VS*), Medium Small (M*S*), Small (*S*), Middle (*M*), Big (*B*), Medium Big (*MB*), Very Big (*VB*)} are created for the output parameters K_p, K_i and K_d. Parameter of membership functions for the error, the error rate, K_p, K_i and K_d are defined with experiences. These parameters are shown respectively in Table 4.2, Table 4.3, Table 4.4, Table 4.5, and Table 4.6. The graphs of membership functions for the error, the error rate, K_p, K_i, and K_d are then shown respectively in Figures A.4 to A.8 in Appendix A.

Table 4.1 Border Values for Fuzzy Sets

Fuzzy Sets	Minimum	Maximum
Error	-3	3
Error Rate	-6	6
Proportional Gain	5	10
Integral Gain	0.1	0.2
Derivative Gain	0	2.5

Table 4.2 Parameters of Membership Functions for Error

Membership Functions	Types	*a*	*b*	*c*	*d*
BN	Trapezoidal	-Infinite	-Infinite	-2.4	-1.2
N	Triangular	-2.4	-1.5	-0.6	-
SN	Triangular	-0.9	-0.9	0.3	-
SP	Triangular	-0.3	0.9	0.9	-
P	Triangular	0.6	1.5	2.4	-
BP	Trapezoidal	1.2	2.4	Infinite	Infinite

Table 4.3 Parameters of Membership Functions for Error Rate

Membership Functions	Types	*a*	*b*	*c*	*d*
BN	Trapezoidal	-Infinite	-Infinite	-4.8	-2.4
N	Triangular	-3.6	-2.1	-0.6	-
Z	Triangular	-1.8	0.0	1.8	-
P	Triangular	0.6	2.1	3.6	-
BP	Trapezoidal	2.4	4.8	Infinite	Infinite

Table 4.4 Parameters of Membership Functions for K_p

Membership Functions	Types	*a*	*b*	*c*	*d*
VS	Trapezoidal	-Infinite	-Infinite	5.50	6.25
MS	Triangular	5.50	6.25	7.25	-
S	Triangular	6.50	7.00	7.50	-
M	Triangular	4.75	7.50	8.25	-
B	Triangular	7.50	8.00	8.50	-
MB	Triangular	7.75	8.50	9.50	-
VB	Trapezoidal	8.75	9.50	Infinite	Infinite

Table 4.5 Parameters of Membership Functions for K_i

Membership Functions	Types	*a*	*b*	*c*	*d*
VS	Trapezoidal	-Infinite	-Infinite	0.110	0.125
MS	Triangular	0.110	0.125	0.145	-
S	Triangular	0.130	0.140	0.150	-
M	Triangular	0.135	0.150	0.165	-
B	Triangular	0.150	0.160	0.170	-
MB	Triangular	0.155	0.170	0.190	-
VB	Trapezoidal	0.175	0.190	Infinite	Infinite

Table 4.6 Parameters of Membership Functions for K_d

Membership Functions	Types	*a*	*b*	*c*	*d*
VS	Trapezoidal	-Infinite	-Infinite	0.250	0.625
MS	Triangular	0.250	0.690	1.125	-
S	Triangular	0.750	1.000	1.250	-
M	Triangular	0.875	1.250	1.625	-
B	Triangular	1.250	1.150	1.750	-
MB	Triangular	1.375	1.810	2.250	-
VB	Trapezoidal	1.875	2.250	Infinite	Infinite

4.3.3 Fuzzy Rules for Self-Adjusting PID Parameters

PID parameters are used for increasing stability, fast response time, decreasing overshoot, and improving steady state error. This makes fuzzy logic rules very important. FL rules definitely need expert control engineering experiences and knowledge. While the rules which should be designed for output parameters are being specified according to these experiences and knowledge, the following information should be noticed [34].

- If the error and the error rate have the same and identical signs, the control variable is far from the required value. If they have different signs, the control variable approaches to the required value.
- If the error is big, K_p should be big, K_i should be very small and K_d should be small to decrease the overshoot and to develop the response time.
- While the error and the error rate are close to zero, K_p should be small, K_i and K_d should be middle degree to ensure minimum overshoot.
- If the error is very small, K_p and K_i should be big, K_d should have a middle degree value to increase stability of the system.

Thirty rules are created for each PID tuning parameter to be optimized. Therefore, it can be said that there are ninety rules, in total. But, these rules can be decreased to thirty if the output parameters are used together. If an example is needed to be given, two rules are given below;

Rule 1: If E is BN and E_r is BN then K_p is VB,

Rule 2: If E is BN and E_r is BN then K_i is VS,

The combination of them can be written in single rule as shown below. It means that the rules number can be decreased by using output together.

Rule 3: If E is BN and E_r is BN then K_p is VB and K_i is VS.

After the all outputs are used together, thirty rules are obtained and given in Table 4.7. After having the rules table, the surfaces for output parameters can be attained according to combination of membership functions, rules and defuzzification. Figures B.1 to B.3 illustrates the surfaces of K_p, K_i, and K_d respectively, in Appendix B.

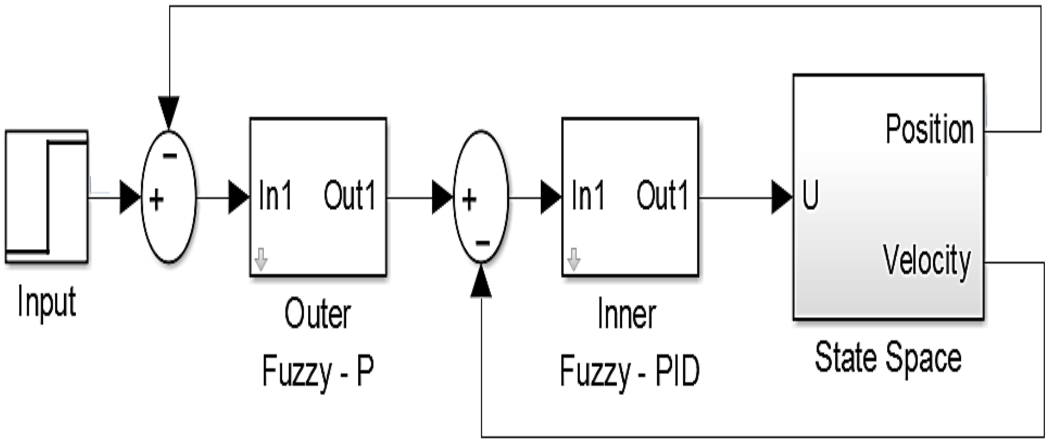
Table 4.7 Rules for PID Tuning Parameters

Rule No	Rule
1	If E is BN and E_r is BN then K_p is VB, K_i is VS and K_d is B
2	If E is BN and E_r is N then K_p is VB, K_i is VS and K_d is S
3	If E is BN and E_r is Z then K_p is MB, K_i is MS and K_d is VS
4	If E is BN and E_r is P then K_p is B, K_i is S and K_d is MS
5	If E is BN and E_r is BP then K_p is M, K_i is M and K_d is MB
6	If E is N and E_r is BN then K_p is VB, K_i is VS and K_d is MB
7	If E is N and E_r is N then K_p is MB, K_i is MS and K_d is VS
8	If E is N and E_r is Z then K_p is B, K_i is S and K_d is MS
9	If E is N and E_r is P then K_p is M, K_i is M and K_d is S
10	If E is N and E_r is BP then K_p is S, K_i is M and K_d is M
11	If E is SN and E_r is BN then K_p is MB, K_i is MS and K_d is M
12	If E is SN and E_r is N then K_p is MB, K_i is MS and K_d is M
13	If E is SN and E_r is Z then K_p is B, K_i is S and K_d is S
14	If E is SN and E_r is P then K_p is M, K_i is M and K_d is S
15	If E is SN and E_r is BP then K_p is S, K_i is B and K_d is M
16	If E is SP and E_r is BN then K_p is MB, K_i is MS and K_d is M
17	If E is SP and E_r is N then K_p is B, K_i is S and K_d is M
18	If E is SP and E_r is Z then K_p is M, K_i is M and K_d is S
19	If E is SP and E_r is P then K_p is S, K_i is B and K_d is M
20	If E is SP and E_r is BP then K_p is MS, K_i is MB and K_d is M
21	If E is P and E_r is BN then K_p is B, K_i is MS and K_d is MB
22	If E is P and E_r is N then K_p is M, K_i is M and K_d is S
23	If E is P and E_r is Z then K_p is MS, K_i is B and K_d is M
24	If E is P and E_r is P then K_p is MS, K_i is MB and K_d is B
25	If E is P and E_r is BP then K_p is VS, K_i is VB and K_d is MB
26	If E is BP and E_r is BN then K_p is M, K_i is M and K_d is VB
27	If E is BP and E_r is N then K_p is M, K_i is B and K_d is MB
28	If E is BP and E_r is Z then K_p is S, K_i is MB and K_d is MB
29	If E is BP and E_r is P then K_p is MS, K_i is VB and K_d is B
30	If E is BP and E_r is BP then K_p is VS, K_i is VB and K_d is VB

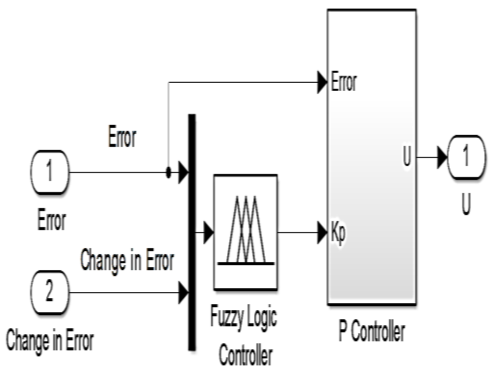
4.4 Structure of Fuzzy-P and Fuzzy-PID Cascade Controller

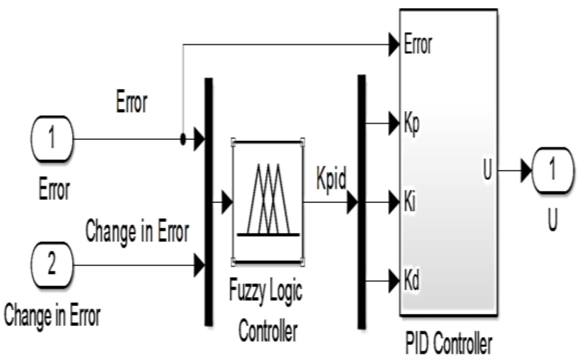
Many authors have considered the effects of cascade controller offering better alternative than the hybrid controller, full-state controller, and traditional controller [35-37]. Data from several studies have suggested that fuzzy cascade controller can be considered to improve the settling time and to minimize the steady state error by comparing to real system motion scenarios. Fuzzy-PID controller results are obtained and compared to the system response. It seems that overshoot and settling time are decreased with the designed controller.

To design fuzzy cascade controller, the inner and the outer loops are created. While Fuzzy-P Controller is used for the outer loop, Fuzzy-PID Controller is used for the inner loop. The structure of Cascade controller is shown in Figure 4.5(a) with Outer Fuzzy-P and Inner Fuzzy PID are respectively in Figures 4.5(b) and 4.5(c).



(a) Structure of Fuzzy-Cascade Controller





(b) Outer fuzzy-P (c) Inner fuzzy-PID

Figure 4.5 Fuzzy Cascade Controller

4.4.1 Inner Loop Controller: Fuzzy Logic-PID Controller

Inner loop controller is frequently used to control the current or velocity of the desired variables. In this design, Fuzzy-PID controller regulates the motor angular velocity. According to the velocity errors and the changes in these errors PID parameters are optimized by using Fuzzy Logic. Then, it is applied as a control signal in the following loop.

4.4.1.1 Inner Loop Controller: Initial Values of PID Parameters

Inner loop controller is used to control velocity of the system as explained in previous section. Figure 4.6 shows a simple block diagram to control velocity of the system.

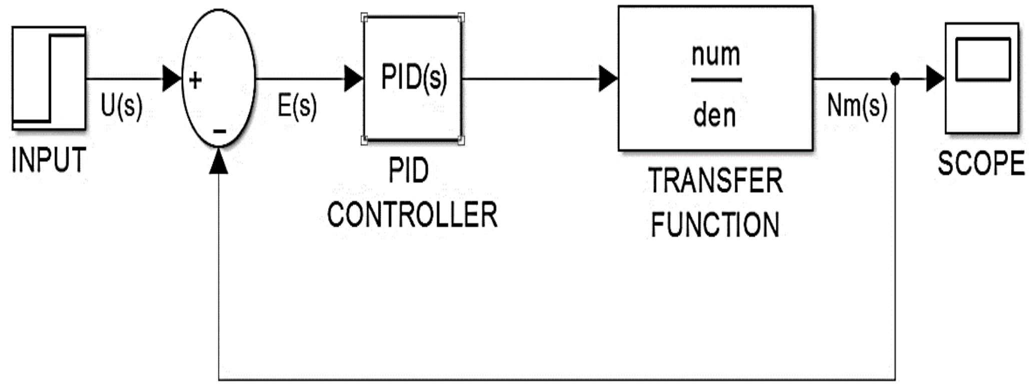


Figure 4.6 Speed Control Block Diagram

Equation (4.3) gives us the transfer function of PID(s). Equation (4.4) specifies the system transfer function in the following:

$$PID(s) = \frac{K_{i\_p}s + K_{i\_d}s^2 + K_{i\_i}}{s} \tag{4.3}$$

$$TF(s) = \frac{N_m(s)}{V(s)} = \frac{1.15}{0.0004s^2 + 0.02s + 0.15} \tag{4.4}$$

The open loop transfer function of the system to control the speed is given in Equation (4.5).

$$\frac{PID(s).TF(s)}{PID(s).TF(s)+1} = \frac{1.15\ (K_{i\_p}s + K_{i\_d}s^2 + K_{i\_i})}{0.0004s^3 + (0.02 + K_{i\_d})s^2 + (0.15 + K_{i\_p})s + (K_{i\_i} + 1.15)} \tag{4.5}$$

The characteristic equation of the system is the denominator of Equation (4.5). It has been known that there are three poles of the characteristic equation. Therefore, the general form of any characteristic equation can be written as given in Equation (4.6).

$$(s+p_1)(s+p_2)(s+p_3) = s^3 + A_1 s^2 + A_2 s + A_3 \tag{4.6}$$

The system characteristic equation can liken to the general characteristic equation form to find initial tuning parameters of K_{i_p}, K_{i_i} and K_{i_d}. The formulations for K_{i_p}, K_{i_i} and K_{i_d} are obtained from equality of the characteristic equation. Their results are given in Equations (4.7-4.9).

$$K_{i\_p} = \frac{0.0004\, A_2 - 0.15}{1.15} \tag{4.7}$$

$$K_{i\_i} = \frac{0.0004\, A_3}{1.15} \tag{4.8}$$

$$K_{i\_d} = \frac{0.0004\, A_1 - 0.02}{1.15} \tag{4.9}$$

K_{i_p}, K_{i_i} and K_{i_d} coefficients are given in Table 4.8, where the poles are chosen by performing many control experiences.

Table 4.8 PID Parameters for Different Poles

p_1	p_2	p_3	K_{i_p}	K_{i_i}	K_{i_d}
50	35	10	0.78	6.09	0.015
50	35	15	0.92	9.13	0.017
70	70	10	2.07	14.04	0.034

Some trials for different poles on the MATLAB/Software package aid us to choose the range of coefficient for fuzzy logic membership functions. Initial values of PID parameters for the inner loop is specified. Then, the range of K_{i_p} is enlarged to {3:5}, K_{i_i} is used for the range of {3:9} and the range of K_{i_d} is selected so small because of its small results for the tried poles. Its range is identified as a set of {0.014:0.017} for the inner loop. These ranges are used in the following section for membership functions of the inner loop.

4.4.1.2 Membership Functions: Linguistic Variable of Inner Loop

Two inputs and three output sets are specified in relation to fuzzy structure as explained in designing of Fuzzy-PID controller system. Two sets are called the velocity error (E_v) and the velocity error rate (E_{v_r}) for inputs and output sets are parameters of PID controller called as the inner proportional gain (K_{i_p}), the inner integral gain (K_{i_i}) and the inner derivative gain (K_{i_d}). Limitations for input and output fuzzy sets are shown in Table 4.9.

Table 4.9 Border Values for Fuzzy Sets

Fuzzy Sets	Minimum	Maximum
Error	-3	3
Error Rate	-6	6
Inner Proportional Gain	3	5
Integral Gain	3	9
Derivative Gain	0.014	0.017

Every fuzzy set has membership functions which are similar to the first design. Even if the names of membership functions are same, the parameters are so different. The input E_{v_r} has 5 membership functions; they are Big Negative (*BN*), Negative (*N*), Zero (*Z*), Positive (*P*), and Big Positive (*BP*). The other input E_v sets on 6 membership functions; they are Big Negative (*BN*), Negative (*N*), Small Negative (*SN*), Small Positive (*SP*), Positive (*P*), and Big Positive (*BP*). Because of zero membership function are divided by two functions as Small Negative and Small Positive for decreasing steady state error of velocity. Seven membership functions; Very Small (*VS*), Medium Small (M*S*), Small (*S*), Middle (*M*), Big (*B*), Medium Big (*MB*) and Very Big (*VB*) are created for output parameters K_{i_p}, K_{i_i} and K_{i_d}. Parameters of membership functions for the velocity error. The velocity error rate is same with the first Fuzzy-PID system as shown in Table 4.2 and Table 4.3, previously. The parameters for K_{i_p}, K_{i_i} and K_{i_d} are specified again by experiences. These parameters are shown respectively in Tables 4.10-4.12. The graphs of membership functions for the velocity error and the velocity error rate don't change because of limitations of them similarity. They are previously presented, respectively in Figures A.4 and A.5 in Appendix A. But, the graphs of membership functions for K_{i_p}, K_{i_i}, and K_{i_d} are changed because of different limitations. They are shown in Figures A.9 to A.11 in Appendix A, respectively.

Table 4.10 Parameters of Membership Functions for K_{i_p}

Membership Functions	Types	*a*	*b*	*c*	*d*
VS	Trapezoidal	-Infinite	-Infinite	3.2	3.5
MS	Triangular	3.2	3.5	3.9	-
S	Triangular	3.6	3.8	4.0	-
M	Triangular	3.7	4.0	4.3	-
B	Triangular	4.0	4.2	4.4	-
MB	Triangular	4.1	4.5	4.8	-
VB	Trapezoidal	4.5	4.8	Infinite	Infinite

Table 4.11 Parameters of Membership Functions for K_{i_i}

Membership Functions	Types	*a*	*b*	*c*	*d*
VS	Trapezoidal	-Infinite	-Infinite	3.6	4.5
MS	Triangular	3.6	4.7	5.7	-
S	Triangular	4.8	5.4	6.0	-
M	Triangular	5.1	6.0	6.9	-
B	Triangular	6.0	6.6	7.2	-
MB	Triangular	6.3	7.4	8.4	-
VB	Trapezoidal	7.5	8.4	Infinite	Infinite

Table 4.12 Parameters of Membership Functions for K_{i_d}

Membership Functions	Types	*a*	*b*	*c*	*d*
VS	Trapezoidal	-Infinite	-Infinite	0.0143	0.0148
MS	Triangular	0.0143	0.0148	0.0154	-
S	Triangular	0.0149	0.0152	0.0155	-
M	Triangular	0.0151	0.0155	0.0160	-
B	Triangular	0.0155	0.0158	0.0161	-
MB	Triangular	0.0157	0.0162	0.0167	-
VB	Trapezoidal	0.0163	0.0167	Infinite	Infinite

4.4.1.3 Fuzzy Rules: Self-Adjusting PID Parameters of Inner Loop

Fuzzy rules are independent from the limitations of membership functions. They depend on how many membership functions there are and how many rules are given. Remember that the number of membership functions for the velocity error is 5, and for the velocity error rate is 6. According to these numbers, 30 rules should be designed for K_{i_p}, 30 rules for K_{i_i} and 30 rules for K_{i_d}. They are shown in Tables 4.13 to 4.15 in a matrix form, respectively.

Table 4.13 Rules for K_{i_p} in Matrix Form

E_v \ E_{vr}	**BN**	**N**	**Z**	**P**	**BP**
BN	VB	VB	MB	B	M
N	VB	MB	B	M	S
SN	MB	MB	B	M	S
SP	MB	B	M	S	MS
P	B	M	MS	MS	VS
BP	M	M	S	MS	VS

Table 4.14 Rules for K_{i_i} in Matrix Form

E_v \ E_{vr}	**BN**	**N**	**Z**	**P**	**BP**
BN	VS	VS	MS	S	M
N	VS	MS	S	M	M
SN	MS	MS	S	M	B
SP	MS	S	M	B	MB
P	MS	M	B	MB	VB
BP	M	B	MB	VB	VB

Table 4.15 Rules for K_{i_d} in Matrix Form

E_v \ E_{vr}	**BN**	**N**	**S**	**P**	**BP**
BN	B	S	VS	MS	MB
N	MB	VS	MS	S	M
SN	M	M	S	S	M
SP	M	M	S	M	M
P	MB	S	M	B	MB
BP	VB	MB	MB	B	VB

4.4.1.4 Defuzzification: Inner Fuzzy-PID Controller

There are more than one defuzzification methods as mentioned in defuzzification section. The common defuzzification methods are area period method, center of gravity, bisector area, mean of area and center of average [30]. In this study, area period method (centroid) is used to optimize the controller parameters. MATLAB/Fuzzy Logic Toolbox is used with Mamdani-Centroid to clarify the output parameters. After the membership functions and the rules are designed, the control surfaces are obtained. They are presented in Figures B.4 to B.6, Appendix B, respectively.

4.4.2 Outer Loop Controller: Fuzzy Logic-P Controller

Outer loop controller is frequently used to control position or velocity of the desired variables. Fuzzy-P controller regulates the angular position of the motor in this design. According to the position errors and the changes seen in errors, K_{o_p} is optimized by using FL rules as a control signal in the following loop.

The outer loop initial tuning parameter of K_{o_p} is defined having performed some simulation tests. According to these tests, the range for the outer P parameter is identified as a set of {20:25}. This range is used to design membership functions of the outer loop.

4.4.2.1 Membership Functions: Linguistic Variables of Outer Loop

Two inputs and an output sets are specified in designing Fuzzy-P controller. These three sets are called; the position error (E_p) and the position error rate (E_{p_r}) for inputs and output set is parameters of P controller called as the outer proportional coefficient (K_{o_p}). Limitations for input fuzzy sets have already defined in the first Fuzzy-PID system. The output fuzzy set has got a range of 20-25. This output set has 7 membership functions, and their limitations for output fuzzy set are given in Table 4.16. The graph of membership function for K_{o_p} is illustrated in Figure A.12, (Appendix A).

Table 4.16 Parameters of Membership Functions for K_{o_p}

Membership Functions	Types	*a*	*b*	*c*	*d*
VS	Trapezoidal	-Infinite	-Infinite	20.50	21.25
MS	Triangular	20.50	21.40	22.25	-
S	Triangular	21.50	22.00	22.50	-
M	Triangular	21.75	22.50	23.25	-
B	Triangular	22.50	23.00	23.50	-
MB	Triangular	22.75	23.60	24.50	-
VB	Trapezoidal	23.75	24.50	Infinite	Infinite

4.4.2.2 Fuzzy Rules: Self-Adjusting PID parameters of Outer Loop

Thirty rules are specified for every set of PID parameters. Thus, 90 rules are given in the previous design. However, in the outer loop there is only one; the outer proportional output. There are 30 rules for optimizing K_{o_p} gain which are given in Table 4.17.

Table 4.17 Rules for K_{o_p} in Matrix Form

E_p \ E_{pr}	**BN**	**N**	**Z**	**P**	**BP**
BN	VB	VB	MB	B	M
N	VB	MB	B	M	S
SN	MB	MB	B	M	S
SP	MB	B	M	S	MS
P	B	M	MS	MS	VS
BP	M	M	S	MS	VS

4.4.2.3 Defuzzification: Outer Fuzzy-P Controller

The same defuzzification method is used to optimize proportional coefficient for the outer loop. MATLAB/Fuzzy Logic Toolbox is used with Mamdani-Centroid to clarify output parameter. The control surface is presented in Figure B.7 for K_{o_p}, (Appendix B).

The control surface characteristic is derived from the control rules and the membership functions. The surfaces demonstrate us that the coefficients of proportional, integral and derivative can be changed according to the error and the error rate. The surfaces provide facileness to know relationship between the error, the error rate and PID parameters. This makes easy to conduct a simulation.

CHAPTER 5

IMPLEMENTATION AND EXPERIMENTAL RESULTS

5.1 Introduction

Motion characteristics for servo presses, soft motion and coining motion characteristics are described. Simulink models of fuzzy-PID, 3-loops-cascade and fuzzy-cascade are explained in this chapter. System response, GA-PID, fuzzy-PID and fuzzy-cascade for step input are compared. Motion scenarios; soft and coining motion are applied to the servo press system. Motor angular positions and stroke positions of servo crank press for fuzzy-PID controller and fuzzy-cascade controller are presented. At the final section, the experimental results, fuzzy-PID and fuzzy-cascade results are compared. The performances of the designed controllers are given.

5.2 Motion Characteristics

Free motion concept is introduced by using servo presses with an improvement of dimensional accuracy. There is always a need for improved plastic flow of metal during metal shaping. Servo presses definitely improve stamping operations; deep drawing, coining, embossing, cold forging, blanking, or progressive die operations etc. The characteristics of material are also important to get an improved output. If the scenarios are not properly chosen and applied, unsatisfactory part quality is resulted. These scenarios are modified especially the working period of the stroke in the slider crank mechanism [38]. Typical servo press motions are shown in Figure 5.1.

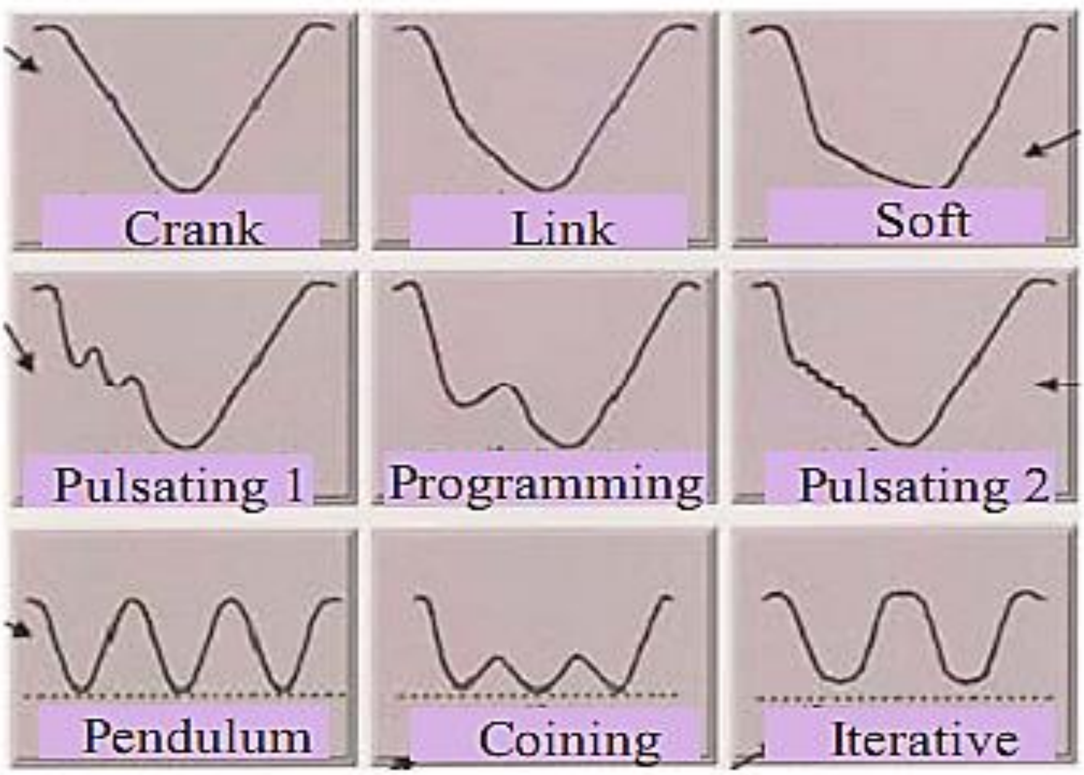


Figure 5.1 Typical Servo Press Motions [38]

Many different motion scenarios are possible depending on the user's requirement. In a previous study, 50 ton AC servo press has been designed and manufactured. Four motion scenarios in metal stamping industry are implemented as crank, link, dwell, and soft motion [39]. These scenarios are designed using TwinCAT/CAM Design Tool [40] while the motions are designed; position, velocity, acceleration, and jerk are considered by assuring motion smoothness. Here they are refer to as 'soft motion' and 'coining motion'. Motions implemented were previously designed by Halicioglu's Ph.D. thesis as a part of industrial project simulations, and the experimental implementations are given.

5.2.1 Soft Motion

Soft motion is performed with 20 stroke/min. Motion includes 5 parts; soft acceleration, deceleration, touch, dwell, and deceleration again. P_1-P_2 is acceleration period; P_2-P_3 represents deceleration period to have soft touching to the metal part to avoid impact; P_3-P_4 is the touching time to material with dwell part; P_4-P_5 represents soft acceleration time from zero to the faster point for the faster returning again; and P_5-P_6 is deceleration period. Table 5.1 gives the details of soft motion, and it is illustrated with Figure 5.2.

Table 5.1 Soft Motion Details [22]

Points	Time (sec)	Ram Position (mm)	Ram Velocity (mm/sec)	Crank Angle (rad)	Crank Velocity (rad/sec)
P_1	0	198	0	2.91	0
P_2	0.4	120	-608	1.69	-6.24
P_3	0.65	41	-47	0.88	-0.55
P_4	2.15	0	0	0	0
P_5	2.45	90	630	1.39	5.95
P_6	3	198	0	2.91	0

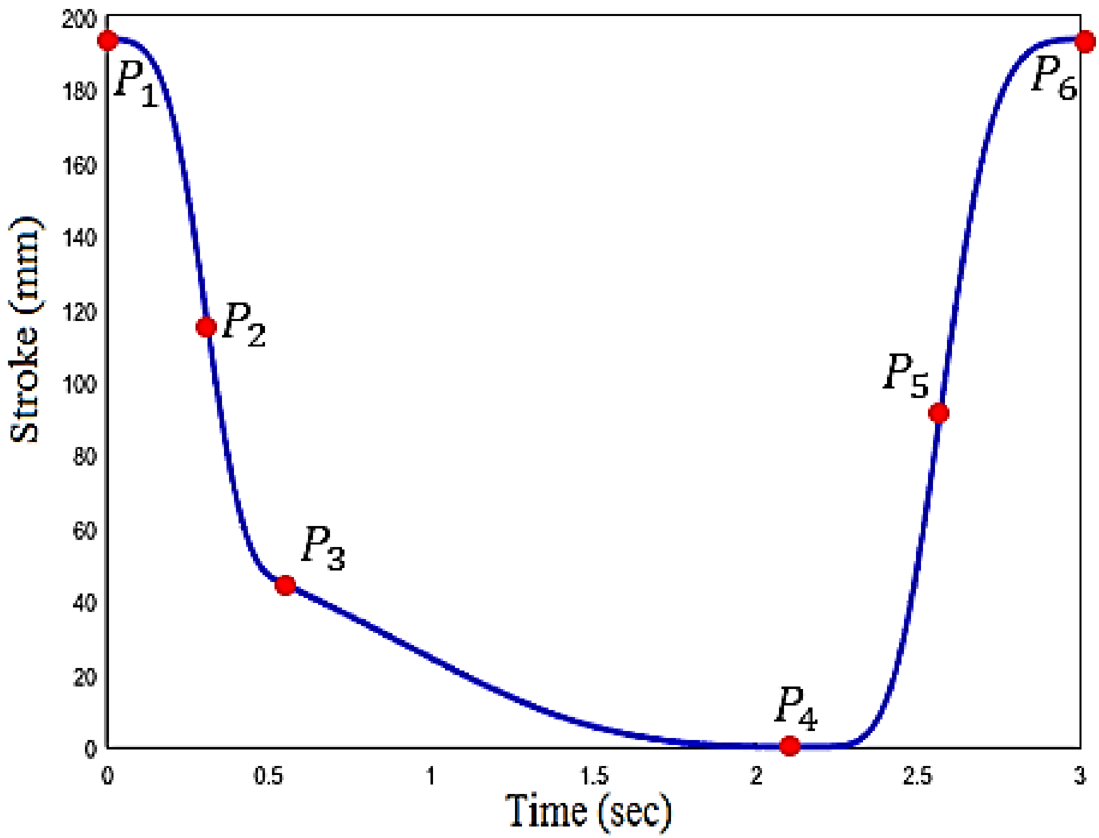


Figure 5.2 Soft Motion Scenario [22]

5.2.2 Coining Motion

Coining motion is also performed in 20 stroke/min. Motion includes 9 parts; P_1-P_2 is acceleration period; P_2-P_3 represents the deceleration for getting slower to avoid impact. P_3-P_4 is an acceleration period to leave from sheet metal. During P_4-P_5; the system becomes slower till reaching at point which refers one third of the stroke. P_5-P_6 is the period of staying at one third of the stroke for 0.04 second. P_6-P_7 period is the acceleration part again to save time. The next period, P_7-P_8 represents the deceleration for slower to avoid impact at the second step of pressing; P_8-P_9 period represents that the ram moves to next point with quick return, and finally P_9-P_{10} represents the deceleration period again to have a soft finishing of motion. Table 5.2 gives the motion kinematics and the motion graph presented in Figure 5.3 with points which is defined characteristic of coining motion scenario.

Table 5.2 Coining Motion Details

Points	Time (sec)	Ram Position (mm)	Ram Velocity (mm/sec)	Crank Angle (rad)	Crank Velocity (rad/sec)
P_1	0	198	0	4.28	0
P_2	0.65	83	-557	2.39	-5.7
P_3	0.9	0	0	1.22	-5.2
P_4	1.07	24.1	230	0.54	-3.65
P_5	1.47	63.3	0	0	0
P_6	1.51	63.3	0	0	0
P_7	1.91	23.2	-230	0.42	3.3
P_8	2.07	0	0	1.23	4.9
P_9	2.3	85	557	2.39	5.7
P_{10}	3	198	0	4.28	0

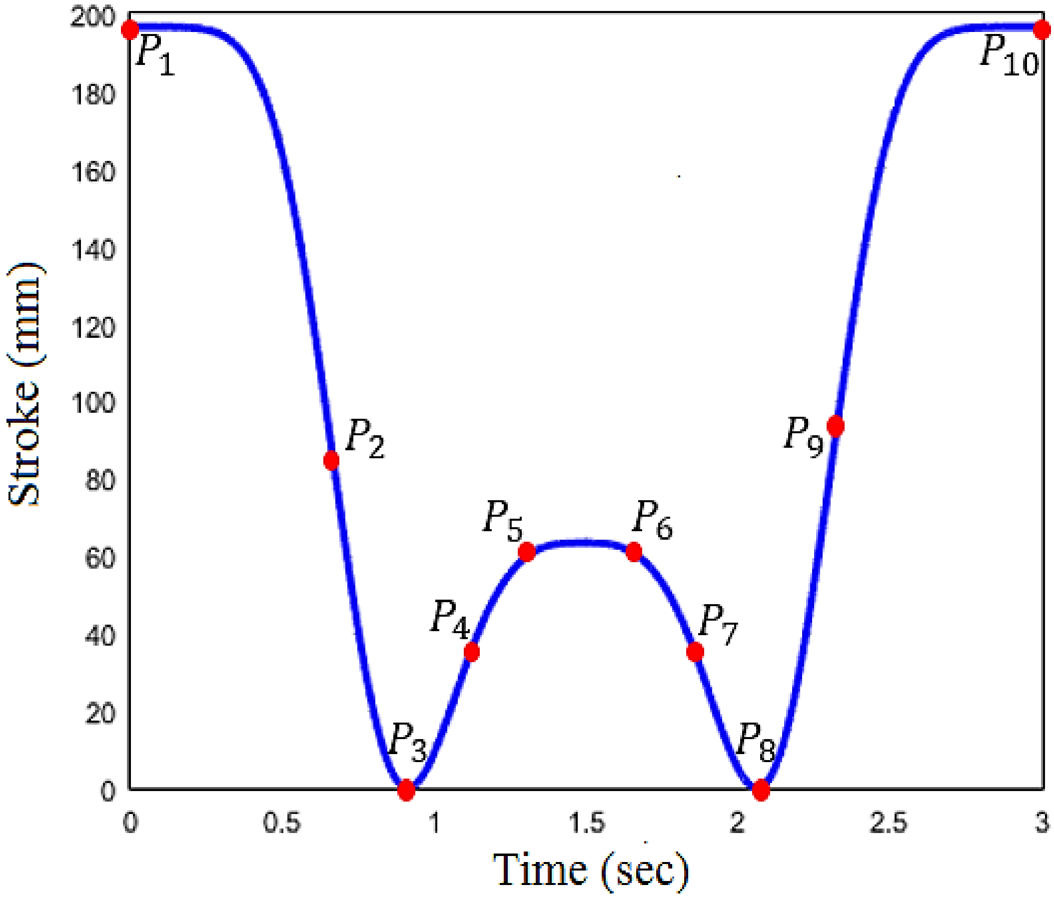


Figure 5.3 Coining Motion Scenario

5.3 Servo Press System with Fuzzy-PID Controller

The dynamics and mathematical model of the servo crank press are determined in a previous study. Fuzzy logic inputs and outputs with fuzzy rules are created to adjust PID parameters to control position of the system represented by its transfer function herein. Fuzzy-PID controller is designed to control position of the system in Chapter 4. The harmony of fuzzy logic approach for PID controller and the system which has transfer function of servo crank press are modeled in Simulink/MATLAB. The block diagram of this model is presented in Figure 5.4.

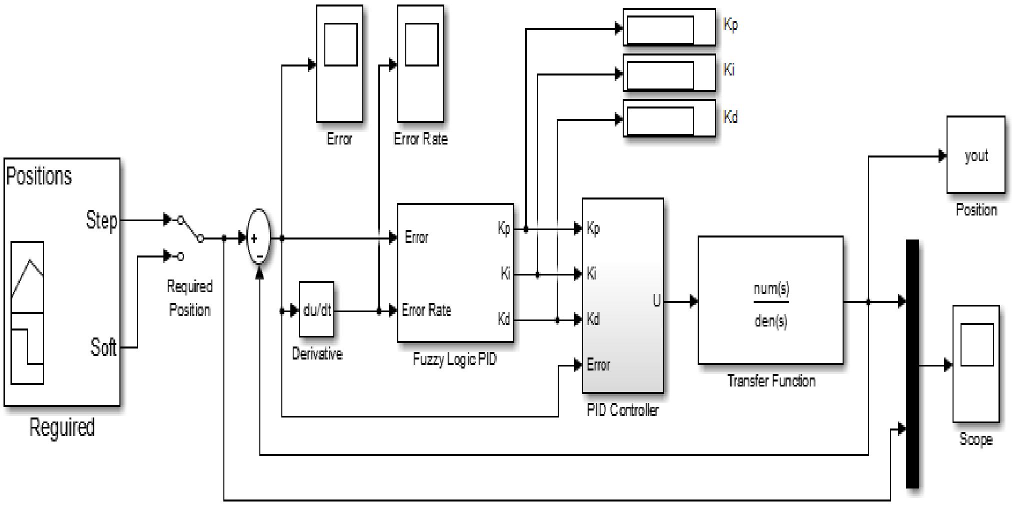


Figure 5.4 Block Diagram for Servo Crank Press with Controller

5.4 Cascade Controller

Cascade control (CC) is used for improving system performance, especially the disturbances in process control. It was introduced by Franks and Warley [41]. The inner loop controller is designed first. The outer loop is performed next. Preferably PI and PID controllers are included. Many contributions are seen in literature. For example, Kaya et al [42] have presented a study on improved cascade control structure for enhanced system performance. The process is separated into two/more parts measuring one/more variables for the inner loop/loops. Figure 5.5 shows the cascade control system. Here the main controller is given by G_{c1} and the secondary controller is shown as G_{c2}.

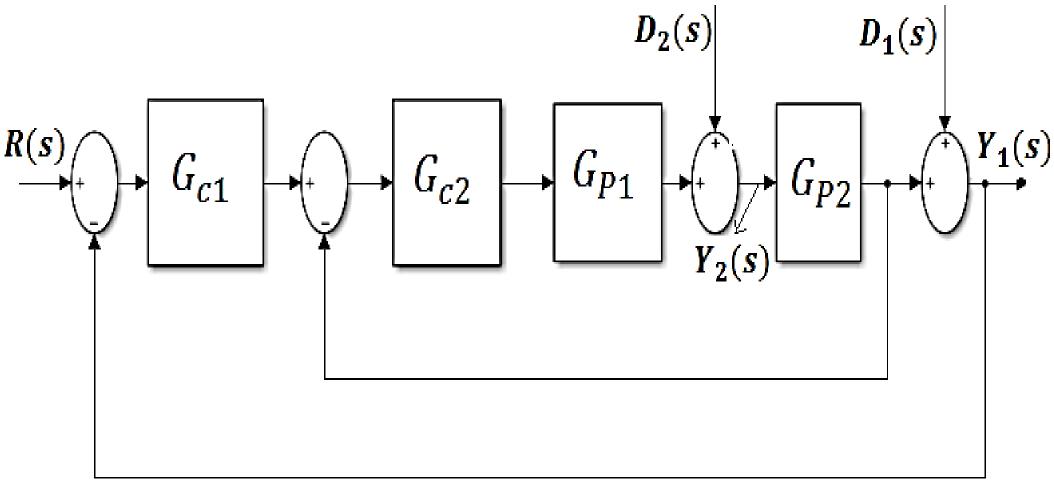


Figure 5.5 Cascade Control System

5.4.1 Servo Press System with 3-Loop-Cascade Controller

AC crank servo press system is placed in University of Gaziantep, Mechanical Engineering Department. Servo Driver system has 3-loop-cascade controller. The first and second inner loops are created to control the motor current and the motor velocity one by one. The outer loop controls position of the motor. The block diagram of the servo crank press system is given in Figure 5.6 with inner and outer loops. It is designed using TwinCAT software program [43].

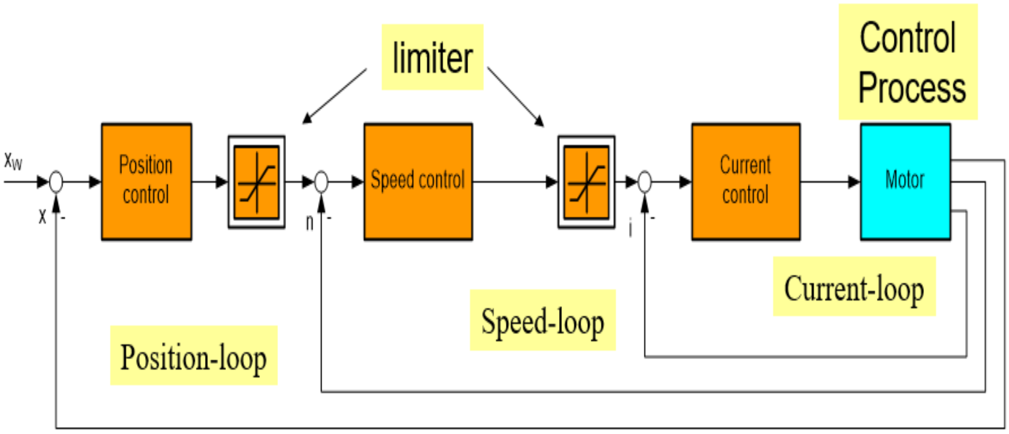


Figure 5.6 Three-Loop-Cascade Control Model [43]

5.4.2 Servo Press System with Fuzzy-Cascade

Transfer function of the plant is given with the mathematical model of servo crank press system. But the transfer function of the system is not enough to use a cascade controller. It is necessary to have an inner loop in the system. Therefore, the velocity should be obtained to use the inner loop. State space matrices should be determined for obtaining the motor angular velocity as given in Chapter 3. One inner loop and one outer loop are generated to control the position and velocity of the motor. The following error is minimized during the positioning. Thus overshoot-free response is obtained into the target position by reducing speed oscillation.

Fuzzy-PID controller for inner loop and fuzzy-P controller for outer loop are explained in Chapter 4. Fuzzy-PID and fuzzy-P controller and the press system are given by state-space representation. The servo crank press is modelled on Simulink/MATLAB software package. The block diagram of the designed model is shown in Figure 5.7.

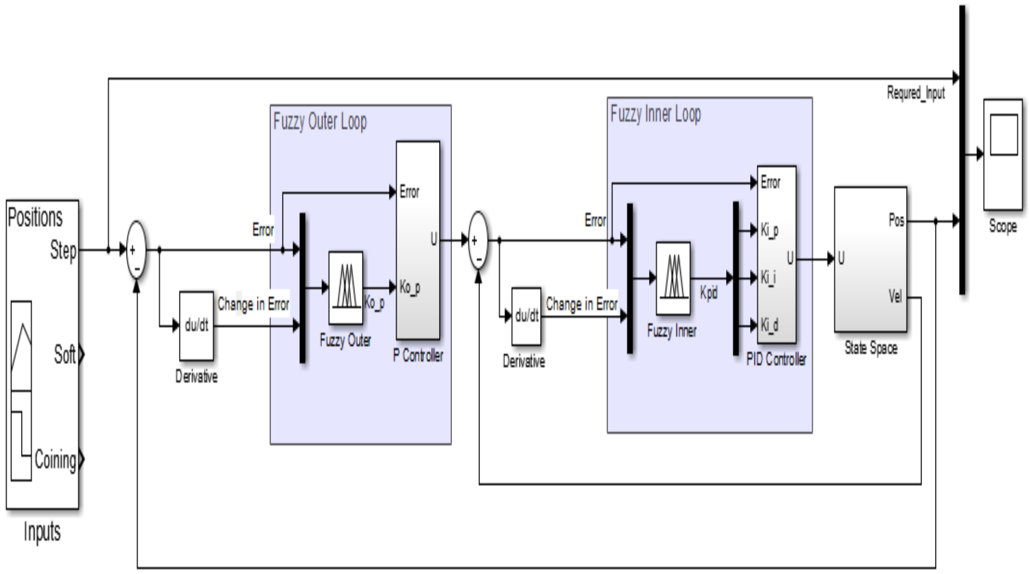


Figure 5.7 Block Diagram for Servo Crank Press with Fuzzy-Cascade Controller

5.5 Implementation Results

Conventional press systems and the hydraulic presses have been applied in metal forming industry. In recent years, servo presses are used as flexible manufacturing systems. Motion flexibility is definitely increased with higher precision Some flexible motion scenarios are created for servo press called dwell, crank, soft, link and coining. Then, some controllers are designed to get different motion scenarios. Fuzzy-PID and fuzzy-cascade controllers are designed in chapter 4. These controllers are connected to the system and the step input for 2 seconds, soft and coining motions are applied to the system for 3 seconds.

Initially to see the system response, GA-PID, fuzzy-PID and fuzzy-cascade controllers are compared for step input. Having performed this test signal, the motor angular positions are analyzed for required soft and required coining motions. PID gains for fuzzy-PID controller, for fuzzy-cascade inner loop PID-controller and for fuzzy cascade outer loop P-controller are analyzed, and found. While looking at the system response, time domain characteristics are studied. The step response for the system, GA-PID, fuzzy-PID and fuzzy-cascade is presented in Figure 5.8.

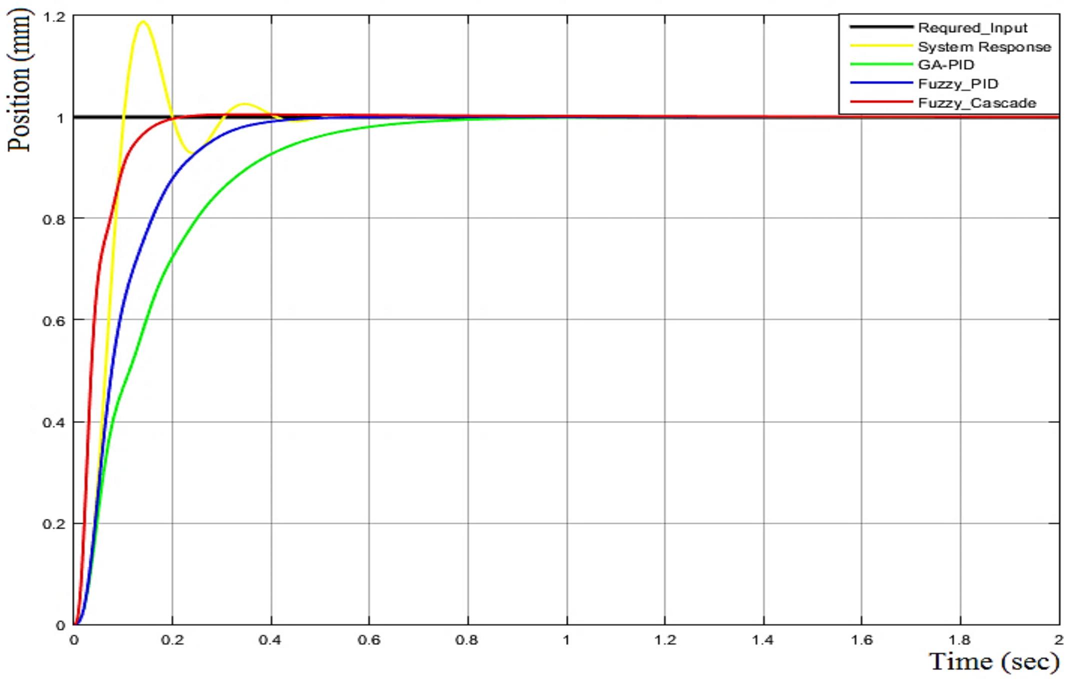


Figure 5.8 Step Response of System

All controllers can be used for the system because they have good settling time, no overshoot and zero steady error or minimum steady state error in Table 5.3. Settling time is slower for GA-PID than the other controllers and the steady state error is %0.6 for fuzzy-PID. So, fuzzy-cascade controller has been the best with the fastest settling time, with no overshoot and with no steady state error.

Table 5.3 Time Domain Characteristics for Controllers

Controllers	**Settling Time (sec)**	**Overshoot (%)**	**Steady State Error (%)**
GA-PID	0.7	0	0.5
Fuzzy-PID	0.4	0	0.6
Fuzzy-Cascade	0.2	0	0

Fuzzy-PID and fuzzy-cascade controllers are focused on this thesis. Therefore, PID tuning parameters for fuzzy-PID and PID for fuzzy-cascade inner loop and P tuning parameter for fuzzy-cascade outer loop graphs are given in Figures 5.9-5.11 respectively. K_p, K_i and K_d for fuzzy-PID controller is changed until the output get the required input. It can be said that it is similar for K_{i_p}, K_{i_i} and K_{i_d} for the inner loop and K_{o_p} for the outer loop of fuzzy-cascade controller.

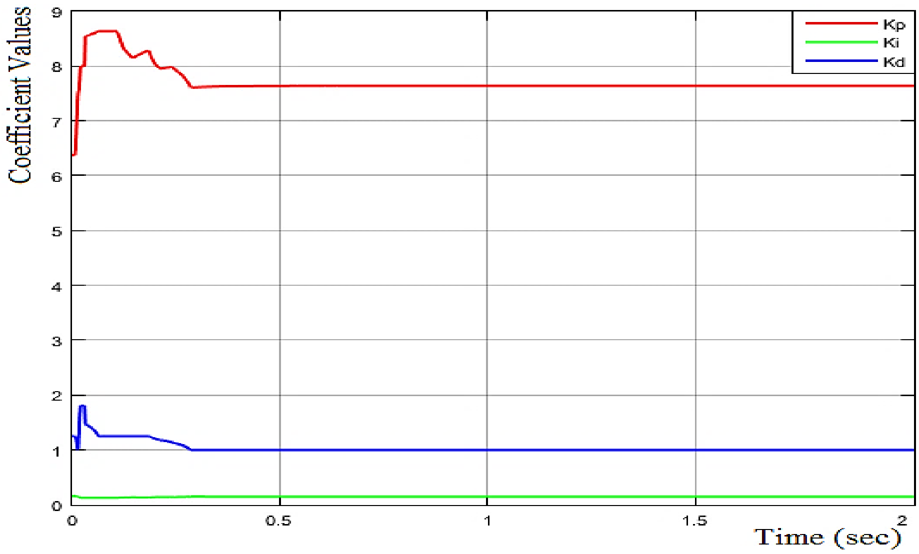


Figure 5.9 K_p, K_i and K_d for Fuzzy-PID of Step Response

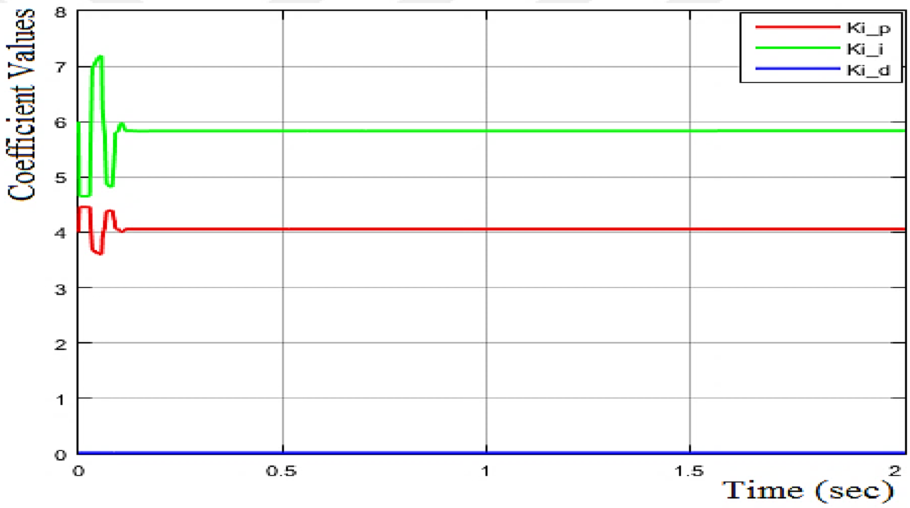


Figure 5.10 K_{i_p}, K_{i_i} and K_{i_d} for Fuzzy-PID of Inner Loop of Step Response

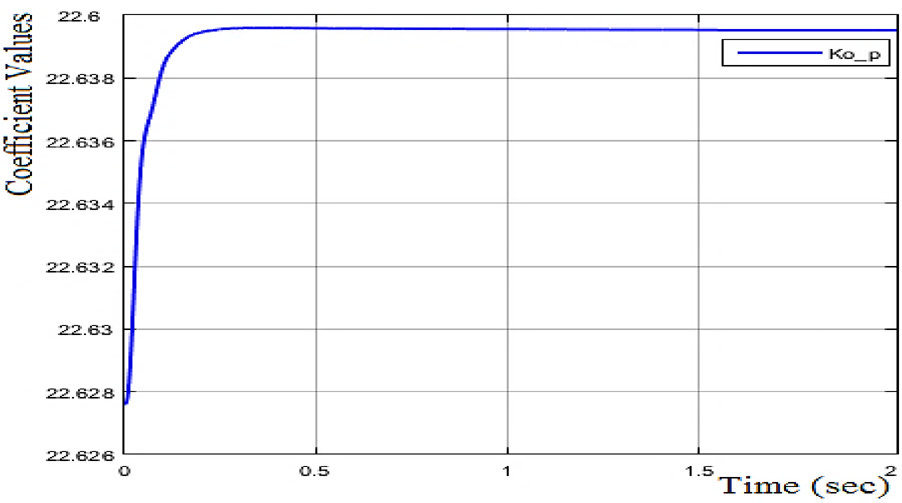


Figure 5.11 K_{o_p} for Fuzzy-P of Outer Loop of Step Response

5.5.1 Fuzzy-PID and Fuzzy-Cascade for Soft Motion

Soft motion is applied for fuzzy-PID and fuzzy-cascade. Motor angular position of the servo press with fuzzy-PID and fuzzy-cascade for soft motion is attained by MATLAB/Simulink. Their curves are presented on a single scope in Figure 5.12.

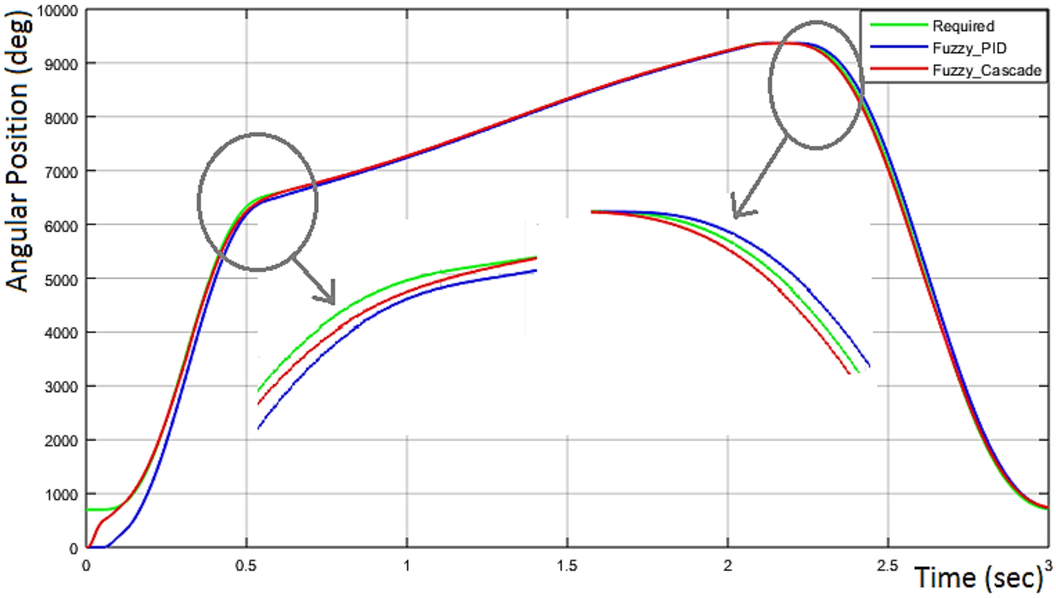


Figure 5.12 Motor Angular Position of Fuzzy-PID and Fuzzy-Cascade Control for Soft Motion

Curves are specified by green for the required input, blue for fuzzy-PID and red for fuzzy-cascade. Then, it is zoom in critical parts of the curves for the angular position of the motor. After looking these parts, it has been seen that the output of fuzzy-cascade controller follows better and more stable than fuzzy-PID controller. K_p, K_i and K_d for fuzzy-PID and K_{i_p}, K_{i_i}, K_{i_d} and K_{o_p} for fuzzy-cascade are changed according to motion to make the system stable, faster, to improve steady state error and overshoot. K_p, K_i and K_d for fuzzy-PID results are shown in Figure 5.13, K_{i_p}, K_{i_i} and K_{i_d} for inner and K_{o_p} for outer fuzzy-cascade are presented in Figures 5.14 and 5.15 respectively.

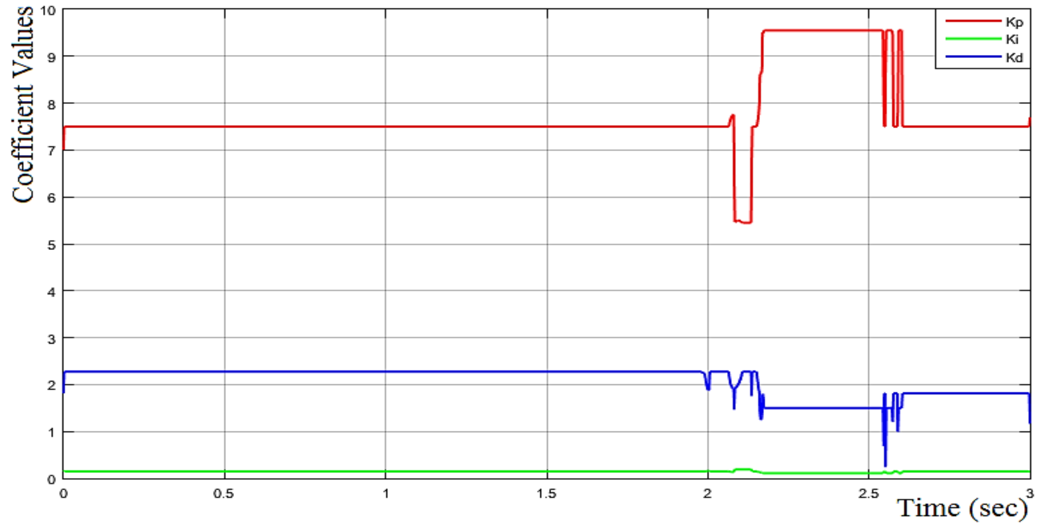


Figure 5.13 K_p, K_i and K_d for Fuzzy-PID of Soft Motion

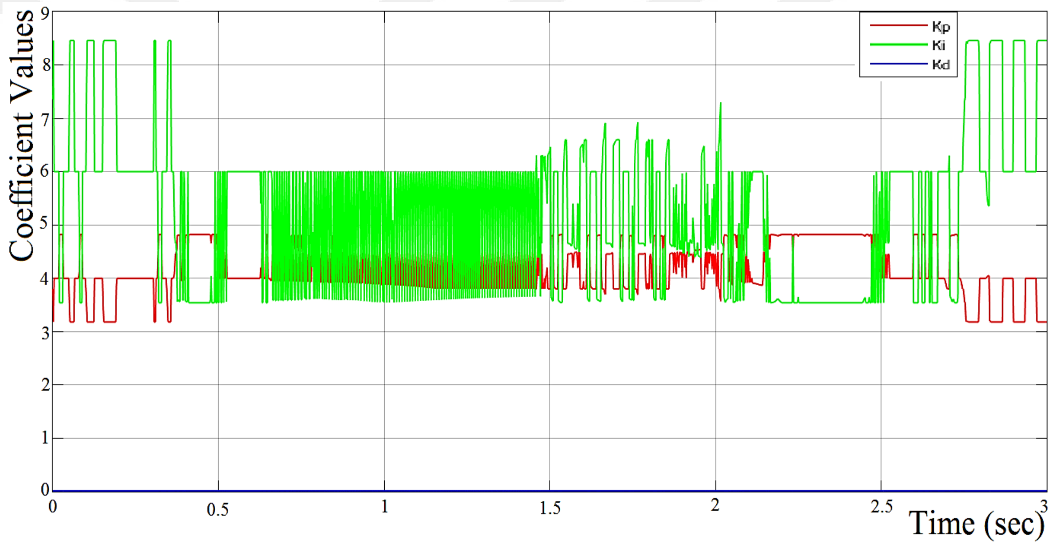


Figure 5.14 K_{i_p}, K_{i_i} and K_{i_d} for Fuzzy-PID of Inner Loop of Soft Motion

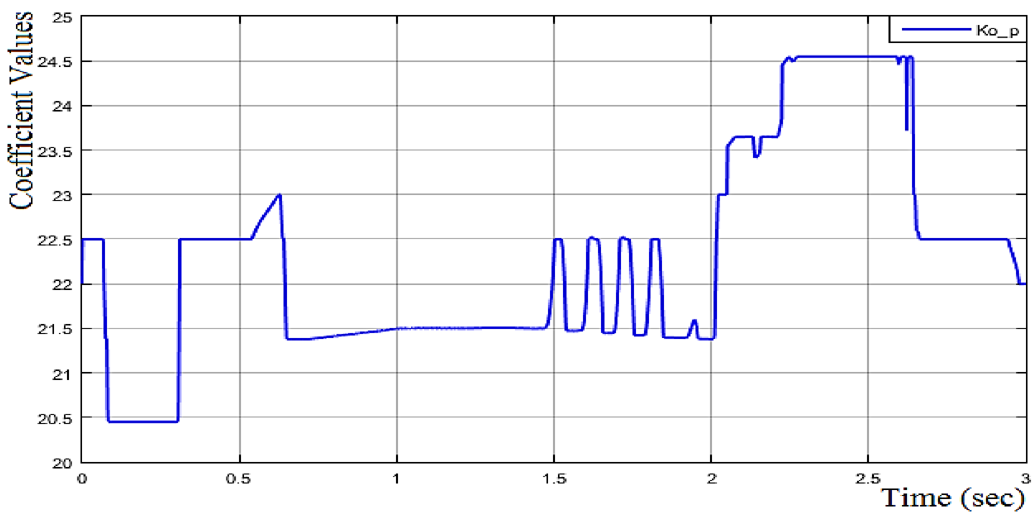


Figure 5.15. K_{o_p} for Fuzzy-P of Outer Loop of Soft Motion

5.5.2 Fuzzy-PID and Fuzzy-Cascade for Coining Motion

In this section, coining motion is applied for fuzzy-PID and fuzzy-cascade. Motor angular position of the servo press with fuzzy-PID and fuzzy-cascade for coining motion is attained. The curves are given below in Figure 5.16.

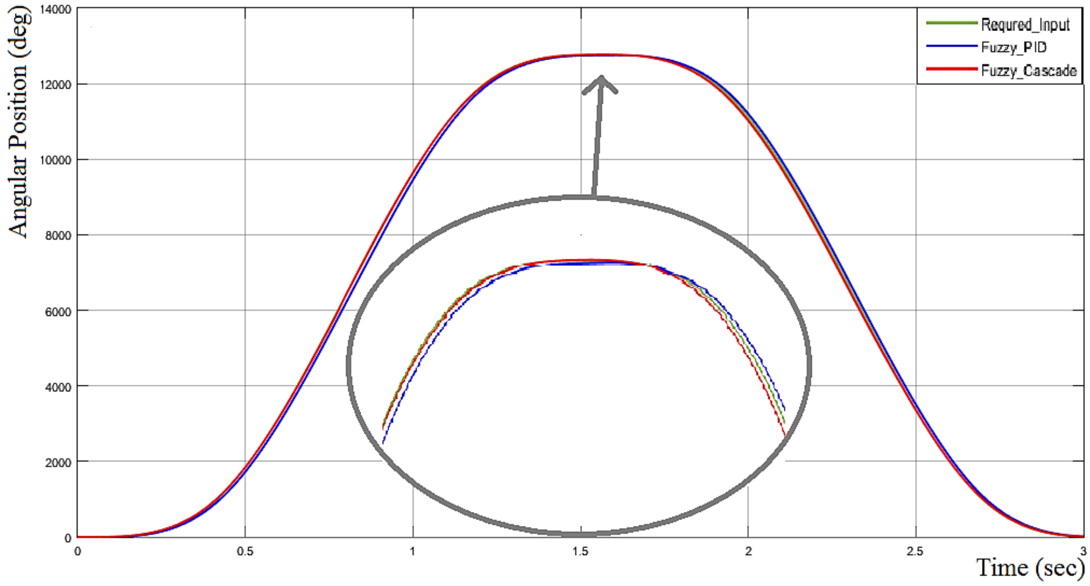


Figure 5.16 Motor Angular Position of Fuzzy-PID and Fuzzy-Cascade Results for Coining Motion Scenario

Curves are specified by green for the required input, blue for fuzzy-PID and red for fuzzy-cascade. Then, it is detailed in critical parts of the curves for the angular position of the motor. It has been seemed that the output of fuzzy-cascade controller follows better and more stable than fuzzy-PID controller. Even if the coining motion scenario is the most difficult to get among soft motion, crank motion and dwell motion scenarios, the output of fuzzy-cascade controller is stable, fast, and robust.

K_p, K_i and K_d for fuzzy-PID and K_{i_p}, K_{i_i}, K_{i_d} and K_{o_p} for fuzzy-cascade are variation during to get motion and making the system stable, faster, improving steady state error and overshoot. Results of K_p, K_i and K_d for fuzzy-PID controller is shown in Figure 5.17, and results of K_{i_p}, K_{i_i}, and K_{i_d} for inner fuzzy-cascade and K_{o_p} for outer fuzzy-cascade are presented in Figures 5.18 and 5.19 respectively.

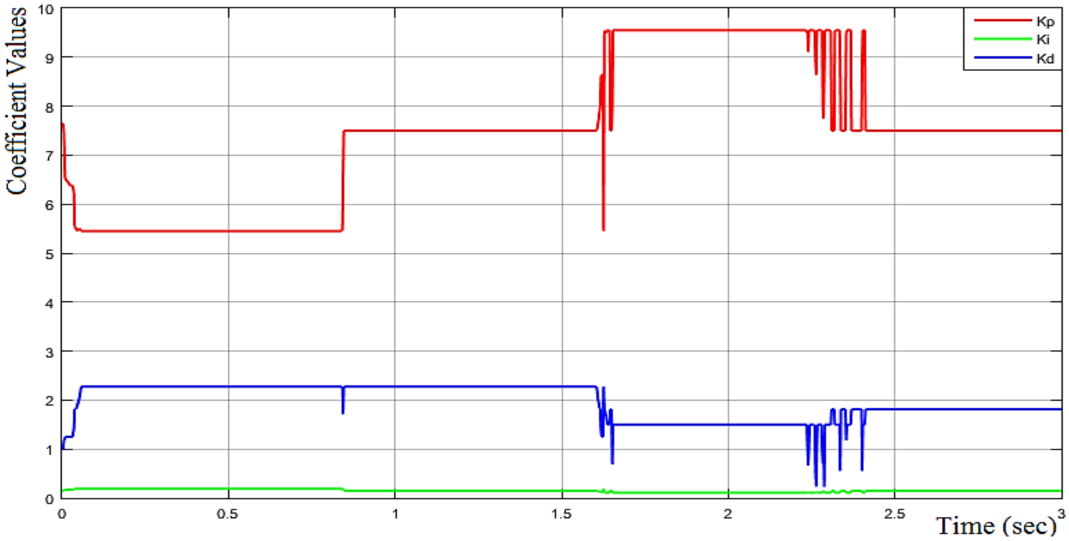


Figure 5.17 K_p, K_i and K_d for Fuzzy-PID of Coining Motion

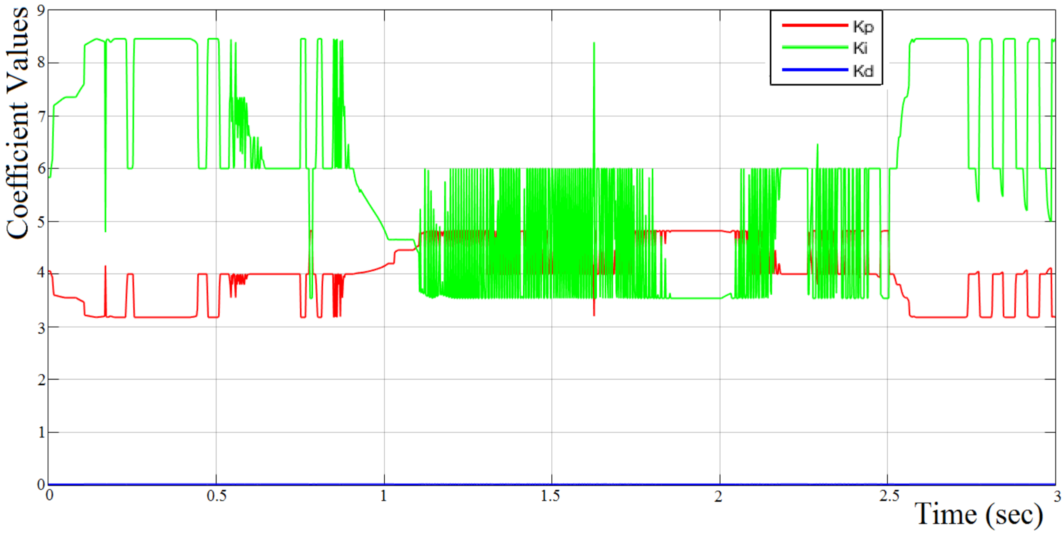


Figure 5.18 K_{i_p}, K_{i_i} and K_{i_d} for Fuzzy-PID of Inner Loop of Coining Motion

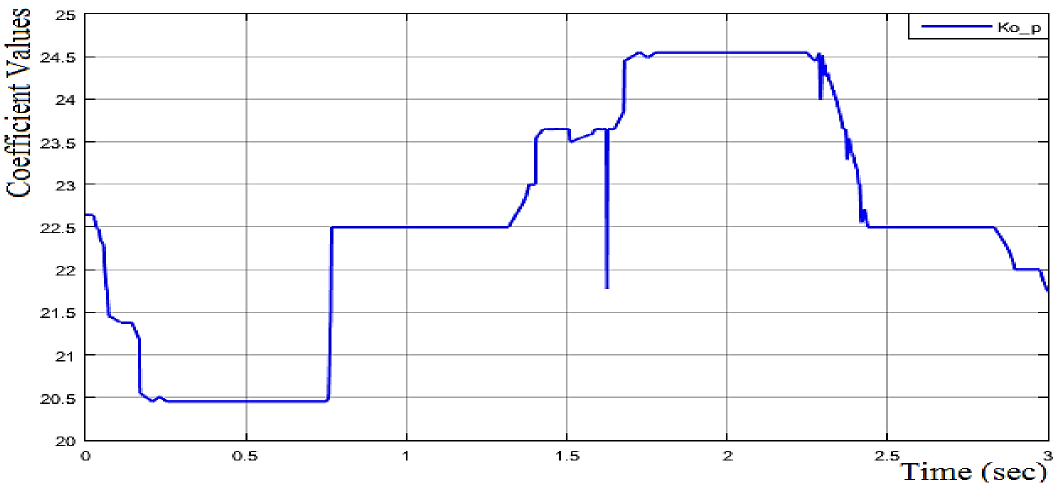


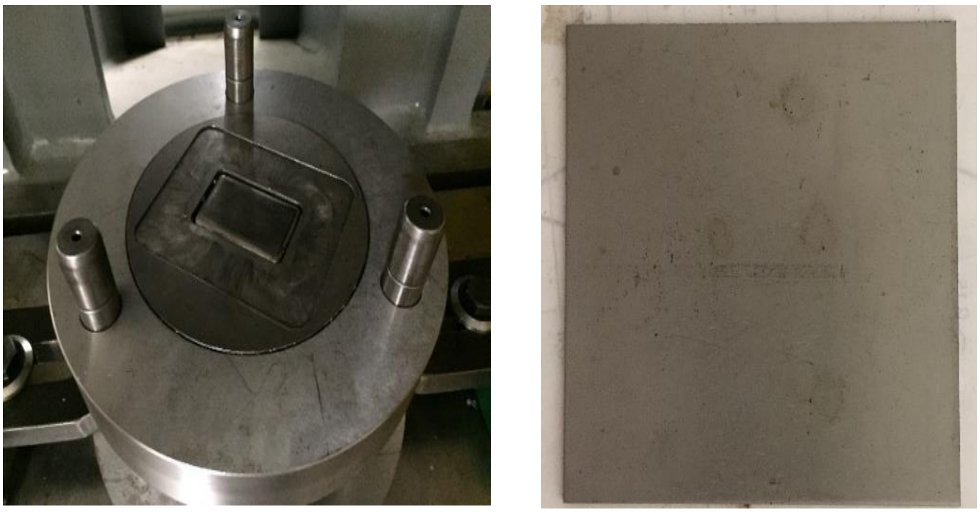
Figure 5.19 K_{o_p} for Fuzzy-P of Outer Loop of Coining Motion

5.6 Experimental Results

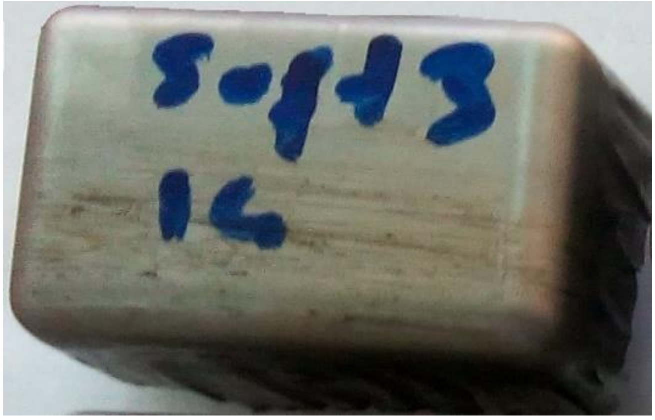
The experimental system which has a 50 tons capacity, AC crank servo press is designed by Halicioglu et al [44]. The system is located at University of Gaziantep, Mechanical Engineering Department. A servo crank press driven by PMSM is controlled by PID-cascade, fuzzy-PID and fuzzy-cascade controllers in this study, after that the position of motor and stroke of servo press for the soft and the coining motion scenarios are applied for three seconds. In the experimental system, PID-cascade control system is used, fuzzy-PID and fuzzy-cascade are compared to PID-cascade controller for motor angular position and for ram position. Then, a deep drawing example is included.

5.6.1 PID-Cascade, Fuzzy-PID and Fuzzy-Cascade for Soft Motion

The experimental system has two press dies which are designed as a part of a project for deep drawing applications. One of them is used during the experiments. It is given in Figure 5.20(a). A sheet metal which has size of $80x80x1\ mm$ and named AISI 316 material is used to have required production. It is illustrated in Figure 5.20(b). Metal shaping is performed by using soft motion scenario. The result of this experiment, a deep drawing production is obtained and given at next page in Figure 5.20(c).



(a) (b)



(c)

Figure 5.20 Deep Drawing Production of Soft Motion

Experimental results of PID-cascade controller are attained from the motor angular encoder and linear encoder by Twin-CAT software program. The motor angular positions of experimental result with fuzzy-PID and fuzzy-cascade are shown for soft motion in Figure 5.21. Fuzzy-cascade controller is given better response than fuzzy-PID controller, even if fuzzy-PID controller is close to perfect. But, the experimental result of angular position is not perfect as simulation because of actual system operating. Having compared the angular position for soft motion, the stroke position of servo press system is estimated.

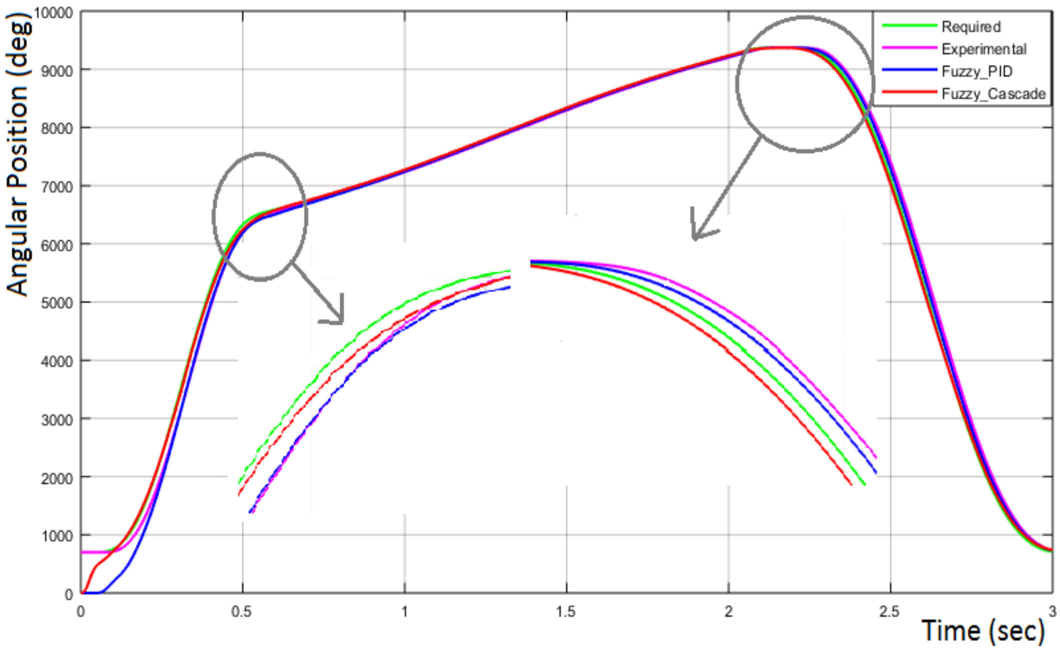


Figure 5. 21 Motor Angular Position of Experimental, Fuzzy-PID and Fuzzy-Cascade for Soft Motion Scenario

The crank ram linear position of experimental result and linear position which is determined by fuzzy-PID and fuzzy-cascade controllers for coining motion is presented in Figure 5.22. Two critical points are generated during the servo mechanism presses on the sheet metal in order to form. Mechanism touches the metal at first point and it press softly. On the other hand, the second point informs us that the mechanism leaves from sheet metal fast to save time. Between these two points, our controller should track the required curve. Improvement in ram position results is exactly seen that fuzzy-cascade controller is the best.

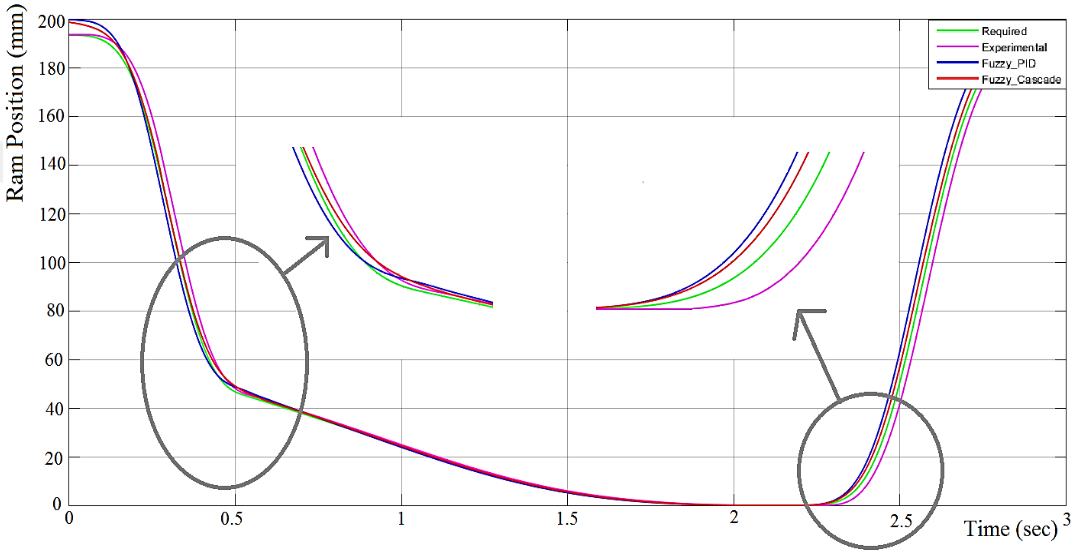


Figure 5.22 Ram Position of Experimental, Fuzzy-PID and Fuzzy-Cascade Results for Soft Motion Scenario

5.6.2 PID-Cascade, Fuzzy-PID and Fuzzy-Cascade for Coining Motion

The rectangular die which is presented in Figure 5.20(a) and (b) are also used for coining motion scenario. The result of this experiment, a deep drawing production is illustrated in Figure 5.23. Rectangular metal size is used to form deeper rectangular in order to obtain more clear results within the scope of the project. The servo press motion for soft and coining were tried on a sample and the images were magnified 100 times under light microscope. It has been observed that these images are increased the surface sensitivity to metal forming. The experimental results and manufactured material is examined. It has been seen that the quality of the produced servo press metal is increased. Different metal alloys and circular die will be used with for future studies. Experimental results of PID-cascade controller for coining motion scenario are obtained from the motor angular encoder and linear encoder for soft motion.

Figure 5.23 Deep Drawing Product of Coining Motion

The motor angular position of experimental result and the angular position with fuzzy-PID and fuzzy-cascade for coining motion are shown in Figure 5.24. The critical points that fuzzy-cascade controller is closest to required motion as perfect. The experimental result of angular position is not perfect as simulation because of environmental conditions. The crank ram linear position of experimental result and linear position which is determined by fuzzy-PID and fuzzy-cascade controllers for coining motion is presented in Figure 5.25.

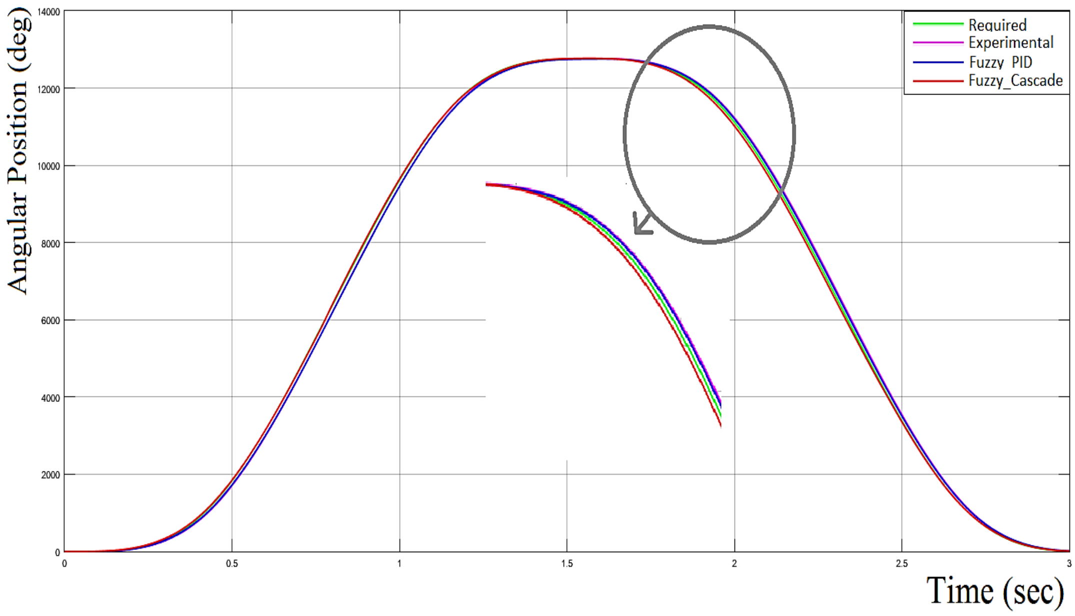


Figure 5.24 Angular Position of Experimental, Fuzzy-PID and Fuzzy-Cascade for Coining Motion Scenario

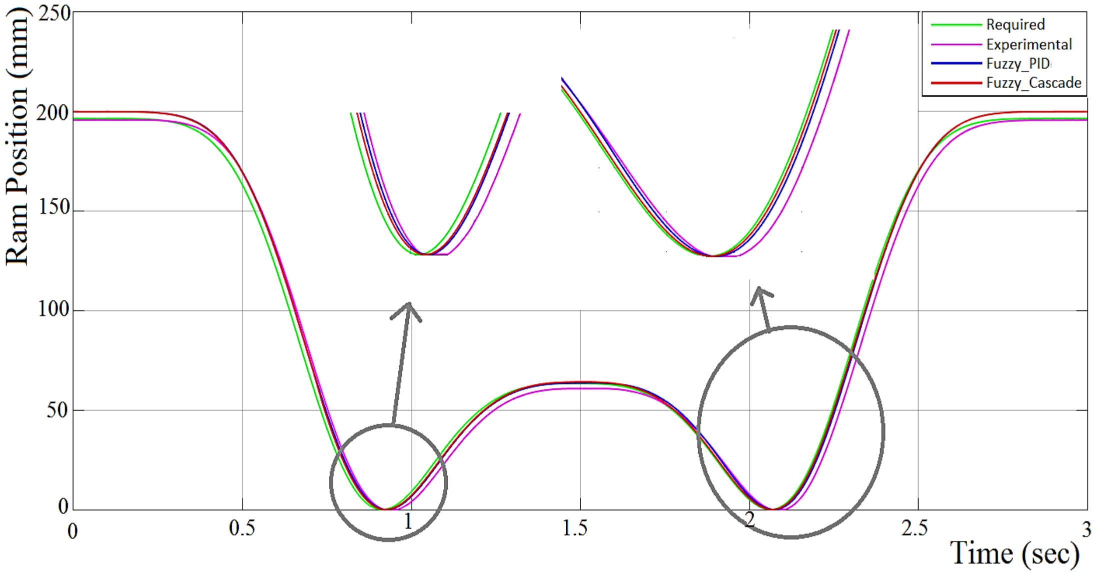


Figure 5.25 Ram Position of Experimental, Fuzzy-PID and Fuzzy-Cascade Results for Coining Motion Scenario

Two critical points are ensued during the servo mechanism presses on the sheet metal and leave the sheet metal to form. First and second critical points show us that mechanism touches and leaves the metal in the short time so our controller should provide that output should track the required curve. These points inform us that the experimental results not good as soft motion scenario. Nevertheless, the coining motion scenario is the most difficult among crank, soft, dwell and link motion. Fuzzy-cascade controller is quite good to follow the required input position as it seems. Improvement in ram position results is exactly seen that fuzzy-cascade controller is the best for coining motion.

CHAPTER 6

CONCLUSIONS

6.1 About Thesis

This research was granted, by University of Gaziantep under Scientific Research Funding (BAP No: MF.YLT.16.09). A metal forming servo crank press has been used in this study. The press has 50 tons industrial prototype and 200 mm stroke capacity. It is built with Coşkunöz Company as a SANTEZ project. Thesis is included six chapters. Literature survey is given for metal shaping presses with control algorithms in previous studies. Fuzzy logic is studied. Fuzzy-PID and fuzzy Cascade-PID based controllers are constructed.AC servo press system is operated by using these algorithms. The design of servo motor position control system depends on performance specifications; time response, stability and disturbance rejection. The transfer function is derived including the actuator dynamics with mechanism. Simulations and experimental results are then presented.

6.2 Contributions

The main contributions are summarized in three parts; motion scenarios, fuzzy control issues and implementations.

- ***Motion Scenarios:***

Although many motion scenarios are available; two of them are chosen in case studies; soft motion and coining motion. Motion characteristics are taken from previous Ph.D study performed at Gaziantep University [22]. A smooth ram and crank motion are designed. The slide motion is altered to get improvement during metal flow. For example; constant velocity motion improves quality of part. Motion cycles are performed in 3 seconds. Different experiments are performed slower crank speeds and faster crank speeds like 1.5 second, 3 seconds and 6 seconds successively. To make a reliable comparison 3 seconds are chosen by referring to previous study. So, by looking at the mathematical model, transfer function of the system is derived. Simulations are obtained and validation is performed by the experiments.

- ***Fuzzy Control Issues:***

A press automation system is available. Cascade Feed Forward (CasFF) controller with PID algorithm is already applied. Auto-tuning of servo system is obtained within the accuracy at points. Fuzzy control starts with heuristics and incorporates to a series of control rules. These rules have varying degrees of membership. Initially the experimental system is studies by using step input as a test signal. AC servo press system is then controlled by fuzzy-PID and Cascade fuzzy-PID. To achieve required control performance fuzzy controller is designed. Case studies are performed as soft motion and coining motion.

- ***Implementations:***

Case studies are applied without punching force in the laboratory. The experimental results are presented with servo motor tracking control performances. Deep drawing operations are performed using soft motion and coining motion (20 stroke/min). A deep drawing example of 40 mm is achieved by using a rectangular die. Twelve ton punching force is applied on Cr-Ni steel sheet having a thickness of 1 mm.

6.3 Recommendations for Future Work

The following points are left to be studied in the future work.

- ***Experiments with higher speeds:***

The press has a velocity capacity of 71 spm with maximum stroke of 200 mm. This is specified, by servo motor capacity. Two case studies have been performed at 20 stroke/min in this study. Future studies can include different motion requirements with higher speeds by using fuzzy control. This is to be investigated to see the relation between speeds and surface quality attained.

- ***Deep Drawing Applications:***

Forming applications are performed by using one material only. Two die designs are used for this purpose. During the first tests; 0,5 mm thickness AISI 316 ve AISI 304 are chosen. In the rectangular die which is designed; AISI 304 is fractured. So deep drawing applications are performed by using AISI 316. Prevention of fracture is another issue to be explored by experts from the materials side. This study is left to future as promising studies. Here the main concentration is done on fuzzy logic idea and its details on AC servo press system's control side.

- ***Hybrid Control Algorithms:***

A hybrid algorithm called 'neuro-fuzzy' will be applied. This idea combines fuzzy logic (FL) with neural network (NN). So, while designing a controller hybrid algorithm will be integrated with the system. AC servo press system will then be controlled by fuzzy-NN alternative in terms of the system performance. The other algorithm to be considered fuzzy-NN PID controllers during metal shaping experiments in future work.

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APPENDIX A

MEMBERSHIP FUNCTIONS

A.1 Membership Functions in MATLAB/Fuzzy Logic Toolbox

The only condition a membership function must really satisfy is that it must vary between 0 and 1. The function itself can be an arbitrary curve whose shape we can define as a function that suits us from the point of view of simplicity, convenience, speed, and efficiency.

The MATLAB/Fuzzy Logic Toolbox includes 11 built-in membership function types. They are in turn, built from several basic functions:

- Piece-Wise Linear Functions
- The Gaussian Distribution Functions
- The Sigmoid Curve
- Quadratic and Cubic Polynomial Curves

All membership functions have the letters ‘mf’ at the end of their names.

- **Triangular and Trapezoidal Membership Functions**

The simplest is the *triangular* membership function; is collection of three points forming a triangle, and the other simple function is also *trapezoidal* membership function; has a flat top and really is just a truncated triangle curve are informed in Chapter 4 because of their useful for controller. The details for the other membership functions are explained herein.

- **Gaussian and Bell Membership Functions**

The *Gaussian* distribution curve has two membership functions: a simple Gaussian curve and a two sided composite of two different Gaussian curves called respectively, ‘gaussmf’ and ‘gauss2mf’.

Three parameters specify the *generalized bell* membership function; has the function name ‘gbellmf’. The bell membership function has one more parameter than the Gaussian membership functions. So, it can approach a non-fuzzy set if the free parameter is tuned. Because of their smoothness and concise notation, Gaussian and bell membership functions are popular methods for specifying fuzzy sets. Both of them have the advantage of being smooth and nonzero at all points. There sample sketches are given in Figure A.1 for Gaussian and Bell membership functions [30].

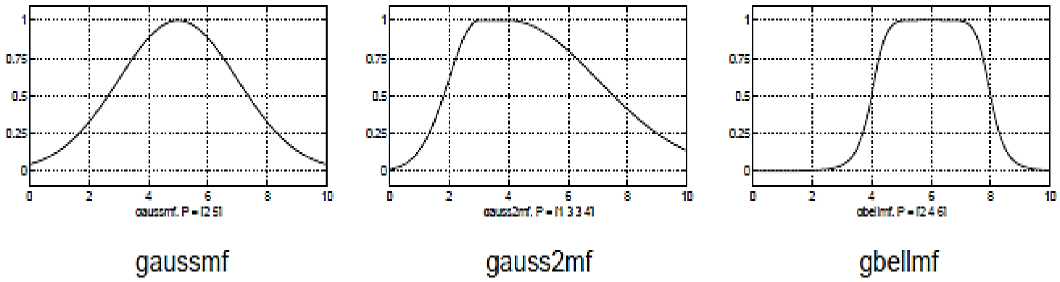

Figure A.1 Sketches for Gaussian and Bell Membership Functions [30]

Although the Gaussian membership functions and bell membership functions achieve smoothness, they are unable to specify asymmetric membership functions.

- **Sigmoidal Membership Functions**

The *sigmoidal* membership function, which is either open left or right. Asymmetric and closed (i.e. not open to the left or right) membership functions can be synthesized using two sigmoidal functions. In addition to the basic ‘sigmf’ which is open left or right side of the function, it can be also had the difference between two sigmoidal functions, ‘dsigmf’, and the product of two sigmoidal functions ‘psigmf’ are presented in Figure A.2 [30].

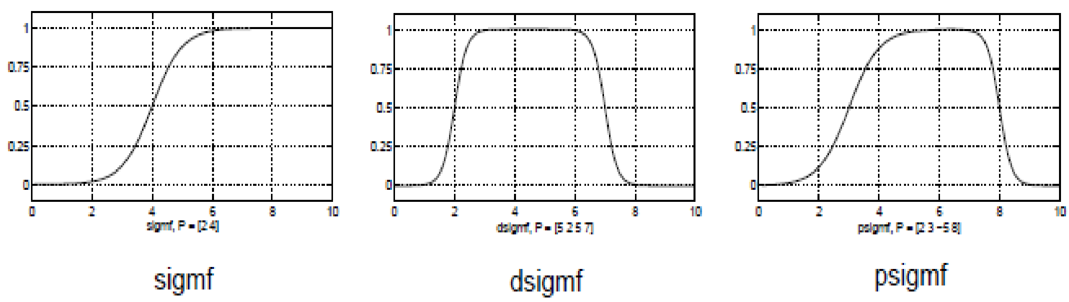

Figure A.2 Sketches for Sigmoidal Membership Functions [30]

- **Polynomial Membership Functions**

Three membership functions are *Z*, *S*, and *Pi* curves for *Polynomial*, all named because of their shape. The function ‘zmf’ is the asymmetrical polynomial curve open to the left, ‘smf’ is the mirror-image function that opens to the right, and ‘pimf’ is zero on both extremes with a rise in the middle, shown in Figure A.3.

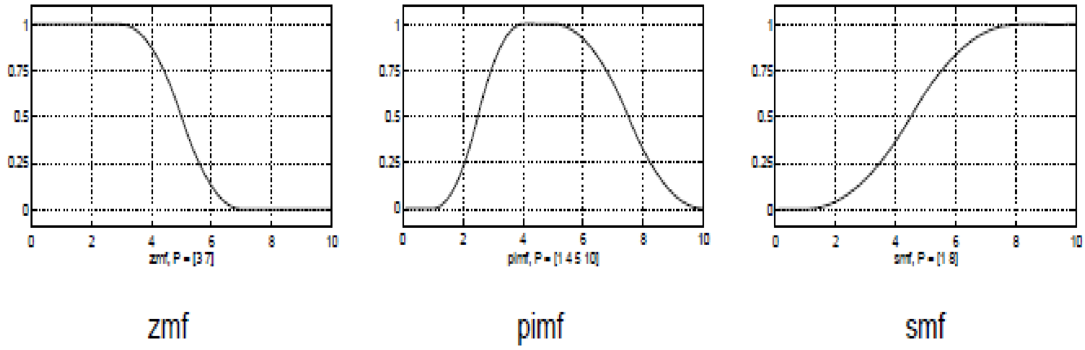

Figure A.3 Sketches for Polynomial Membership Functions [30]

There is a very wide selection to choose from when you’re selecting a membership function. You can also create your own membership functions with the toolbox. However, if a list based on expanded membership functions seems too complicated, you could probably get along very well with just one or two types of membership functions. For example, the triangle and trapezoid functions. The selection is wide for those which can explore the possibilities. But, expansive membership functions are not necessary for good fuzzy inference systems [30].

A.2 Membership Functions of Controllers for Servo Press

All membership functions used for the controller are derived by using two different membership functions; the simplest is the *triangular* membership function, and the other simple *trapezoidal* membership function the information about their sketches are given herein.

Two inputs and three output sets are specified in relation to fuzzy structure for the fuzzy-PID controller. Two sets are called the error (E) and the error rate (E_r) for inputs. Three sets tuning parameters of PID controller are called the proportional gain (K_p), the integral gain (K_i) and the derivative gain (K_d) for the output. The universe of discourse for fuzzy variable of the error and the error rate is in areas (-3 3) or (-6 6). The ranges of fuzzy variable of proportional, integral and derivative parameters of fuzzy PID controller are defined in Chapter 3 (5 10), (0.1 0.2) and (0 0.25) respectively. Range values for input and output fuzzy sets are indicated in Chapter 4. Graphs of membership functions for the error, the error rate, K_p, K_i, and K_d are then shown respectively, in Figures A.4 to A.8 [33].

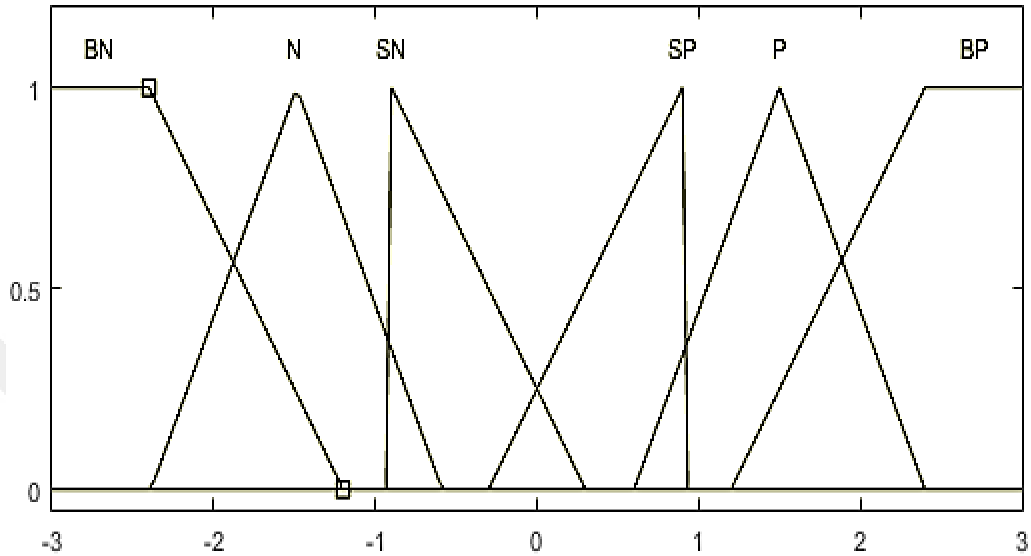

Figure A.4 Graph of Membership Functions for *Error*

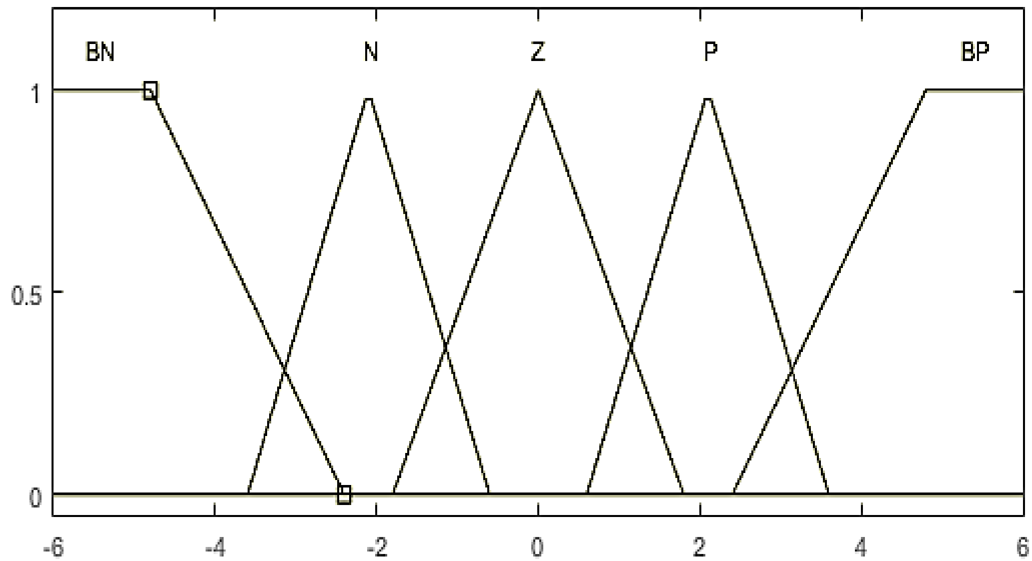

Figure A.5 Graph of Membership Functions for Error Rate

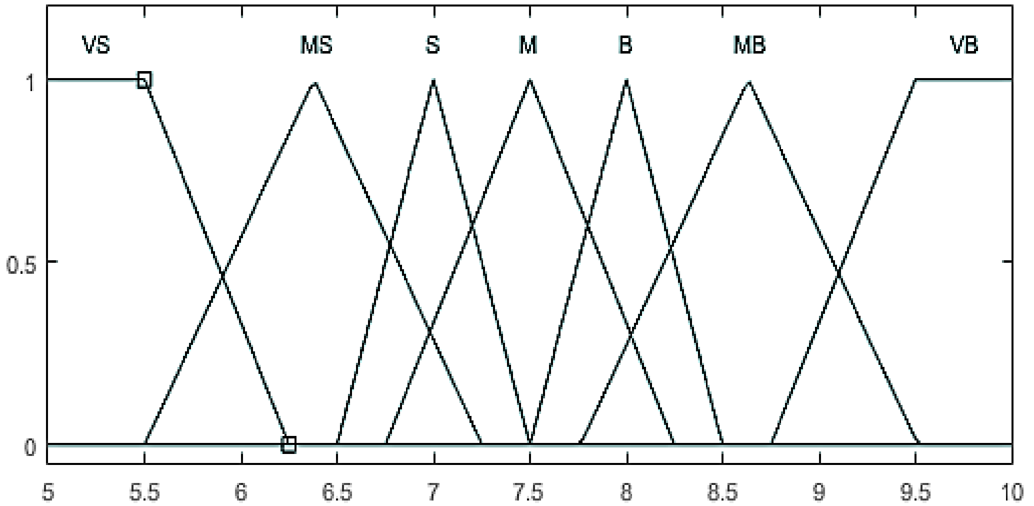

Figure A.6 Graph of Membership Functions for K_p

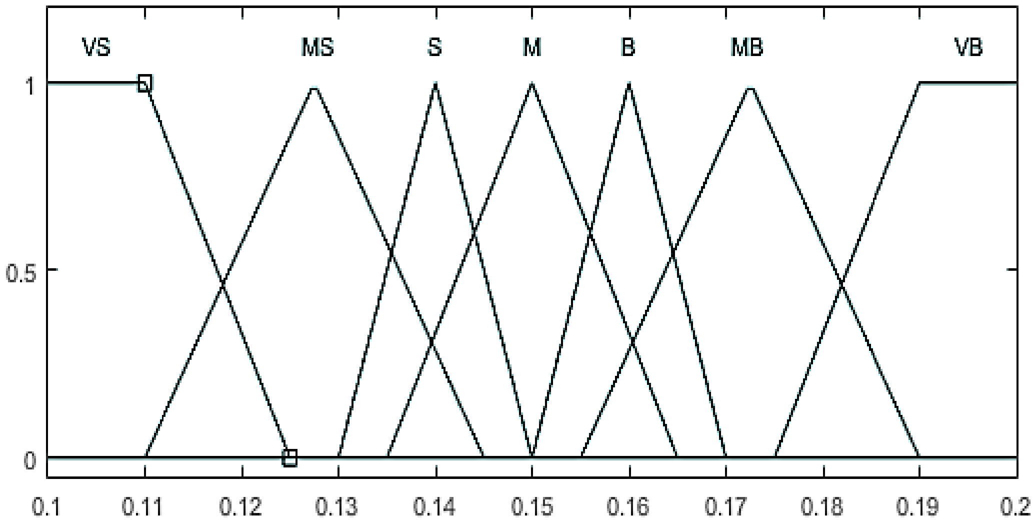

Figure A.7 Graph of Membership Functions for K_i

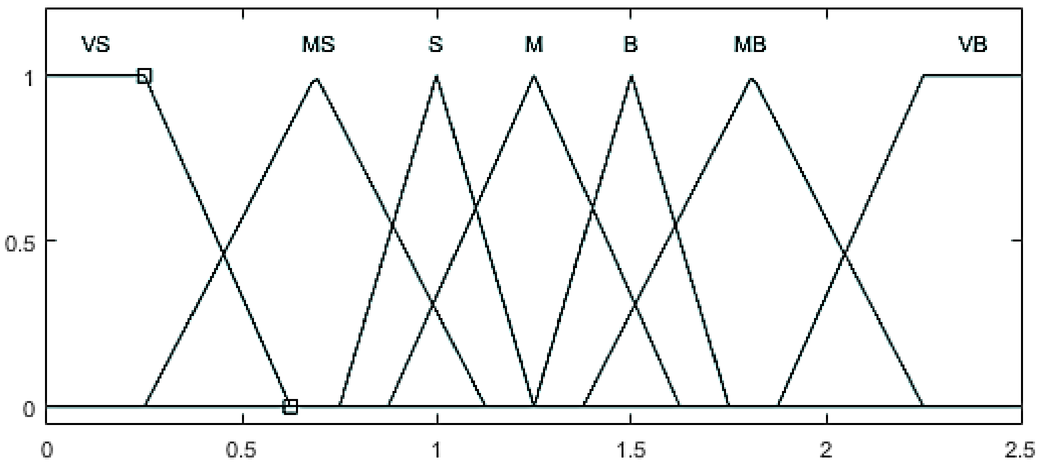

Figure A.8 Graph of Membership Functions for K_d

Two inputs and three output sets are specified in relation to fuzzy structure explained while designing a Fuzzy-PID controller system. Two sets are called the velocity error (E_v) and the velocity error rate (E_{v_r}) for inputs and output sets. The parameters of PID controller called the inner proportional gain (K_{i_p}), the inner integral gain (K_{i_i}) and the inner derivative gain $(\mathrm{K}_{\mathrm{i\_d}})$. The ranges of fuzzy variable of membership functions of inner fuzzy-PID controller are defined. These lower and upper value are shown in Tables 4.10-4.12, respectively in Chapter 4. Graphs of membership functions for the velocity error, the velocity error rate are same with membership functions for the error and the error rate shown in Figure A.4 and A.5. The outputs of K_{i_p}, K_{i_i}, and K_{i_d} are then shown in Figures A.9 to A.11.

Membership functions of outer fuzzy-P controller can be shown as membership functions of inner controller are presented. There is only single difference between the inner and the outer controller; is output of the outer controller. While the inner controller has three outputs, the outer controller has only one output called outer proportional gain (K_{o_p}). Two inputs are specified in relation to fuzzy structure explained while designing a Fuzzy-PID controller system. Two sets are called the position error $\left(E_p\right)$ and the position error rate (E_{p_r}) for inputs the ranges of fuzzy variable of membership functions of outer fuzzy-P controller for K_{o_p} are defined. Their limits are shown in Tables 4.16, Chapter 4. Graphs of membership functions for the velocity error, the velocity error rate are same with membership functions for the error and the error rate as shown in Figure A.4 and A.5, and for output of K_{o_p} is shown in Figures A.12.

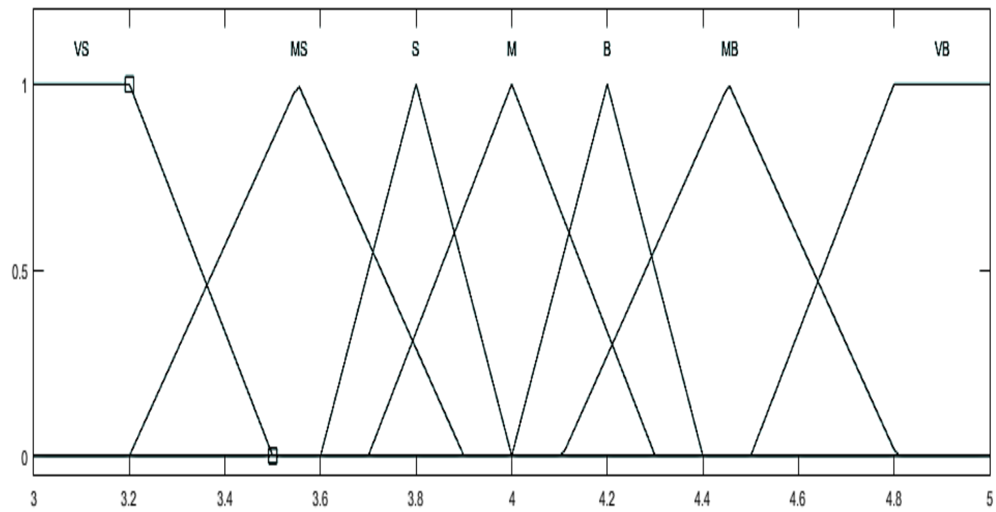

Figure A.9 Graph of Membership Functions for K_{i_p}

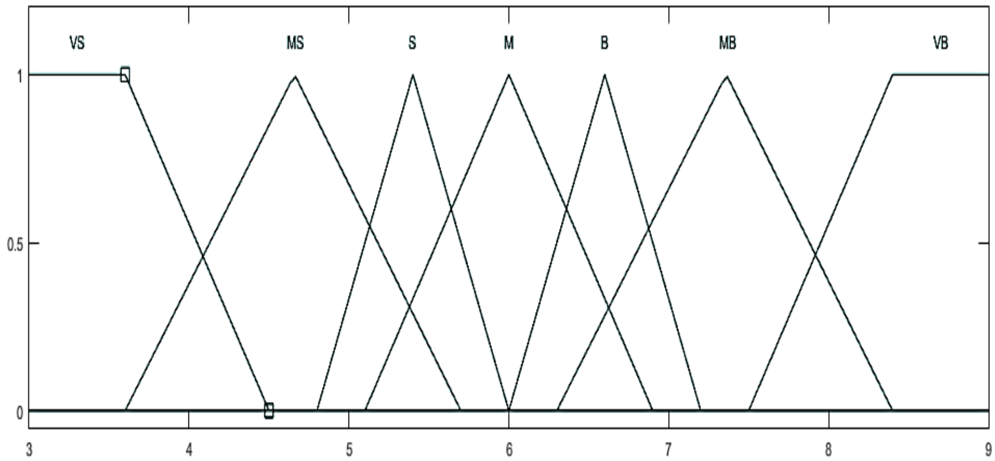

Figure A.10 Graph of Membership Functions for K_{i_i}

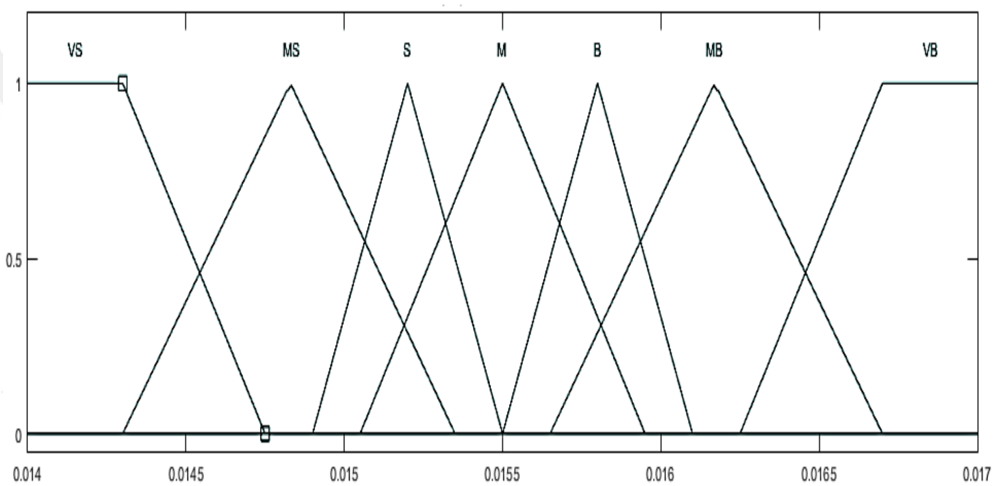

Figure A.11 Graph of Membership Functions for K_{i_d}

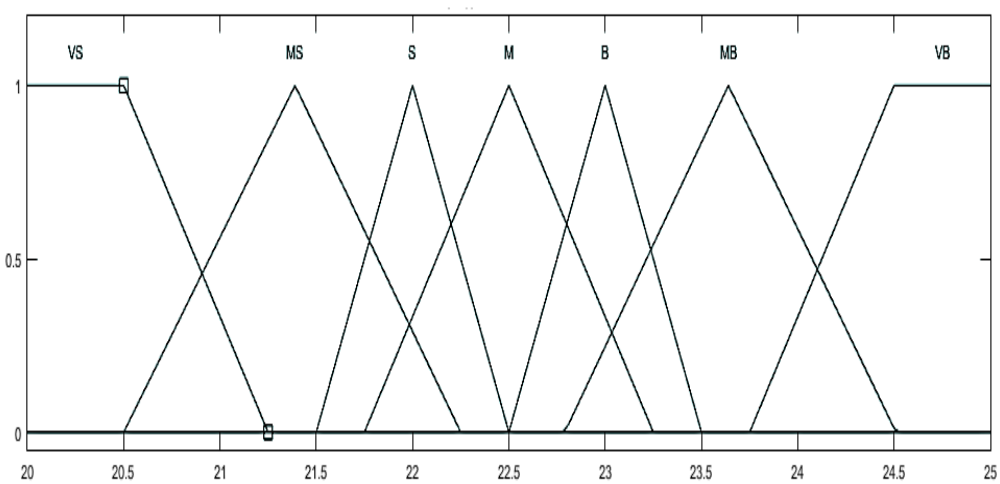

Figure A.12 Graph of Membership Functions for K_{o_p}

APPENDIX B

OUTPUT SURFACES FOR CONTROLLERS

According to the surface for each output, a three-dimensional curve that represents the mapping from error and error rate to output can be seen. This curve represents two-inputs and one-output.

The Surface Viewer on MATLAB has a special capability that is very helpful in cases with two (or more) inputs and one output: The axes can be grabbed by using the mouse and reposition them to get a different three-dimensional view on the data.

B.1 The Surfaces

The control surface characteristic is derived from the control rules and the membership functions. The surfaces demonstrate us that the coefficients of proportional, integral and derivative according to the error and the error rate. The surfaces provide facileness to know relationship between the error, the error rate and PID parameters. This makes easy to conduct a simulation.

The combination of membership functions, rules and defuzzification gives us the surfaces for the outputs. Figures B.1 to B.7 illustrate the surfaces of K_p, K_i, K_d, K_{i_p}, K_{i_i}, K_{i_d} and K_{o_p} respectively.

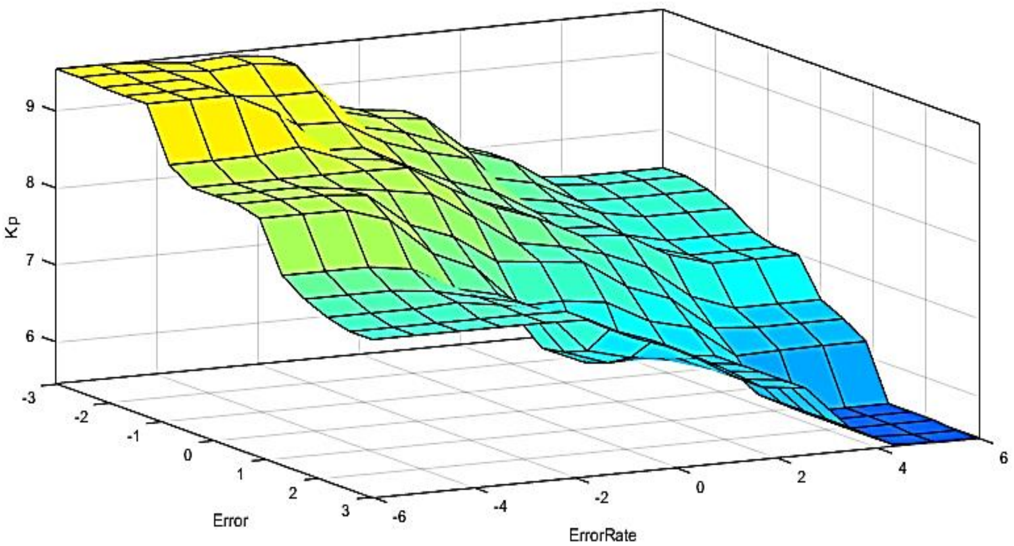

Figure B.1 Control Surface of K_p

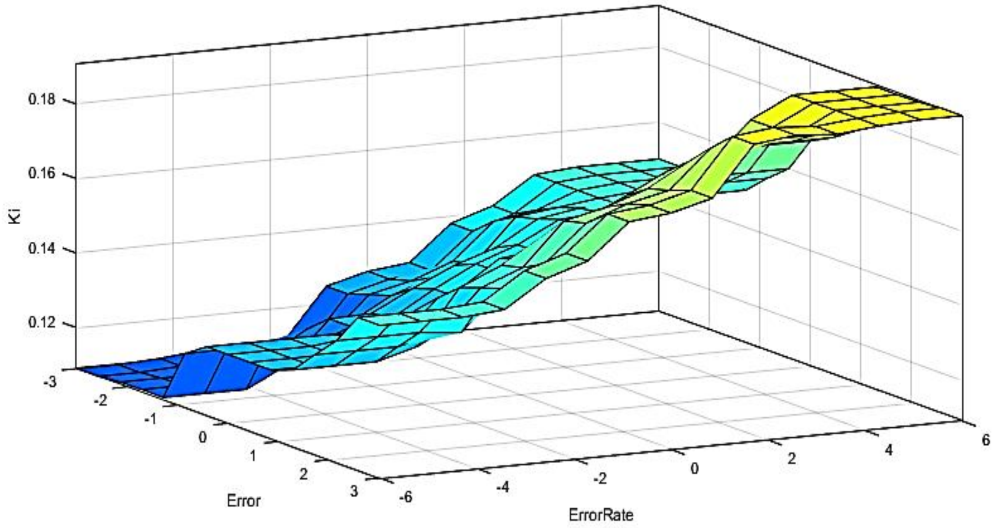

Figure B.2 Control Surface of K_i

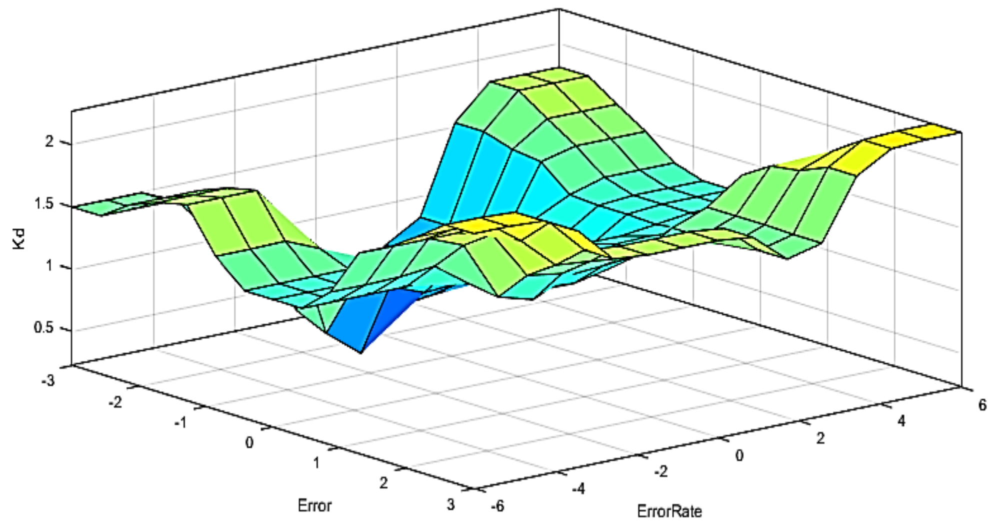

Figure B.3 Control Surface of K_d

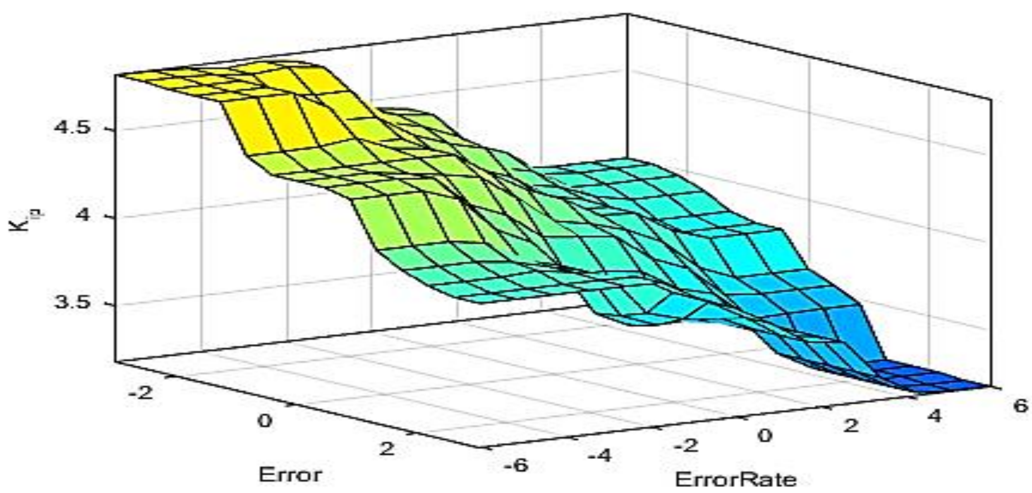

Figure B.4 Control Surface of K_{i_p}

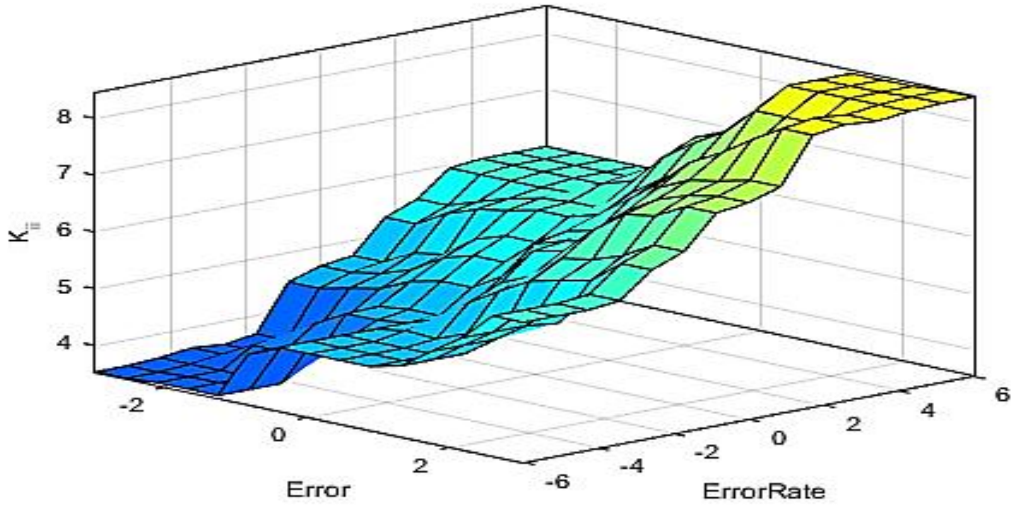

Figure B.5 Control Surface of K_{i_i}

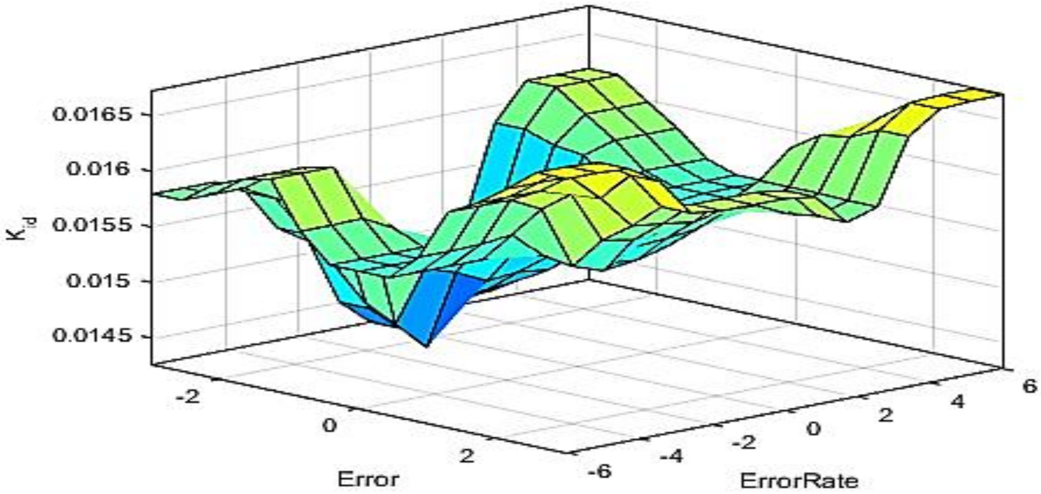

Figure B.6 Control Surface of K_{i_d}

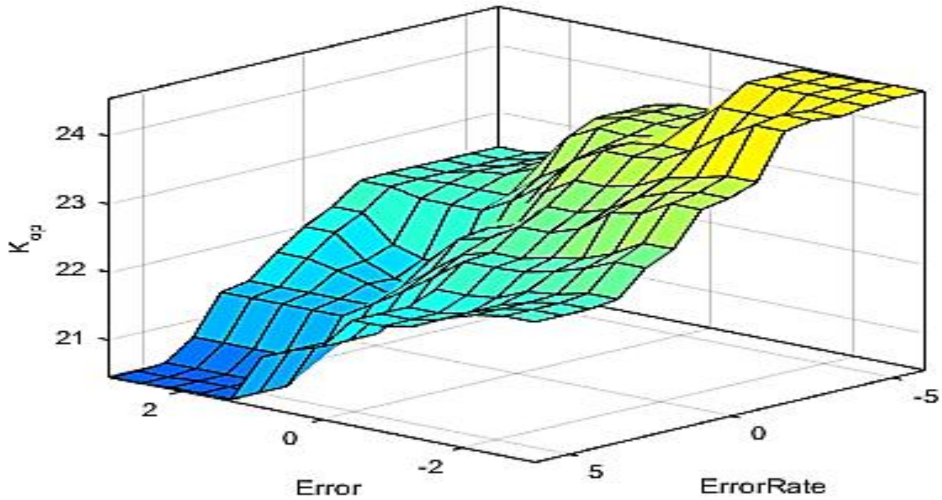

Figure B.7 Control Surface of K_{o_p}