İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

SELF TUNING PID PARAMETERS USING FUZZY LOGIC VS NONLINEAR CONTROLLERS

M.Sc. Thesis by

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PID PARAMETRELERININ BULANIK MANTIK ILE AYARLANMASI VE DOĞRUSAL OLMAYAN PID DENETLEYICILER İLE KARŞILAŞTIRILMASI

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LIST OF ABBREVIATIONS

PID	: Proportional-Integral-Derivative
ZN	: Ziegler Nichols method
IFE	: Incremental fuzzy expert control
FGS	: Fuzzy gain scheduling
FSW	: Fuzzy set-point weighting
SSP	: Self tuning of a single parameter method
FLC	: Fuzzy Logic Controller
Z	: Zero
N	: Negative
M	: Medium
NM	: Negative medium
PB	: Positive big
PM	: Positive medium
NPID	: Nonlinear PID
NNTPID	: Nonlinear Norm Transform PID
PID-ZN	: PID parameters tuned by Ziegler-Nichols method.
SOPTD	: Second order plus time delay

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LIST OF SYMBOLS

K_p : Proportional gain
T_i : Integral gain
T_d : Derivative gain
μ : Membership function
e : Error
$\dot{e}$: Derivative of error or change of error
u : Control input

PID PARAMETRELERININ BULANIK MANTIK ILE AYARLANMASI VE DOĞRUSAL OLMAYAN PID DENETLEYICILER İLE KARŞILAŞTIRILMASI

ÖZET

PID denetleyiciler, basit yapıları ve tasarım kolaylıkları nedeniyle en çok kullanılan kontrol algoritmalarıdır. Proses kontrol uygulamalarının %95 inden fazlası PID ve özellikle PI denetleyiciler ile yapılmaktadır. Zaman içinde çok sayıda denetleyici algoritmaları geliştirilse de , endüstride özellikle yüksek performans gerektirmeyen sistemler için yaygın kullanımı devam etmektedir. Gerçek sistemlerdeki doğrusal olmayan yapı ve oluşan parametre değişiklikleri nedeniyle, teoride uygulanan yöntemlerin uygulanmasında güçlükler yaşanmaktadır. Bu nedenle çeşitli metodolojiler geliştirilmiştir. Bu metodolojilerden biri bulanık mantık kuramıdır.

Bulanık mantık, birçok mühendislik bilimlerinde, tasarım yapılarında kullanılmaya başlanmıştır. Bu artan ilginin hayata yansıması olarak günlük hayatta kullandığımız bazı ürünleri gösterebiliriz.

Bu çalışmada, bulanık mantık kontrol sistemlerindeki denetleyicilerin ayarlanmasında kullanılmıştır. Bu amaçla uygulanan birçok bulanık kontrol metodu vardır. Öncelikle PID parametrelerinin ayarlama metodlarından Ziegler-Nichols, Cohen –Coon and IMC metodlarını, daha sonra bu metodlar ile ayarlanmış denetleyicilerin performansını arttırmaya yönelik kullanılan bulanık ayarlama metodlarından ;arttırımlı bulanık uzman PID denetleyicisi, ayarlama noktasının bulanık ayarlanması, bulanık kazanç ayarlama ve tek parametrenin bulanık ayarlanması metodları açıklanacaktır. Ayrıca doğrusal olmayan PID denetleyiciler ele alınmıştır. Doğrusal olmayan PID denetleyicilerinin araştırılmasının nedeni, bulanık sistemlerin doğrusal olmayan bir yapıya sahip olmasıdır. Farklı sistemler için araştırılan metodların MATLAB/SIMULINK ortamında simülasyonları yapılmış ve karşılaştırılmalı olarak incelenmiştir.

SELF TUNING PID PARAMETERS USING FUZZY LOGIC VS NONLINEAR CONTROLLERS

SUMMARY

PID controllers are the most common control algorithm due to their simple structure and ease of design. In process control, more than 95% of the control loops are PID control, most of them are actually PI controller. Although many control algorithms are developed over several decades, PID controllers are still the majority of the regulators used in industrial control systems especially when the performance requirements are not too high. Due to the existence of nonlinearity and parameter changes during the operations, it is usually difficult to conduct theoretical analysis. Therefore some useful techniques are developed. One of these techniques is fuzzy logic method.

Fuzzy logic have become a widely used design structure in many engineering sciences. Growing interest to the design of fuzzy systems can be seen in our daily life with the products being used.

In this study, fuzzy systems are used to control the process, especially, auto tuning the current PID controller. There are a lot of methods for this purpose. Some of these methods are introduced. Fuzzy tuning PID methods which are incremental fuzzy expert control, fuzzy gain scheduling, set-point weighting, fuzzy self tuning of a single parameter and two types of nonlinear PID controllers are introduced. The reason why nonlinear PID methods investigation is fuzzy controller is a kind of nonlinear controllers. Therefore it is needed to include nonlinear PID controllers and compare. Simulation results are obtained using SIMULINK and evaluated for different types of systems.

1. PID CONTROL

The PID controller is the most common form of feedback. It became the standard tool. PID controllers are today found in all areas where control is used. The controllers come in many different forms. PID control is often combined with logic, sequential functions, selectors, and simple function blocks to build the complicated automation systems used for energy production, transportation, and manufacturing. PID controllers have survived many changes in technology, from mechanics and pneumatics to microprocessors via electronic tubes, transistors, integrated circuits. The microprocessor has had a significant influence on the PID controller. Practically all PID controllers made today are based on microprocessors. This has given opportunities to provide additional features like automatic tuning, gain scheduling, and continuous adaptation.[1]

Although many control algorithms are developed over several decades, PID controllers are still the majority of the regulators used in industrial control systems especially when the performance requirements are not too high.

The design and analysis of such a controller require to know the three parameters, proportional gain (Kp), integral time constant (Ti), and derivative time constant (Td).

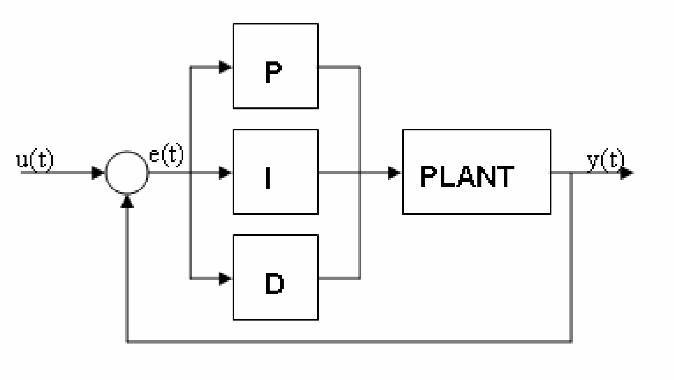


Figure 1.1 Block Diagram of PID Controller

Control law can be stated as 1.1

$$u(t) = Kp\left[e(t) + Td\frac{de}{dt} + \frac{1}{Ti}\int e(\tau)d\tau \right] \qquad (1.1)$$

$$e(t) = y_{sp}(t) - y(t)$$

u(t) is control input, e(t) is error which is difference between actual output and desired input .

$$u(t) = Kp.e(t) + Kd\frac{de}{dt} + Ki\int e(\tau).d\tau \qquad (1.2)$$

The control signal (1.2) is a combination of three terms; the P term (which is proportional to the error), the I term (which is proportional to the integral of the error), and the D term (which is proportional to the derivative of the error). The controller parameters are proportional gain K, integral time Ti, and derivative time Td. The integral, proportional and derivative part can be interpreted as control actions based on the past, the present and the future. The derivative part can also be interpreted as prediction by linear extrapolation.

1.1. Tuning of PID Parameters

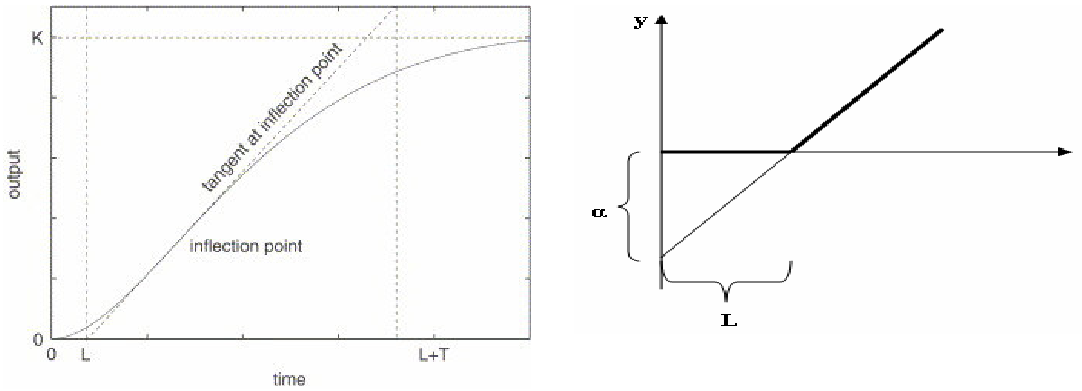
Although PID controllers are widely used in industry, the tuning of these parameters can be very challenging. There are several methods in the literature. In this study, they are divided into two groups which are fixed parameter tuning and online tuning methods using fuzzy logic. In this chapter fixed parameter tuning methods are introduced. These are Ziegler-Nichols and set-point weighting method, Cohen-Coon method, internal model controller tuning methods. Among these methods, ZN and set-point weighting methods are emphasized. Cohen- Coon and IMC method is mentioned briefly.

1.1.1.Ziegler-Nichols Method

If a mathematical model of the plant can be obtained, then it is possible to apply different design techniques to define the controller parameters. On the other hand if the system is complicated and getting the mathematical model is difficult, then experimental approaches must be used to tune the PID parameter.

Ziegler –Nichols proposed rules for tuning PID controllers (K_p, T_i, T_d) base on control engineering experience (1.1). In other words, the ZN method is the result of experimental step responses. Ziegler and Nichols developed the rules based on the transient response characteristics of the systems and determined the values of PID parameters. The suggested idea is based on the value of K_p that causes in marginal stability when only proportional controller is employed. Ziegler Nichols method (ZN) is useful for plants of which mathematical models are unknown or difficult to obtain. This method guarantees the stability of the system. [3]

There are two ways of implementing Ziegler-Nichols tuning rules. In the first method, registration of the open loop step response of the system. The parameters are determined from a unit step response of the process. The point where the slope of the step response is determined and the tangent at this point are drawn in Figure 1.2. The intersections of tangent line and coordinate axes give the parameters α and L. ZN method gives PID parameters directly as functions of α and L; stated in Table 1.1. [4]



(a) (b)

Figure 1.2 (a) Step input response of a typical control system (b) Characterization of a Step Response in ZN First Method [3]

Table 1.1 PID Controller Parameter Obtained From ZN First Method

Controller	K	Ti	Td
P	$\frac{1}{\alpha}$		
PI	$\frac{0.9}{\alpha}$	$3L$	
PID	$\frac{1.2}{\alpha}$	$2L$	$\frac{L}{2}$

Ziegler-Nichols second method is based on simple properties of the process dynamics. Rules are developed on the values of ultimate gain (K_u) and ultimate period (T_u). These parameters are determined in the following steps. Starting point is assuming that there is only P controller in the systems and change the gain until system oscillates continuously (Figure 1.3).

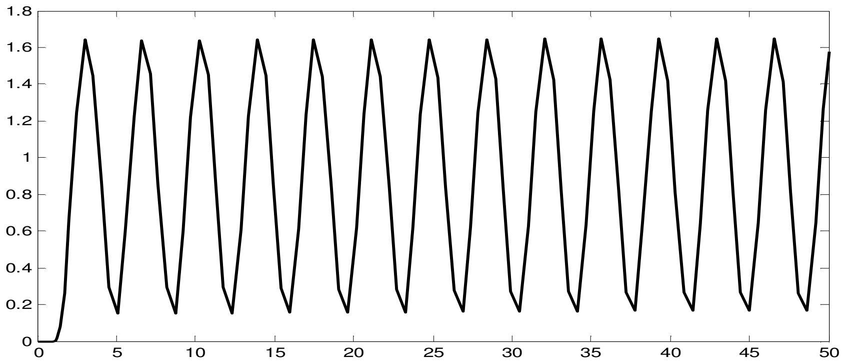


Figure 1.3 Oscillatory Response of P Controlled System which has Ultimate Gain

At this point the gain is K_u and the oscillation period is T_u. ZN has given simple formulas for tuning PID controllers in terms of ultimate gain and ultimate period. These are given in Table 1.2

Table 1.2 PID Controller Parameters Obtained From ZN Second Method

Controller	K	Ti	Td
P	$0.5K_u$		
PI	$0.4K_u$	$0.8T_u$	
PID	$0.6K_u$	$0.5T_u$	$0.125T_u$

Ziegler Nichols tuning rules have been widely used to tune PID controllers in process control systems where the plant dynamics are not precisely known. Other important property of ZN method is that these values are determined experimentally. After calculating these parameters, the unit step response of PID controlled system can be obtained as seen in Figure 1.4.

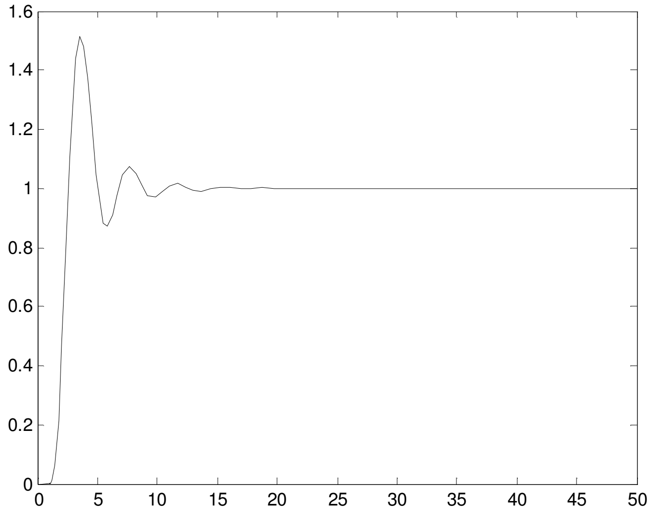


Figure 1.4 Unit Step Response of a PID Controlled System Designed by ZN Tuning Rules

1.1.2.Set-point Weighting Method

It is well known that feedback systems with PID controllers tuned according to the Ziegler–Nichols step response method has good disturbance rejection. However, the compensated system response to a step input has, in general, high overshoot, and the control signal is usually high, which may lead the actuator to saturation. To avoid these situations, set point for the proportional action can be weighted by means of a constant parameter b<1.

$$e(t) = b.y_{sp}(t) - y(t) \qquad \textbf{(1.3)}$$

The set-point weight *b* was originally introduced to reduce overshoots in the closed loop set-point step response. With this modification following expression can be applied to Equation1.4

$$u(t) = Kp(b.y_{sp}(t) - y(t)) + K_d \frac{de(t)}{dt} + K_i \int e(\tau)d\tau \qquad \textbf{(1.4)}$$

In this way, a simple two degrees of freedom scheme is implemented Figure 1.5, one is assigned to the attenuation of load disturbances, the other is to the set-point following.

$$Gff = Kp(b + \frac{1}{sTi} + sTd)$$
$$Gc = Kp(1 + \frac{1}{sTi} + sTd) \qquad \textbf{(1.5)}$$

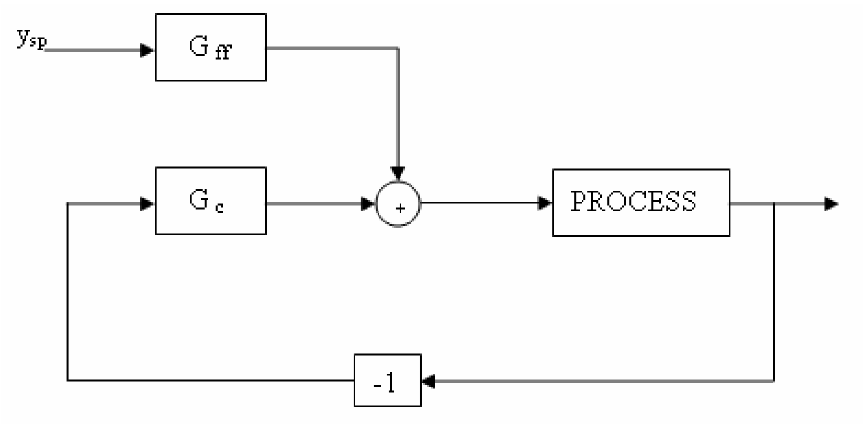


Figure 1.5 Two Degrees-Of-Freedom Schema Of PID Controller With Set-Point Weighting

It is not an easy to choose its value b. Sometimes the closed loop response is very sensitive to the weights: a little change in their values can result in a completely different response of the control system [4].

Set-point weighting is very useful in order to shape the response to set-point changes; but it is needed to follow a procedure to determine parameter b. Äström and Hägglund mentioned a method in [4]. By the dominant pole design method, it is easy to find. With this method, the closed loop system will have two complex poles and one pole $-p_0$ on the real axis. This pole may be slower than the other poles. With the set-point weighting, the closed loop system has a zero at

$$s = -z_0 = \frac{1}{bT_i} \qquad \textbf{(1.6)}$$

By choosing b so that $z_0 = p_0$, we make sure that the set-point does not excite the mode corresponding to the pole in $-p_0$. This works well and gives good transient responses for the systems where the dominant poles are well damped (i.e. $\xi = 0.7$). For the systems where the poles are not so well damped, the choice $z_0 = 2p_0$ gives systems with less overshoot.

A suitable choice of parameter b is consequently;

$$b = \begin{cases} \dfrac{0.5}{p_0 T_i} & if\, \xi < 0.5 \\ \dfrac{0.5 + 2.5(\xi - 0.5)}{p_0 T_i} & if\, 0.5 \le \xi \le 0.7 \\ \dfrac{0.5}{p_0 T_i} & \xi > 0.7 \end{cases} \qquad \textbf{(1.7)}$$

1.1.3.Cohen-Coon Method

Cohen Coon Method is based on the first order plus time delay process model

$$Gp = \frac{Kp}{1+sT}.e^{-sL} \qquad \textbf{(1.8)}$$

The main design criterion is rejection of load disturbances. It tries to place dominant poles that give a quarter amplitude decay ratio. For P and PD controllers the poles are adjusted to give maximum gain, subject to the constraint on the decay ratio. For PI and PID control the integral gain is maximized. This corresponds to minimization of integrated error, the integral error due to a unit step load disturbance. For PID controllers three closed-loop poles are assigned; two poles are complex and the third pole is located at the same distance form the origin as the other poles.

Table 1.3 Controller Parameters from Cohen-Coon Method

$\frac{ke^{-\theta s}}{\tau s+1}$	K	T_i	T_d
P	$\frac{1}{k}\left(\frac{\tau}{\theta}+0.35\right)$		
PI	$\frac{0.9}{k}\left(\frac{\tau}{\theta}+0.92\right)$	$\frac{3.3\tau+0.3\theta}{\tau+2.2\theta}\theta$	
PD	$\frac{1.24}{k}\left(\frac{\tau}{\theta}+0.13\right)$		$\frac{0.27\tau-0.09\theta}{\tau+0.13\theta}\theta$
PID	$\frac{1.35}{k}\left(\frac{\tau}{\theta}+0.18\right)$	$\frac{2.5\tau+0.5\theta}{\tau+0.61\theta}\theta$	$\frac{0.37\tau}{\tau+0.19\theta}\theta$

The parameters $\alpha = \frac{Kp.L}{T}$ and $\tau = \frac{L}{L+T}$ are used in Table 1.3. If the process model is defined by these three parameters K_p, L and T, then it is possible to give tuning formulas with the help of Table 1.3. It may be difficult to choose desired closed-loop poles for higher order systems.

If τ is small, controller parameters are close to others which are obtained by ZN tuning rules.

1.1.4.Internal Model Control Method

Internal model principle is a general method for design of control systems that can be applied to PID control. A block diagram of such a system is shown in Figure 1.6

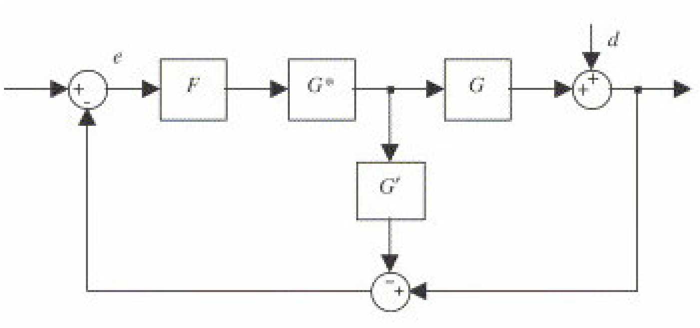


Figure 1.6 Block Diagram of a Closed-Loop System with a Controller Based on the Internal Model Principle

The internal model control methodology may be used to obtain PID or fractional PID controllers. It makes use of the control scheme of Figure 1.6. In that control loop, G is the plant to control, G* is an inverse of G (or at least a plant as close as possible to the inverse of G), G′ is a model of G and G_F is some carefully chosen filter. If G′ were exact, the error e would be equal to disturbance d. If, additionally, G* were the exact inverse of G and G_F were unity, control would be perfect. Since no models are perfect, e will not be exactly the disturbance. That is also exactly why G_F exists and is usually a low-pass filter: to reduce the influence of high-frequency modelling errors. It also helps ensuring that product G_FG^* is realisable.

Plant model G;

$$G = \frac{Kp}{1+sT}.e^{-sL} \quad \textbf{(1.9)}$$

Controller Transfer function; Gc ;

$$Gc = \frac{Gf.G*}{1-GfG*G'} \quad \textbf{(1.10)}$$

The inverse of the plant model G*;

$$G^* = \frac{1+sT}{Kp} \quad \textbf{(1.11)}$$

The filter G_f ;

$$G_f = \frac{1}{1+sT_f} \quad \textbf{(1.12)}$$

If the time delay is approximated by second order Padè approximation

$$e^{-sL} \approx \frac{1-sL/2}{1+sL/2} \quad \textbf{(1.13)}$$

As a result of arrangements transfer function of the controller is achieved

$$G_c(s) = \frac{(1+sL/2)(1+sT)}{K_p.s(L+T_f+sT_fL/2)} \approx \frac{(1+sL/2)(1+sT)}{K_p.s(L+T_f)} \quad \textbf{(1.14)}$$

An interesting future of the internal model control, robustness can be adjusted by selecting the filter G_f accordingly. [6]

2. FUZZY CONTROL

Conventional control techniques are generally requires mathematical models of systems to design a controller. On the other hand, most of real–life systems' mathematical models are not very easy to obtain. Therefore all the information; numerical and linguistic information should be investigated throughout the modelling stage.

Even if a relatively accurate model of a dynamic system can be developed, it is generally too complex to use in controller development, especially for many conventional control design procedures that require some assumptions.

In such cases, fuzzy control provides an efficient structure to include linguistic information from human experts into numerical information. This is not possible in conventional control techniques. In this type of case, fuzzy controllers can be preferred.

The concept of Fuzzy Logic was proposed by Lotfi Zadeh, a professor at the University of California at Berkley, and presented not as a control methodology, but as a way of processing data by allowing partial set membership rather than crisp set membership. This approach to set theory was not applied to control systems until the 70's due to insufficient small-computer capability prior to that time. Professor Zadeh taught that people do not require precise, numerical information input, and yet they are capable of highly adaptive control. If feedback controllers could be programmed to accept noisy, imprecise input, they would be much more effective and perhaps easier to implement.

As the complexity of a system increases, it becomes more difficult and sometimes impossible to make a precise model.

Fuzzy Logic is also considered as a problem-solving control system methodology. It can be implemented in hardware, software, or a combination of both.

Fuzzy Logic was conceived as a better method for sorting and handling data but has verified to be a best choice for many control system applications since it mimics human control logic. It can be built into anything from small, hand-held products to large automated process control systems. It uses an imprecise but very helpful language to deal with input data more like a human operator. The approach to control problems is generally to mimic how an operator would make decisions, only much faster.

Fuzzy controllers are used to control consumer products, such as washing machines, video cameras, and, as well as industrial processes.

2.1. Internal Structure of Fuzzy Controllers

The fuzzy controller has four main components: First part is the "rule-base" where the knowledge is held in the form of a set of rules. Second part is the "inference mechanism" where evaluations are made, which control rules are related at that time and then decides what the input to the plant should be given. Third part is the "fuzzification" simply modifies the inputs so that they can be interpreted and compared to the rules in the rule-base. Last part of a fuzzy controller is the "defuzzification" that converts the fuzzy outputs decided by the inference mechanism into the crisp inputs to the plant.

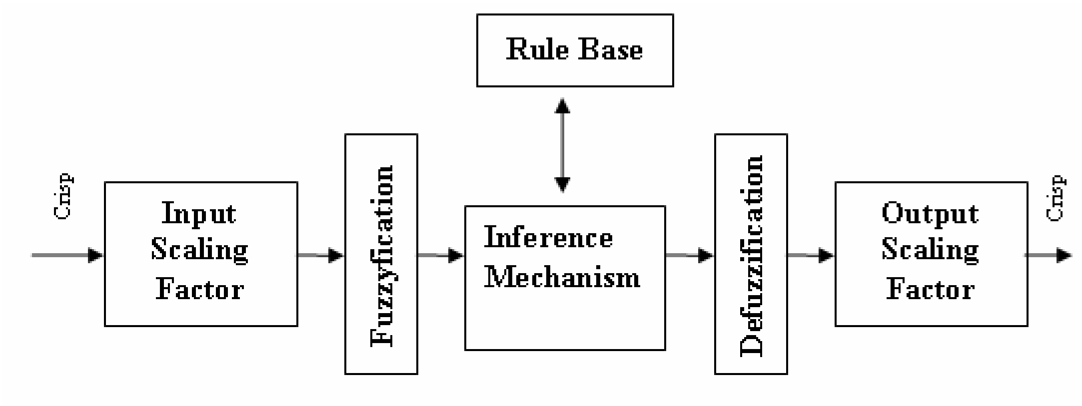


Figure 2.1 Internal Structure of a Fuzzy Controller

2.1.1.Fuzzification

Fuzzification is the first step in the fuzzy inference process. This involves a transformation of crisp inputs into fuzzy inputs. Crisp inputs are exact inputs measured by sensors and passed into the control system for processing, such as temperature, pressure, rpm's, etc. Each crisp input that is to be processed by the

Fuzzy Inference Unit has its own group of membership functions or sets to which they are transformed. This group of membership functions exists within a universe of discourse that holds all relevant values that the crisp input can possess. Three fuzzy sets are defined to fuzzify the crisp values of weather temperature. These sets cover the other sets partially. Therefore some crisp inputs can be member of different fuzzy sets. However each input has different degrees of membership. These membership degrees are evaluated in controller processes.

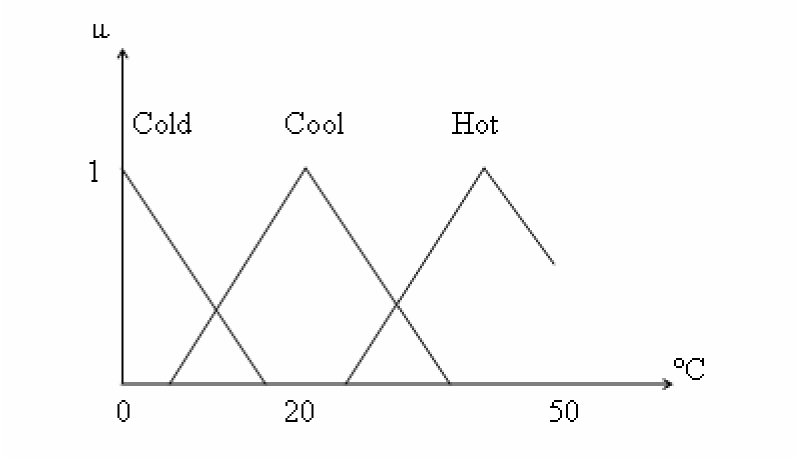


Figure 2.2 Membership Functions of Weather Temperature

2.1.2.Rule Base

The rules may use several variables both in the condition and the conclusion of the rules. The controllers can therefore be applied to both multi-input-multi-output (MIMO) problems and single-input-single-output (SISO) problems. The typical SISO problem is to regulate a control signal based on an error signal. The controller may actually need both the error, the change in error, and the integrated error as inputs, because in principle all three are formed from the error measurement. To simplify, the control objective is to regulate some process output around a prescribed set-point or reference.

Basically a linguistic controller contains rules in the IF-THEN format,

1. If error is Negative and change in error is Negative then output is Negative Big
2. If error is Negative and change in error is Zero then output is Negative Medium
3. If error is Negative and change in error is Positive then output is Zero
4. If error is Zero and change in error is Negative then output is Negative Medium

….

The rules can be presented as rule table format as Table 2.1.

Table 2.1 Rule Table Representation

		Change in error		
		N	**Z**	**P**
error	**N**	NB	NM	Z
	Z	NM	Z	PM
	P	Z	PM	PB

2.1.3.Inference Mechanism

The inference mechanism has two basic tasks: One is to determining the degree, to which each rule is relevant to the current situation. Inputs that passed through the fuzzification stage are evaluated for each rule in the rule base. Depending on the inputs, one or more than one rules may be satisfied.

Other task is deciding the control action using the current inputs and the information in the rule-base. The output of the inference mechanism becomes the input of the defuzzification stage.

2.1.4.Defuzzification

The output of the inference mechanism is the input the defuzzification stage. The decided control action which has fuzzy values is converted into the crisp values with the help of defuzzification methods. There are many methods to defuzzify the fuzzy values. The "centroid" method is very popular, in which the “centre of mass" of the result provides the crisp value. Another approach is the “height” method, which takes the value of the biggest contributor.

3. PID TUNING METHODS USING FUZZY LOGIC

Fuzzy controllers of various types have been developed. The application of fuzzy logic to PID controller design can be classified into two major categories in terms of their construction.

The gains of the conventional PID controller are tuned on-line by the knowledge base and fuzzy inference, and then the conventional PID controller generates the control signal.

A typical fuzzy logic controller is constructed as a set of heuristic control rules, and the control signal is directly deduced from the knowledge base and the fuzzy inference.[7]

In this study, fuzzy logic controllers are use to tune the parameters of conventional PID controllers as seen in Figure 3.1. Our main concern is to improve the performance of PID controllers.

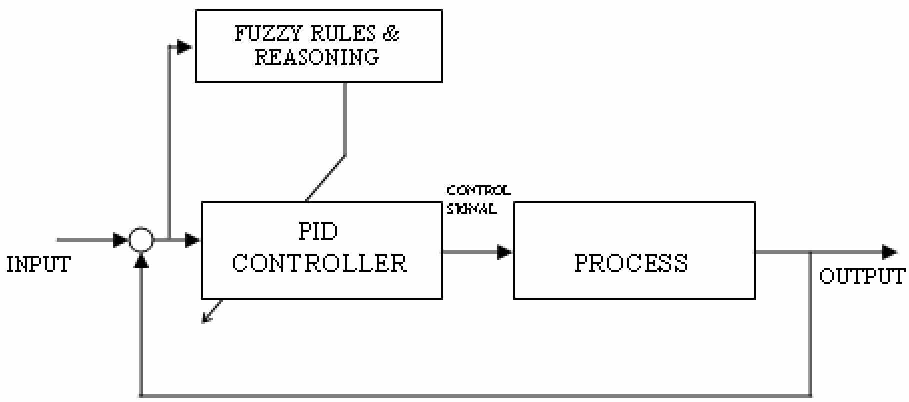


Figure 3.1 Block Diagram of Fuzzy Tuning PID Controlled System

3.1. Incremental Fuzzy Expert PID Control

Incremental fuzzy expert PID control is based on the tuning of existing values of PID controller parameters by fuzzy logic mechanism. The parameters are adjusted during the operation to improve the characteristics of the output. The tuning mechanism is developed according to the error and the rate of change of error of the closed loop system. The control rules are built up concerning the effects of the PID gains.

- Integral term is responsible for the overshoot, by slightly decreasing it at the moment when the system response exceeds the value 1, one can reduce the overshoot. On the other hand, a small increase of the integral term during the rise in the response leads to a 10-20% improvement in the rise time.
- Derivative term is responsible for the smoothness of the step response, a small increase in it during rise and in steady state eliminates the small oscillations.
- Increasing the proportional term leads to decrease in rise time and increase the oscillations. This term should be decreased to avoid oscillatory behaviour.

Fuzzy control is constructed by inspiration of the human control behaviours. These are generally based on following rules;

If the output has the desired value and the error derivative is zero, we then keep constant the output of the controller. If the output diverges from the desired value, our action then depends on the signum and the value of the error and its derivative.

If the conditions are such that the error can be corrected quickly by itself, we then keep the controller output constant or almost constant. Otherwise, we change the controller output to achieve satisfactory results [8]

Macvicar- Whealean matrix is built up by the help of these principles. Most of the human controllers act through these principles.

Tzafestas and Papanikkolopoulos [8] proposed an algorithm to adjust the controller parameters which are already tuned by Z-N formula (Figure 3.1). The current values of proportional, integral and derivative gains are increased or decreased by a fuzzy inference system, with respect to following relation (3.1);

$$
\begin{aligned}
P &= P + CV\{e(t), \dot{e}(t)\} \times k_1 \\
I &= I + CV\{e(t), \dot{e}(t)\} \times k_2 \\
D &= D + CV\{e(t), \dot{e}(t)\} \times k_3
\end{aligned}
\tag{3.1}
$$

$CV\{e(t), \dot{e}(t)\}$ is output of fuzzy inference system based on Macvicar- Whealean rule matrix.

Table 3.1 Macvicar –Whelean Rule Matrix

	-L	-M	-S	-O	+O	+S	+M	+L
-L	+O	+S	-M	-L	-L	-L	-L	-L
-M	+S	-O	-S	-M	-M	-M	-L	-L
-S	+M	+S	-O	-S	-S	-S	-M	-L
-O	+M	+M	+S	+O	-O	-S	-M	-M
+O	+M	+M	+S	+O	-O	-S	-M	-M
+S	+L	+M	+S	+S	+S	+O	-S	-S
+M	+L	+L	+M	+M	+M	+S	+O	+O
+L	+L	+L	+L	+L	+L	+M	+O	+O

k_1, k_2, k_3 are constant parameters that determines the range of variation of each term. For example, if a tuning method ensures very small rise time and large overshoot, the integral term should have a large range of variation. The values of k_1, k_2, k_3 can be determined by both stability analysis and the particular characteristics of closed-loop response. Block diagram of IFE scheme is represented in Figure 3.2.

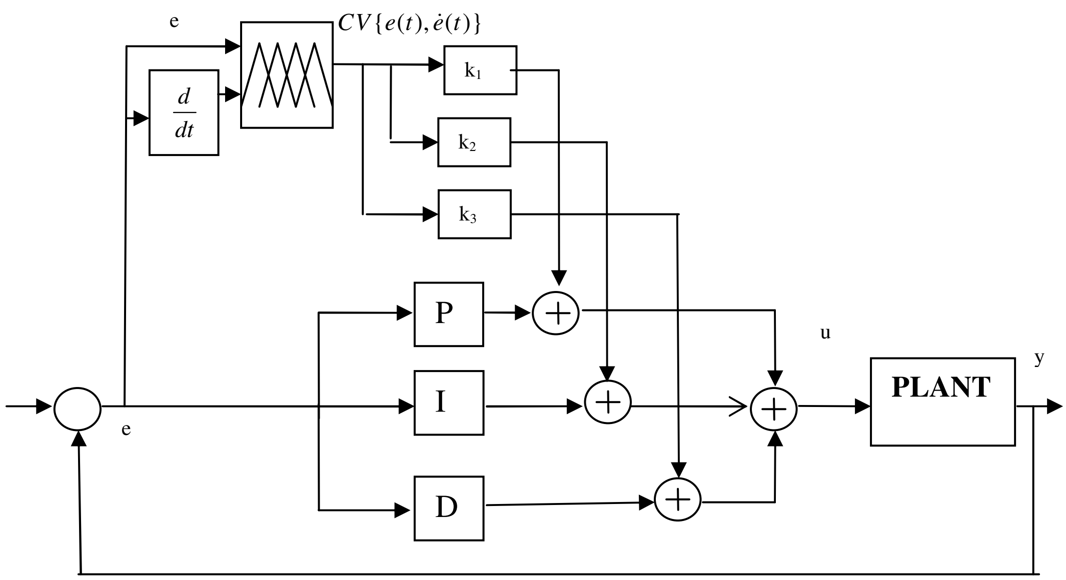


Figure 3.2 Block Diagram of Incremental Fuzzy Expert PID Method

3.2. Fuzzy Set-point Weight Tuning

The Method proposed by Visioli [9] states the fuzzifying the set point weight (i.e. mentioned section 1.1.2). The idea of multiplying the set-point value for the proportional action by a constant parameter less than one is effective in reducing the overshoot but has the disadvantage of increasing the rise time. To achieve both the aims of reducing the overshoot and decreasing the rise time, a fuzzy module can be used to modify the weight depending on the current output error and its time derivative. The three parameters of the PID are tuned according to the Ziegler-Nichols method, so that good load disturbance attenuation is assured. The parameters of the fuzzy module can be easily tuned by hand. The typical tuning problem consists of selecting the values of these three parameters (K_p, K_d, K_i), and many different methods have been proposed in the literature in order to meet different control specifications such as set-point following, load disturbance attenuation, robustness with respect to model uncertainties and rejection of measurement noise. Using the Ziegler–Nichols formula generally results in good load disturbance attenuation but also in a large overshoot and settling time for a step response that might not be acceptable for a number of processes. Increasing the gain generally results these two aspects. An effective way to cope with this problem is to weight the set-point for the proportional action by means of a constant b so that we get the following expression 3.2

$$e(t) = b.y_{sp}(t) - y(t) \qquad \textbf{(3.2)}$$

With this modification following expression (3.2) can be obtained. The control law can be written as

$$u(t) = Kp(b.y_{sp}(t) - y(t)) + K_d \frac{de(t)}{dt} + K_i \int e(\tau) d\tau \qquad \textbf{(3.3)}$$

$b = w + f(t)$

w is a positive constant (w≤ 1)

$f(t)$ is the output of fuzzy inference system.

Membership functions for the two inputs e and $\dot{e}$ and the output of the fuzzy inference system f .

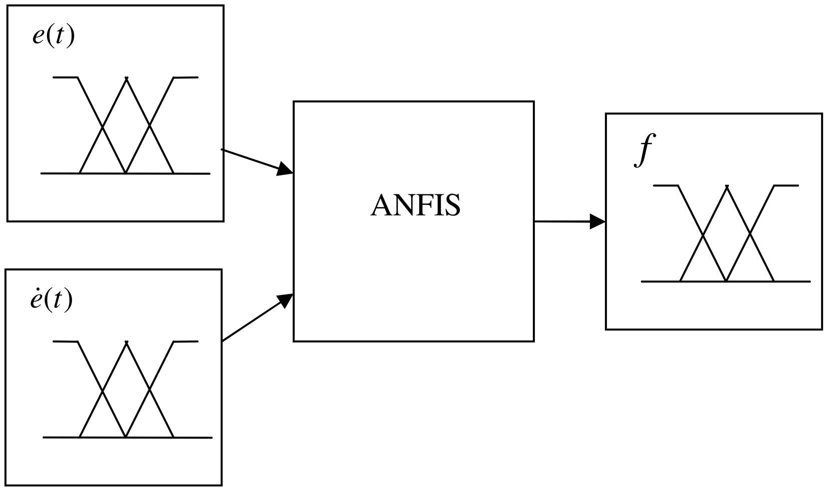


Figure 3.3 ANFIS Structure

Five triangular membership functions are defined for each input. Nine triangular membership functions are defined for the output.(Figure 3.4 and 3.5)

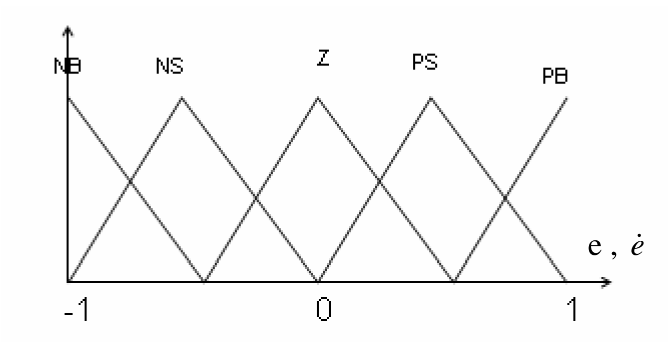


Figure 3.4 Membership Functions For Two Inputs for e And $\dot{e}$ of The Fuzzy Inference System

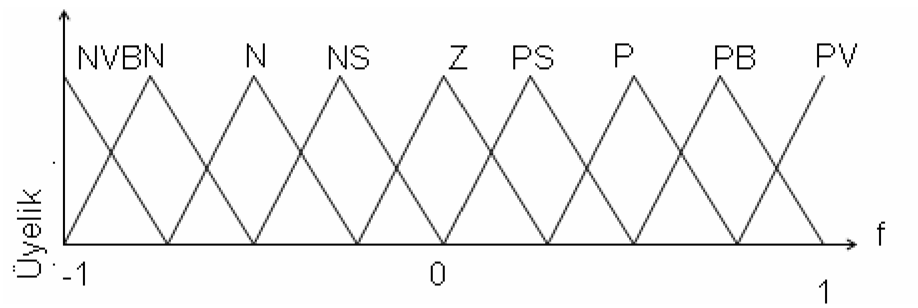


Figure 3.5 Membership Functions for the Output f of the Fuzzy Inference System

Table 3.2 Basic Rule Table of Fuzzy Inference System

		Δe				
		NB	NS	Z	PS	PB
e	NB	NVB	NB	NM	NS	Z
	NS	NB	NM	NS	Z	PS
	Z	NM	NS	Z	PS	PM
	PS	NS	Z	PS	PM	PB
	PB	Z	PS	PM	PB	PVB

The parameters of the fuzzy module can be easily tuned. To achieve both the aims of reducing the overshoot, and decreasing the rise time, a fuzzy module can be used to modify the weight depending on the current error and its rate of change.

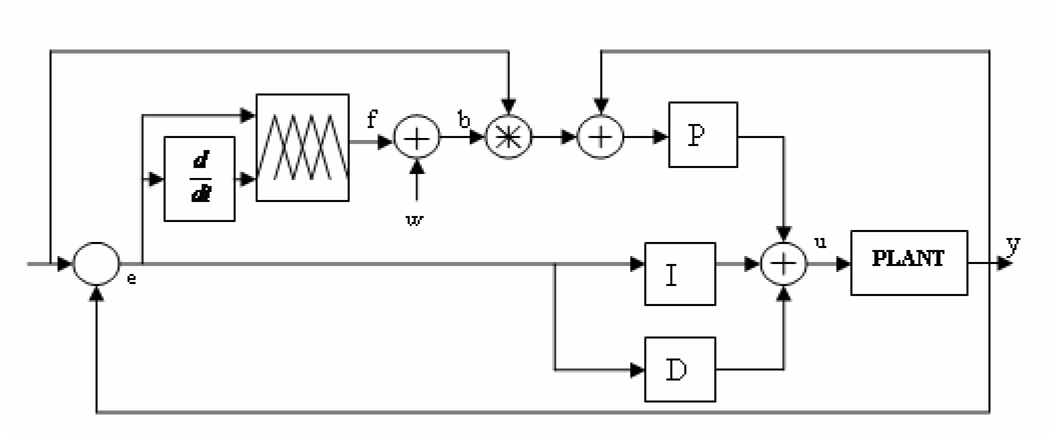


Figure 3.6 FSW Method Block Diagram

The value of three parameters Kp, Ti, Td is determined by help of Ziegler-Nichols method, but the value of w is can be found by iteratively with decreasing values of w until no better results are achieved. On the other hand, some automatic tuning methods can be implemented. In practical case, the functionality is important. Genetic algorithms have been used to define the parameters. We can search for the value of w using genetic algorithm in order to minimize the values of integrated absolute error (3.4).

$$IAE = \int_0^\infty \left| y_{sp}(t) - y(t) \right| .dt \qquad \textbf{(3.4)}$$

3.3. Fuzzy Gain Scheduling

Fuzzy Gain scheduling is a rule based scheme for gain scheduling issues. This type of fuzzy PID controller is composed of the conventional PID control system in combination with a set of fuzzy rules and inference mechanism. The PID gains are tuned on-line in terms of rule base and inference mechanism. Fuzzy gain scheduling is implemented expecting that operating regions are associated with overlapping membership functions of the fuzzy sets defined in the scheduling variable space and that a fuzzy inference mechanism is used to dynamically interpolate the controller parameters around region boundaries based on known local controller parameters. [10]. Zhao [11] states a rule based scheme for gain scheduling of PID controllers for process control. This scheme utilizes fuzzy rules and reasoning to determine the controllers' parameters. Based on fuzzy rules, human expertise is utilizes for PID gain scheduling. As a result, better performance is expected than of the PID controllers with fixed parameters. Controller parameters can be obtained as follows;

$$\begin{aligned} K_p &= (K_{p,\max} - K_{p,\min}).K_p' + K_{p,\min} \\ K_d &= (K_{d,\max} - K_{d,\min}).K_d' + K_{d,\min} \\ K_i &= \frac{K_p^2}{\alpha K_d} \end{aligned} \qquad \textbf{(3.5)}$$

Where Kp', Kd' and a is determined by fuzzy mechanism and $K_{p,\max}, K_{p,\min}, K_{d,\max}, K_{d,\min}$ are used to normalize into the range between zero and one. Based on the extensive simulations, a rule of thumb for determining the range of Kp and Kd has been given as stated in 3.6.

$$\begin{aligned} K_{p,\min} &= 0.32K_u & K_{d,\min} &= 0.08K_u.t_u \\ K_{p,\max} &= 0.6K_u & K_{d,\max} &= 0.15K_u.t_u \end{aligned} \qquad \textbf{(3.6)}$$

Kp', Kd' and α are outputs of a fuzzy mechanism based on $e(t)$ and $\dot{e}(t)$. The membership functions for $e(t)$ and $\dot{e}(t)$ is shown Figure 3.7. N presents negative, P positive, Z approximately zero, S small, M medium, B big. Consequently NM is negative-medium, PB is positive big and so on.

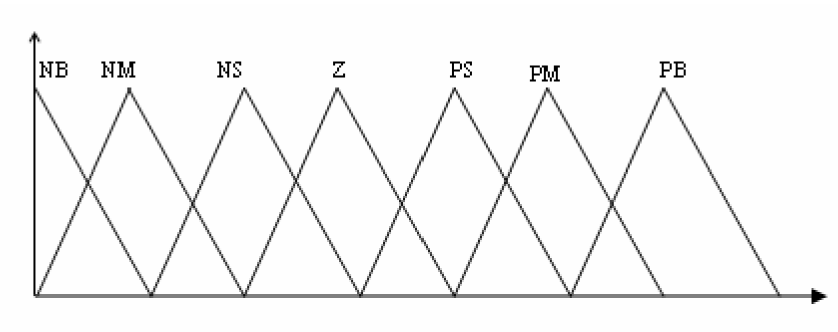


Figure 3.7 Membership Functions for Inputs $e(t)$ and $\dot{e}(t)$

Membership Functions for K_p' and K_d' are shown in Figure 3.8 and Figure 3.9. Four singletons is used to define the output of α as Figure 3.9

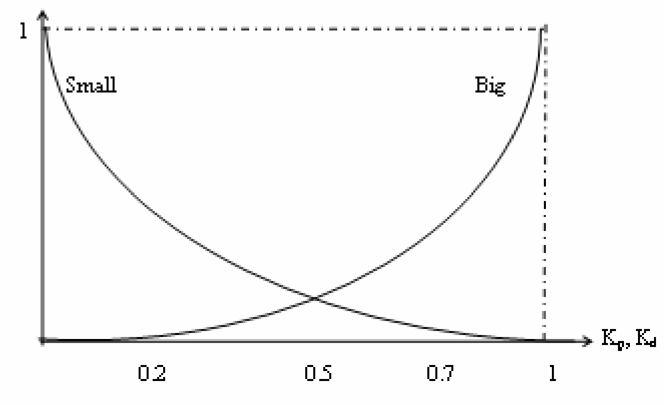


Figure 3.8 Membership Functions for Kp' and Kd'

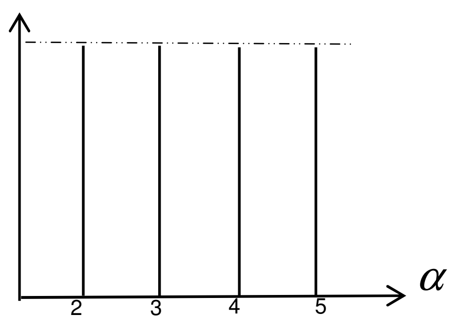


Figure 3.9 Membership Functions for α

Rule tables may be determined heuristically based on the step time response of the process. For example, at the beginning the proportional gain Kp' should be Big and Kd' is small in order to get big control signal. Rule tables for the Kp', Kd' and α are given in Table 3.3, Table 3.4 and Table 3.5 respectively.

Table 3.3 Rule base for Kp'

		Δe						
		NB	NM	NS	Z	PS	PM	PB
e	NB	B	B	B	B	B	B	B
	NM	S	B	B	B	B	B	S
	NS	S	S	B	B	B	S	S
	Z	S	S	S	B	S	S	S
	PS	S	S	B	B	B	S	S
	PM	S	B	B	B	B	B	S
	PB	B	B	B	B	B	B	B

Table 3.4 Rule base for Kd'

		Δe						
		NB	NM	NS	Z	PS	PM	PB
e	NB	S	S	S	S	S	S	S
	NM	B	B	S	S	S	B	B
	NS	B	B	B	S	B	B	B
	Z	B	B	B	B	B	B	B
	PS	B	B	B	S	B	B	B
	PM	B	B	S	S	S	B	B
	PB	S	S	S	S	S	S	S

Table 3.5 Rule base for a

		Δe						
		NB	NM	NS	Z	PS	PM	PB
e	NB	2	2	2	2	2	2	2
	NM	3	3	2	2	2	3	3
	NS	4	3	3	2	3	3	4
	Z	5	4	3	3	3	4	5
	PS	4	3	3	2	3	3	4
	PM	3	3	2	2	2	3	3
	PB	2	2	2	2	2	2	2

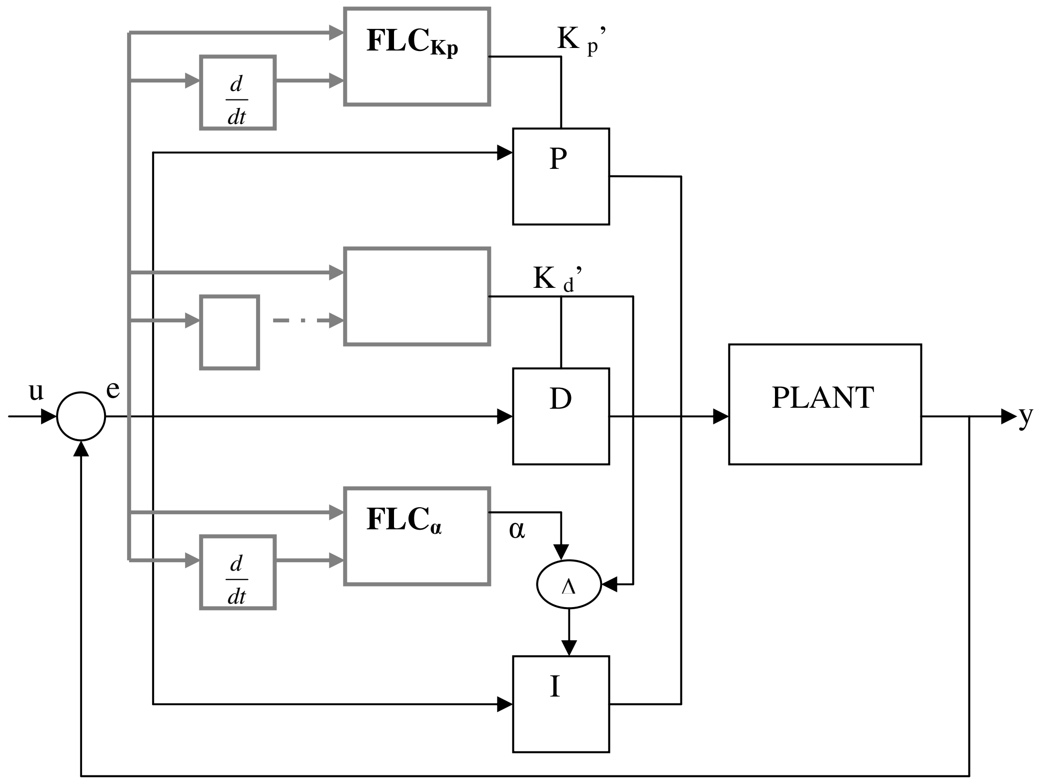


Figure 3.10 Fuzzy Gain Scheduling Scheme

3.4. Fuzzy Self Tuning of a Single Parameter

In the last decade, several studied are published in this category of fuzzy PID controller. The method devised by He [1] consists of parameterising the Ziegler-Nichols formula by means of a single parameter α, then using an online fuzzy inference system to tune the parameter α. In this way, the three PID parameters can be expressed as 3.7

$$Kp = 1.2\alpha(t)ku$$

$$Ti = 0.75\frac{1}{1+\alpha(t)}tu$$

$$Td = 0.25Ti \qquad \textbf{(3.7)}$$

$$\alpha(t+1) = \begin{cases} \alpha(t) + \gamma h(t)(1-\alpha(t)) \_\_\_ for \_\_\_ \alpha(t) > 0.5 \\ \alpha(t) + \gamma h(t)\alpha(t) \_\_\_\_\_\_\_ for \_\_\_ \alpha(t) < 0.5 \end{cases}$$

Where γ is a positive constant and it has to be chosen in the range [0.2, 0.6].

h(t) is the output of the fuzzy inference system and defined by seven triangular membership functions for two inputs $e(t)$ and $\dot{e}(t)$. Initial value of α(t) is set to equal to 0.5. It has to be noted that the initial values of α(t) is set equal to 0.5, which corresponds to the Ziegler- Nichols formula. The point is , for this method, the tuning of the scaling coefficient of the fuzzy module and of the parameter γ is left to the user and no rules of thumb are given for this task.

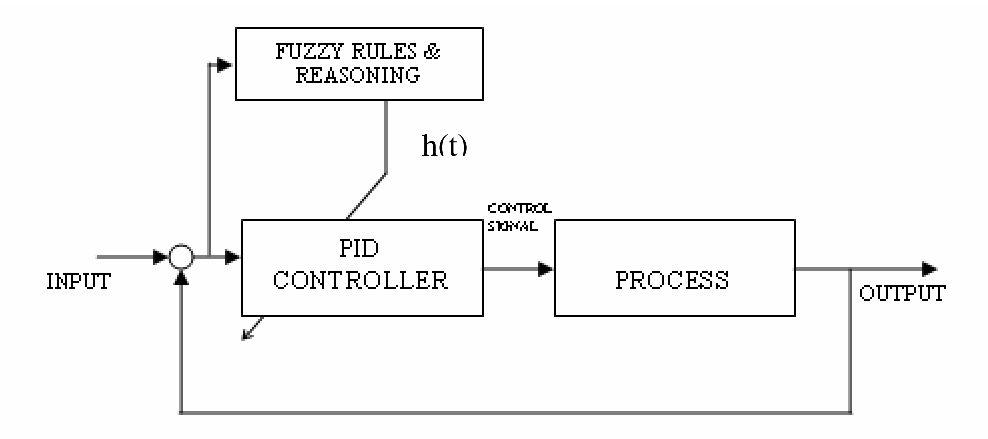


Figure 3.11 Block Diagram of Self-Tuned PID Controlled System

4. NONLINEAR PID CONTROLLERS

PID control algorithm has been widely used due to the simple structure and effectiveness. For some cases, additional lead and lag compensators may help to get better performance.

PID controller algorithm is based on the linear combination of the current (P), past (I) and future (D) of the error. This linearity may cause restrictions in performance. In addition differential part of the control signal is sensitive to noise and integral part is used to eliminate the steady state error but at the same time it leads the unstability of the system. In order to overcome the limitations, PID controllers with nonlinear characteristics can be implemented.

In recent years, fuzzy logic controllers, especially PID type fuzzy controllers have been widely used in industrial processes owing to their heuristic nature associated with simplicity and effectiveness for both linear and nonlinear systems. In fact, for single-input single output systems, most of fuzzy logic controllers are essentially of PD type, PI type or PID type with nonlinear gains. Because of the nonlinearity of the control gains, fuzzy PID controllers possess the potential to achieve better system performance over conventional PID controllers provide the nonlinearity can be suitably utilized. On the other hand, due to the existence of nonlinearity, it is usually difficult to conduct theoretical analyses to explain why fuzzy PID controllers can achieve better performance.

Fuzzy controllers are mentioned in the previous sections, it is obviously seen that the great performance improvement is achieved by using fuzzy tuning mechanism. This is basically because of the nonlinear property of the fuzzy controllers. For that reason searching other nonlinear PID controllers would be meaningful. Since the fuzzy PID controller is a nonlinear controller, it is necessary to compare it with some generic nonlinear controllers. By analyzing the fuzzy PID controller, it is found that its gains are variable with respect to the system states (e and Δe).

4.1. Shinskey's Nonlinear PID Controller

There is a kind of nonlinear PID controllers described by Shinskey [12] which exhibit similar characteristics like the fuzzy PID controllers. It is an error-squared controllers. They are created with a continuous nonlinear function whose gain increases with the error, which could be mathematically expressed as (4.1)

$$u(t) = Kp(L + (1-L).|e(t)|).e(t) + Kd.\frac{de(t)}{dt} + Ki\int e(\tau).d\tau \qquad (4.1)$$

Where L is adjustable parameter between 0 and 1 ,and represents the degree of nonlinearity of the controller. If L=1 we have a linear PID controller on the other hand, if L=0 the controller is highly nonlinear. It is not desirable for L to equal to zero, as this would make the controller insensitive to small errors. In this control method, there are four parameters to tune, the PID gains and L constant. After seriously evaluating the performance of nonlinear PID controllers, fuzzy mechanism can be implemented to tune the nonlinearity constant L. In simulation chapter, a fuzzy mechanism is implemented to tune the parameter L.

4.2. Nonlinear PID Controller Based on Nonlinear Norm Transformation

As an extension of conventional PID control , Nonlinear controllers has two classes of applications: One is nonlinear systems, where NPID control is used to contain the nonlinearity of systems; the other is linear systems, where NPID control is used to achieve performance which is not achievable by linear compensation.

As a typical realization of NPID, the NPID controller based on nonlinear norm transformation (NNTPID for short in the following) can be provided to reduce rising time for step response and to improve tracking accuracy.

An exponential transform is applied to the system error before it is sent to the control system. The exponent value α indicates the nonlinear degree of the transformation which is called nonlinear norm α transformation. The control structure of NPID based on nonlinear transformation is shown in the figure below.[13]

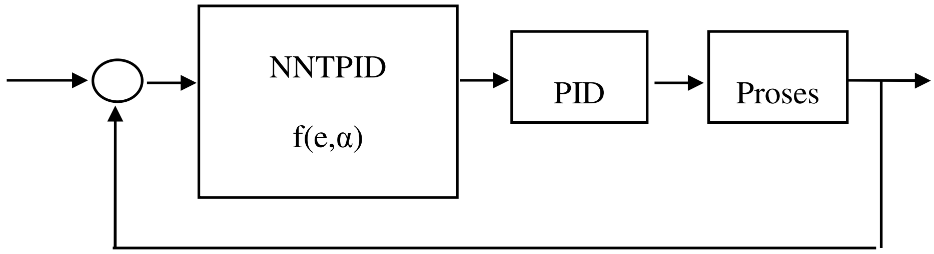


Figure 4.1 System Block Diagram

The process of nonlinear norm transformation can be expressed as follows;

$$e' = f(e,\alpha) = sign(e)\left|e\right|^{\alpha} \quad (4.2)$$

where $0 < \alpha < 1$

The value of α is between 0 and 1. The response analysis shows that nonlinear PID controllers improve the performance of the output and provide better robustness. Based on the [13] , $\alpha = 0.6$ is applied to the system to form a NNTPID controller.

4.3. Improved Nonlinear Norm Transform PID

Another type of nonlinear PID structure is proposed by Chen Z. et al, applied in [13]. Method is called Nonlinear Norm Transformation PID (NNTPID). The modification is based on the different characteristics of the P, I, and D controller. Adjustment is achieved by using three different nonlinear norm transformations $f(e,\alpha_p)$, $f(e,\alpha_i)$, $f(e,\alpha_d)$ for the P, I and D structure.

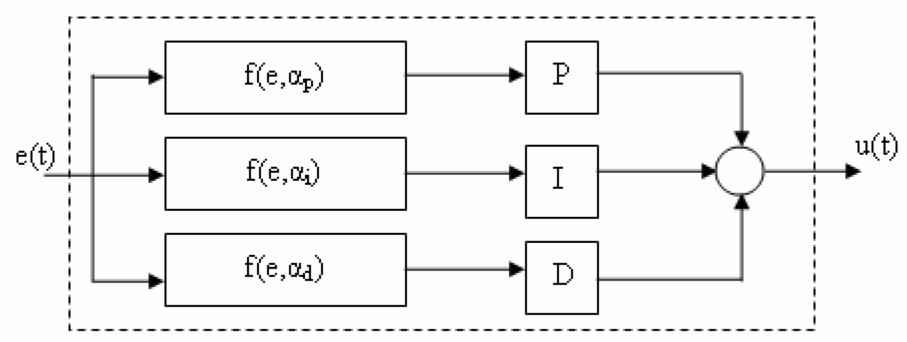


Figure 4.2 Improved NNTPID Scheme

The control structure can be described as follows;

$$u(t) = Kpf(e, \alpha_p) + ki\int f(e, \alpha_I)d\tau + Kd.\frac{df(e, \alpha_D)}{dt} \tag{4.3}$$

$$e' = f(e, \alpha) = sign(e)|e|^{\alpha}$$

The key concept is adjusting $\alpha_i>1$ as the system converges quicker. Chen Z. states that integral control is thinking like a human and summarizes the operating experience to decide the final output of the whole controller [13].

In this study, an additional improvement is applied on the nonlinear norm transformation scheme. The idea is basically developed to the unit step response characteristics. Since the error signal is between 0 and 1, effects of the norm value is evaluated. The benefits of the nonlinear proportional term (α_p) is to make the proportional control more sensitive to small errors than linear form, consequently reducing the function of the integral control. Moreover, it can be reduces the integral action by choosing $0 < \alpha_i < 1$. For the differential term, α_D can be chosen less than 1, in view of the fact the derivative action helps to prevent overshooting. Therefore after several simulations, better performance is achieved by adjusting norm as $\alpha_P = 1$, $\alpha_i = 0.6$ and $\alpha_D = 0.2$.

5. SIMULATIONS and DISCUSSIONS

The performances of the different controllers have been evaluated on different types of systems. The unit step responses are simulated with Matlab/ Simulink for all processes**.**

5.1. Conventional PID Tuning Methods

For the systems $G_1(s)$, the PID controller parameters are tuned by Ziegler-Nichols method. Then all fuzzy tuning methods that are mentioned in the previous sections and nonlinear PID control transformations are applied. The response signals are evaluated.

$$G_1(s) = \frac{1}{(s+1)^3} \quad \textbf{(5.1)}$$

To implement Ziegler –Nichols, starting point is assuming that there is only P controller in the systems and change the gain until system oscillates continuously. Ultimate gain and ultimate period must be calculated. Ultimate gain is proportional gain that leads the system oscillate. To calculate these parameters, these steps should be followed.

Characteristic equation ;

$$(s+1)^3 + K_u = 0 \quad \textbf{(5.2)}$$

Using Routh's array; critical gain K_u that cause oscillation can be found. At ultimate gain of Ku=8 the following output is obtained.

Then we can compute period of oscillation (P_u) at ultimate gain by replacing s with jω.

$$Pu = \frac{2\pi}{\omega} \quad \textbf{(5.3)}$$

where $\omega = \sqrt{3}$

P_u=3.625

When ultimate and ultimate period values are computed, the values of K_p, T_i, T_d can be easily set with the help of Ziegler-Nichols Table 1.2.

$$\begin{aligned} Kp&=0.6*Ku \\ Ti&=0.5*Pu \\ Td&=0.125*Pu \end{aligned} \quad \textbf{(5.4)}$$

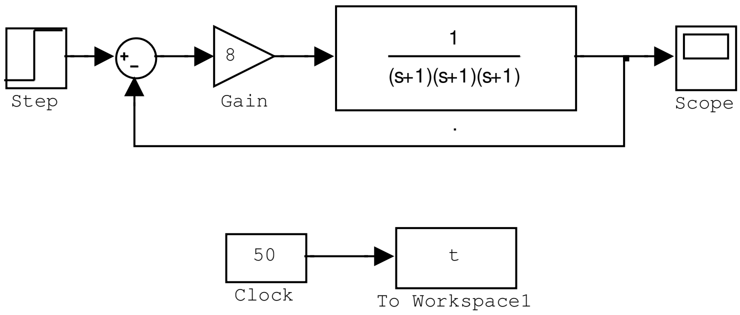


Figure 5.1 Block Diagram of P Controlled System

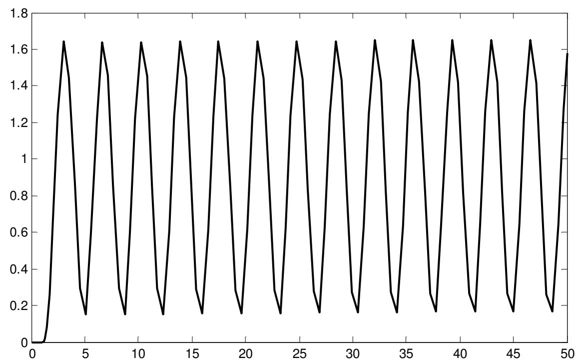


Figure 5.2 Oscillatory Output

The controller parameters are set as (5.4)

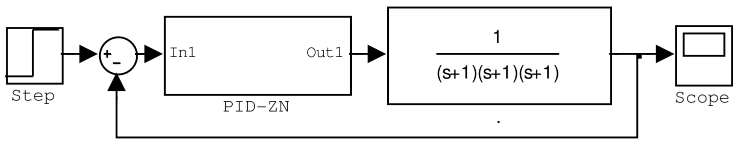


Figure 5.3 Block Diagram

System output controlled by PID –ZN is presented in Figure 5.4

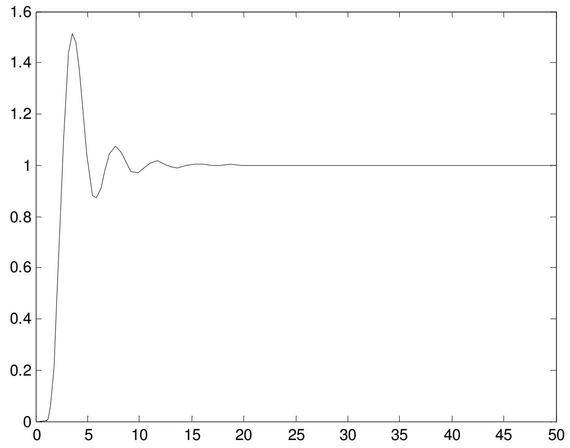


Figure 5.4 Output of PID Controlled System

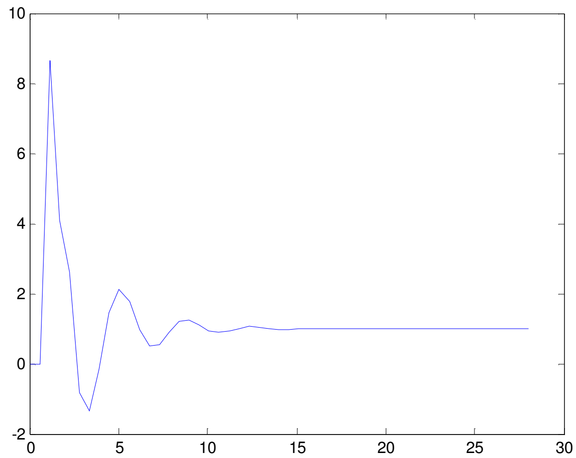


Figure 5.5 Control Signal of PID Controller

Ziegler-Nichols tuning methods are simple to calculate and implement. It is required little process information. These are the reasons why this method is widely used. Controllers designed by the Ziegler-Nichols rules, consequently, give closed loop systems with high overshoot and poor robustness. The method results that it is not enough to describe process dynamics by only two parameters. Some improved tuning methods can be applied to decrease the disadvantageous of the Ziegler-Nichols method.

In order to decrease the disadvantages of ZN method, set-point weighting can be useful. The set-point for the proportional action can be weighted by means of a constant b.

$$e(t) = b.y_{sp}(t) - y(t) \quad \textbf{(5.5)}$$

With this modification following expression can be applied to equation 1.4

$$u(t) = Kp(b.y_{sp}(t) - y(t)) + K_d \frac{de(t)}{dt} + K_i \int e(\tau) d\tau \quad \textbf{(5.6)}$$

In this way, a simple two degrees of freedom scheme is used; one is assigned to the attenuation of load disturbances, the other is to the set-point following.

$$\begin{aligned} Gff &= Kp(b + \frac{1}{sTi} + sTd) \\ Gc &= Kp(1 + \frac{1}{sTi} + sTd) \end{aligned} \quad \textbf{(5.7)}$$

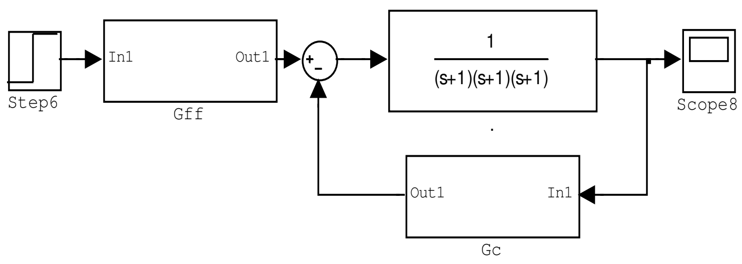


Figure 5.6 Block Diagram of Two degree of Freedom Controller

By changing parameter b, we can decrease percent overshoot (%). In this case, a procedure is needed to determine the parameter b. The method is stated in chapter 1.1.2.

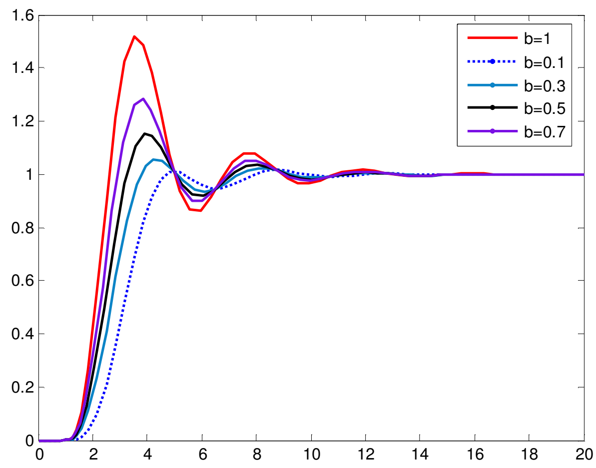


Figure 5.7 Output Results with Respect to Different b Parameters

Following figure is derived when b is equal to 0.3. When b =1, the same output is obtained as ZN-PID. The set-point weighting can be a solution for the problem of high overshoot. On the other hand, the main drawback of set-point weighting method is that it leads to an increasing of rise time as the effect of proportional constant is reduced. Another difficulty of this method is tuning four parameters; PID parameters and the weighting constant b.

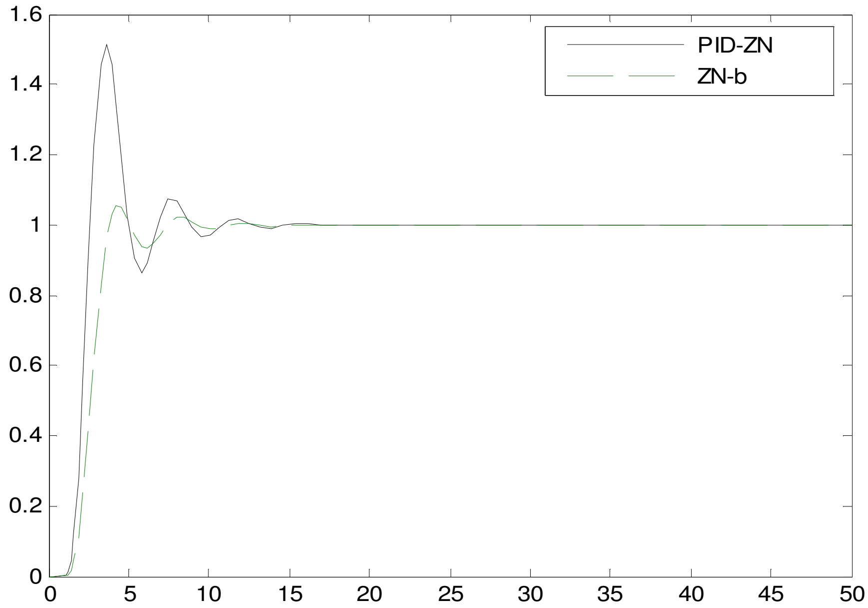


Figure 5.8 Comparison of Output Signals of Two Models Ziegler Nichols Method and Set-Point Weighting Method

While criticising the performances of conventional tuning method, it should be evaluated the sensitivity to the system parameter changes. Assume the system parameter; in this case one pole of the system G_1 is changed due to the effect of the working conditions. The output responses are compared.

$$G_1 = \frac{1}{(1+s)^2(s+0.5)} \quad \textbf{(5.8)}$$

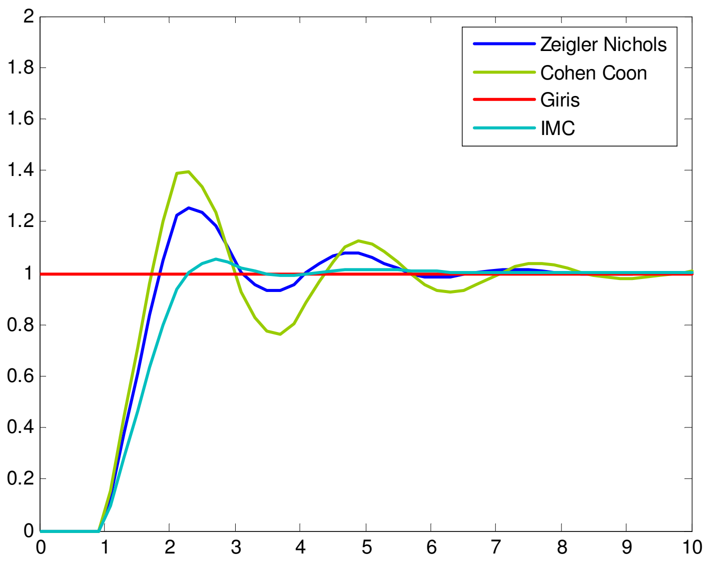


Figure 5.9 Comparison of Output Signals of Controllers Tuned by Ziegler-Nichols, Cohen-Coon and IMC Methods

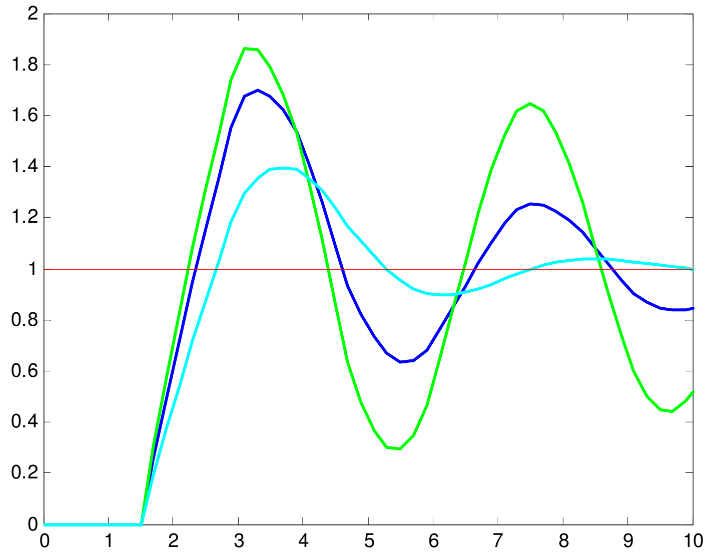


Figure 5.10 Comparison of Responses Under Condition of Parameter Change

5.2. Fuzzy Self-Tuning PID Methods

5.2.1.Third Order System

In literature, there are several fuzzy methods used to tune the PID parameters. Methods mentioned in chapter 3 are applied to the system $G_1(s)$. First method (chapter 3.1) is incremental fuzzy expert PID control.

$$
\begin{aligned}
P &= P + CV\{e(t), \dot{e}(t)\} \times k_1 \\
I &= I + CV\{e(t), \dot{e}(t)\} \times k_2 \\
D &= D + CV\{e(t), \dot{e}(t)\} \times k_3
\end{aligned} \qquad \textbf{(5.9)}
$$

The parameters which are before hand tuned by Ziegler-Nichols method are increased or decreased on-line during operation. The fuzzy mechanism does this adjustment based on the error and the change of error. Therefore, there are two inputs $e(t), \dot{e}(t)$ and one output f. Five membership functions for each input (Figure 5.11) and nine membership functions for the output (Figure 5.12) are assigned. Consequently, 25 rules are used to define tuning mechanism Table 5.1

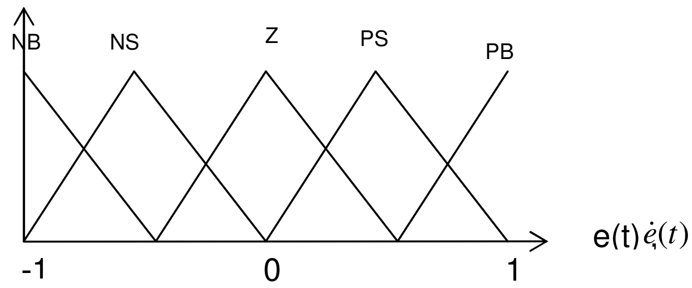


Figure 5.11 Membership Functions for Inputs

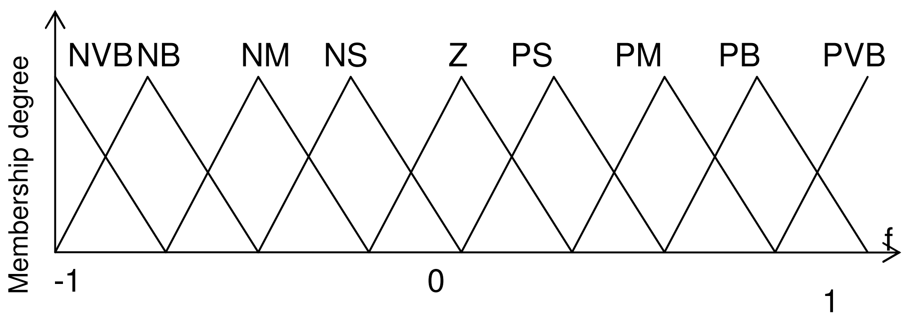


Figure 5.12 Membership Functions for Output f

Table 5.1 Rule Base for FSW

		Δe				
		NB	NS	Z	PS	PB
e	NB	NVB	NB	NM	NS	Z
	NS	NB	NM	NS	Z	PS
	Z	NM	NS	Z	PS	PM
	PS	NS	Z	PS	PM	PB
	PB	Z	PS	PM	PB	PVB

After defining the membership functions and rules , ANFIS tool is used to form the tuning mechanism. ANFIS tool is also used in all following fuzzy tuning methods.

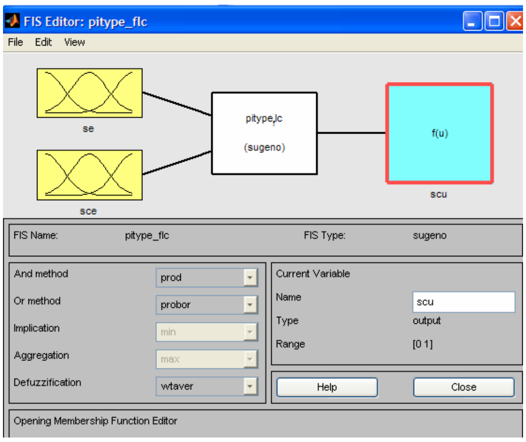


Figure 5.13 Anfis Structure of Fuzzy Tuning Mechanism

Difficulty of this method is adjusting k_1, k_2, k_3 parameters. These parameters (as pointed out chapter 3.1) define the range of variation. Hence, these can be identified depending on the desired system characterisation, stability analysis or genetic algorithm methods. For system $G_1(s)$, these parameters are chosen as 5, 0.1 and 0.1.

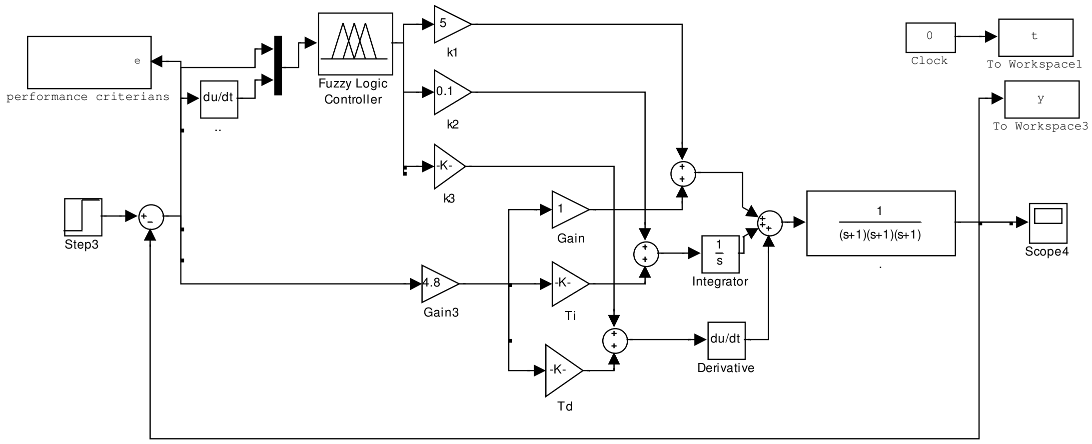


Figure 5.14 Simulink Presentation of IFE Method for System G_1

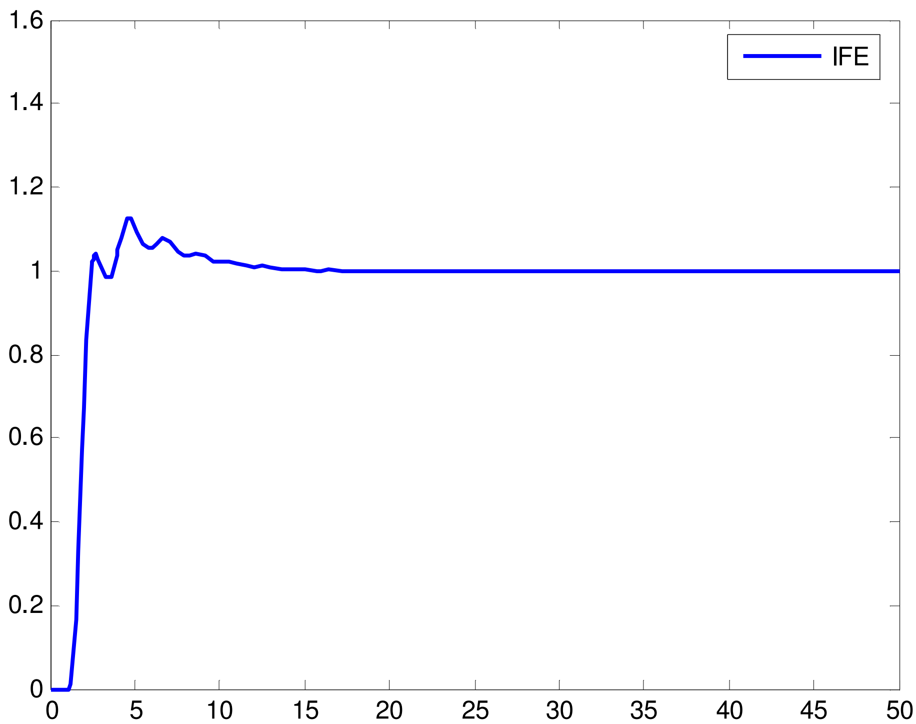


Figure 5.15 Output Signal of Incremental Fuzzy Expert Controlled System

Concerning rise time, settling time and performance criterions, incremental fuzzy expert PID control has better performance than of ZN –PID. Tuning of three k1, k2, k3 parameters that multiply the two inputs e(t) and $\dot{e}(t)$ is difficult task as it is not clear how these parameters influence the performance of the overall controller.

Fixed set-point weighting method has already discussed in chapter 1.1.2. The drawbacks of this method can be removed by tuning the weighting constant b with a fuzzy mechanism. The method is called fuzzy set-point weighting. Same numbers of membership functions are defined as previous method.

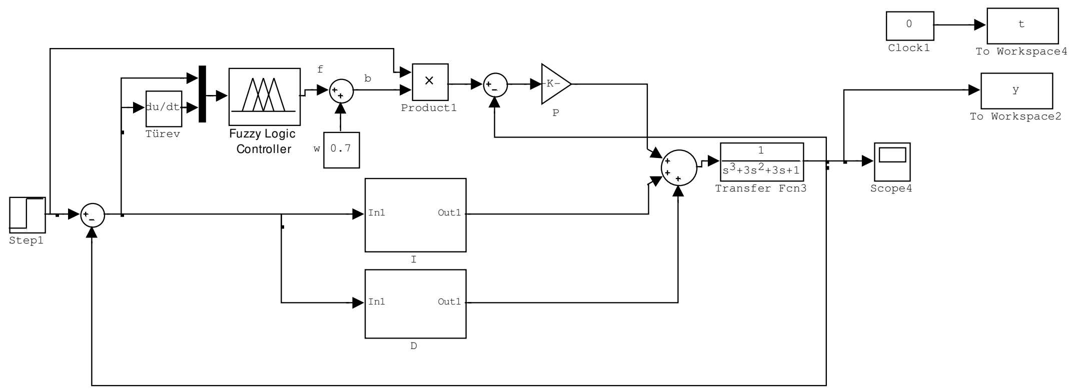


Figure 5.16 Block Diagram of FSW method

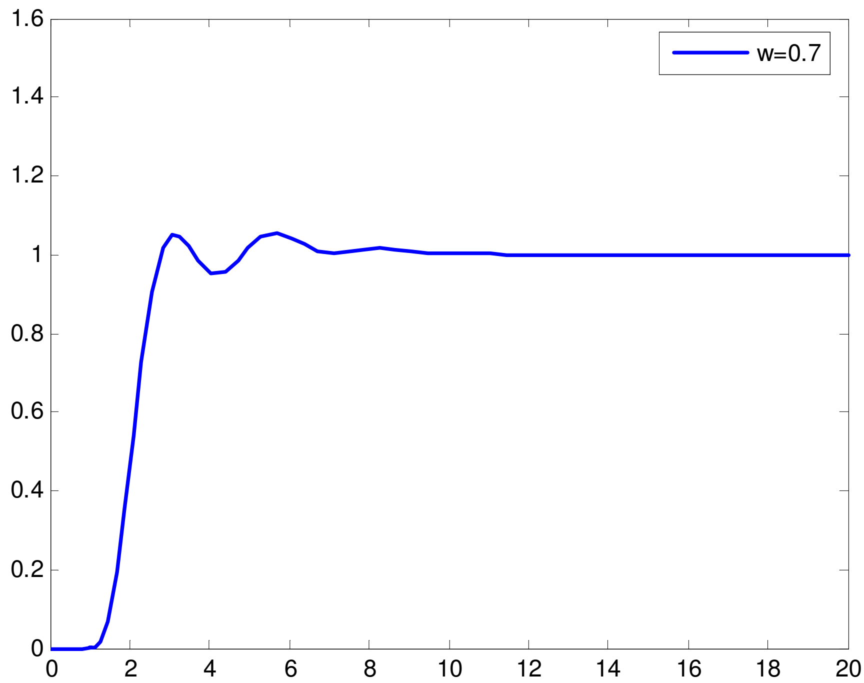


Figure 5.17 Output signal of Fuzzy Set-point Weighting

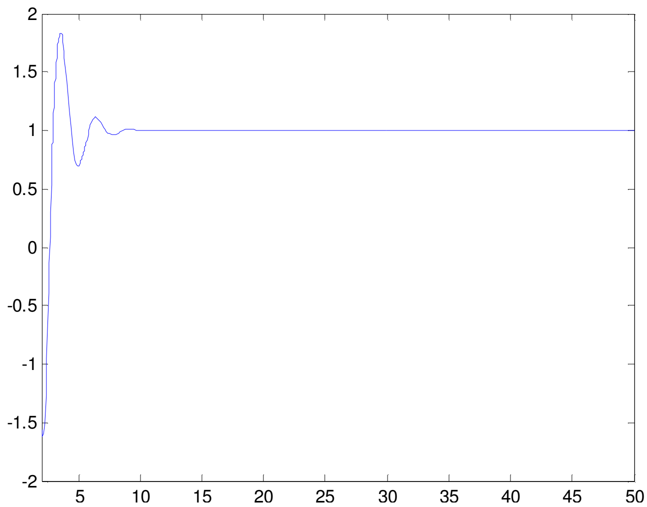


Figure 5.18 Control signal of FSW Controller

The choice of w is also problematic. As previously expressed in (Chapter 3.2), w is can be found iteratively by increasing until no better results are achieved. On the other hand, genetic algorithms may have been used to define the parameter in order to minimize the values of integrated absolute error. Here it is chosen as 0.7. From Figure 5.17, we can derive that both overshoot & rise time can be decreased from ZN response with FSW method. FSW in general gives better performance.

In fuzzy gain scheduling method, three fuzzy mechanisms are used to tune the PID parameters. Each one uses the system error and change of error as input and with different rule bases decides the control action (i.e. Kp', Kd' and α). These three rule bases and membership functions had been already defined in chapter 3.3.

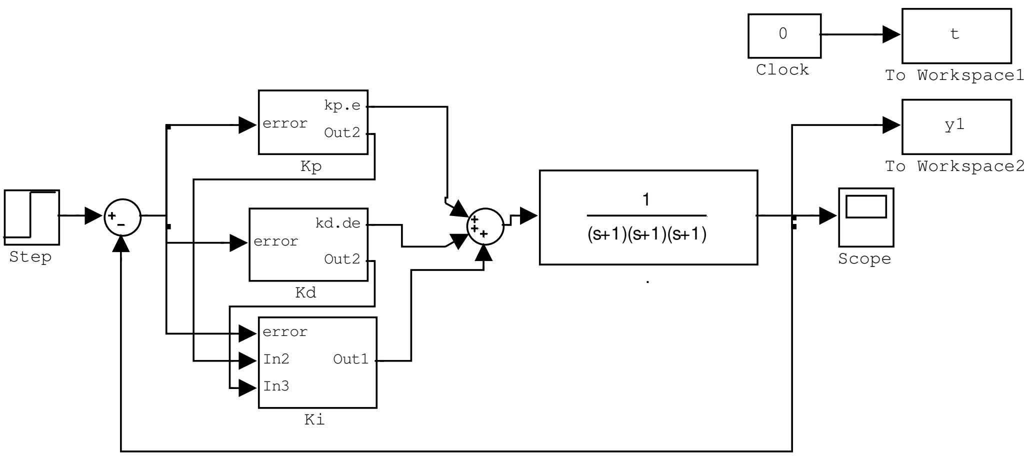


Figure 5.19 Block Diagram of Fuzzy Gain Scheduling Method

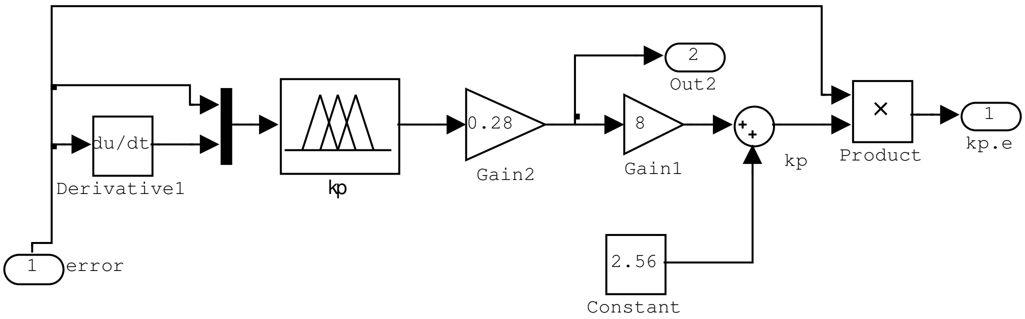


Figure 5.20 Block diagram of Kp

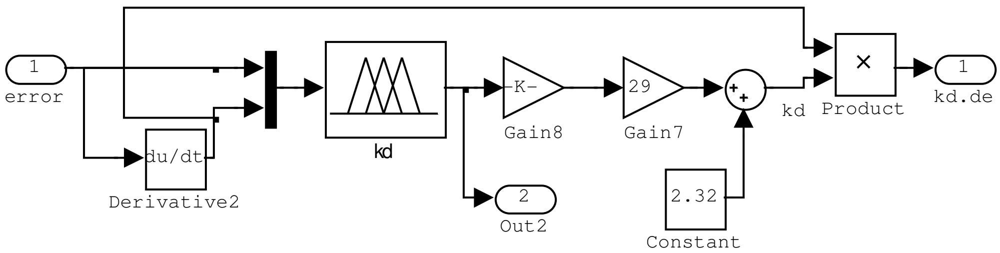


Figure 5.21 Block diagram of Kd

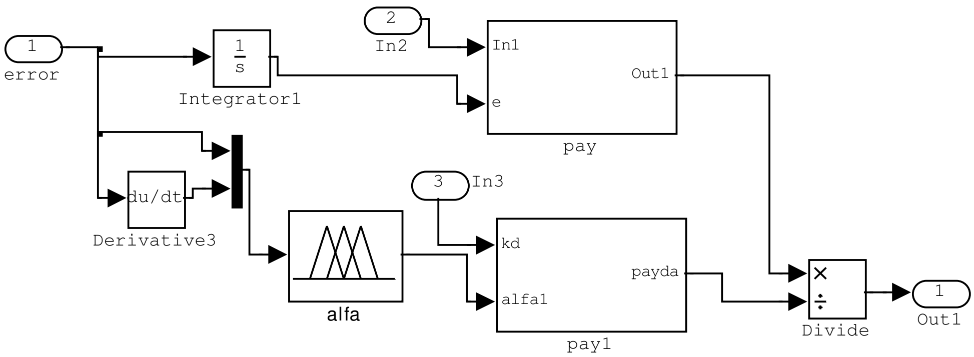


Figure 5.22 Block diagram of Ki

Table 5.2 Performance Criteria of System $G_1(s)$

G1	Standart PID		FLC		
	ZN	ZN-b	FGS	IFE	FSW
IAE	2,20	1.20	2,13	1,77	1,31
ITAE	7,44	2,24	6,66	14,60	2,62
ISE	1,20	1.02	1,28	0,80	0,89
ITSE	2,60	2,24	2,44	1,49	1,38

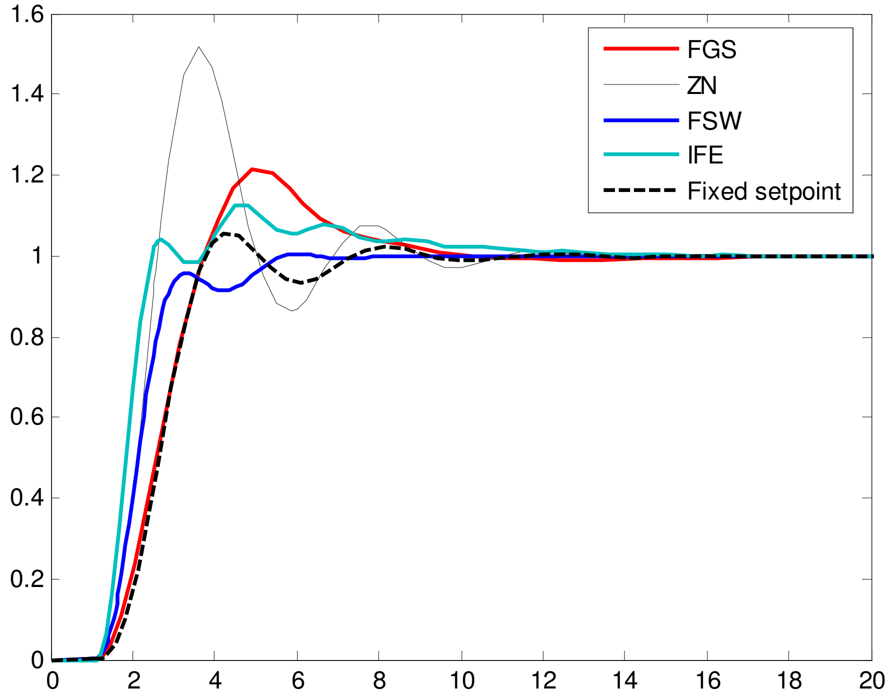


Figure 5.23 Comparisons of Output Signals

Concerning the rise time, settling time and other performance measures, the methods that fuzzy tuning mechanism used can improve the performances. Specifically, IFE (incremental fuzzy expert PID) and FSW (fuzzy set-point weighting) are able to improve the performances achieved by fixed parameter settings. Besides the fuzzy tuning mechanisms, genetic algorithms may be used to tune other parameters. In FSW and IFE methods, it is needed to use genetic algorithm to tune parameters other than controller parameters.(k_1, k_2, k_3 and for FSW ; w). With the method; Self tuning of a single parameter, the response signal is not comparable with other fuzzy tuning methods.

In contrast, a conventional controller depends on system parameters. If the parameters change, then we need to re-design our controller. With fuzzy control this is not necessary because a fuzzy system provides robustness of the system. While criticising the performances of the fuzzy tuning method, it should be evaluated the sensitivity to the system parameter changes. Assume the systems parameter; in this case one pole of the system G_1 is changed due to the effect of the working conditions (5.8). The output responses are compared.

$$G_1 = \frac{1}{(1+s)^2(s+0.5)} \tag{5.10}$$

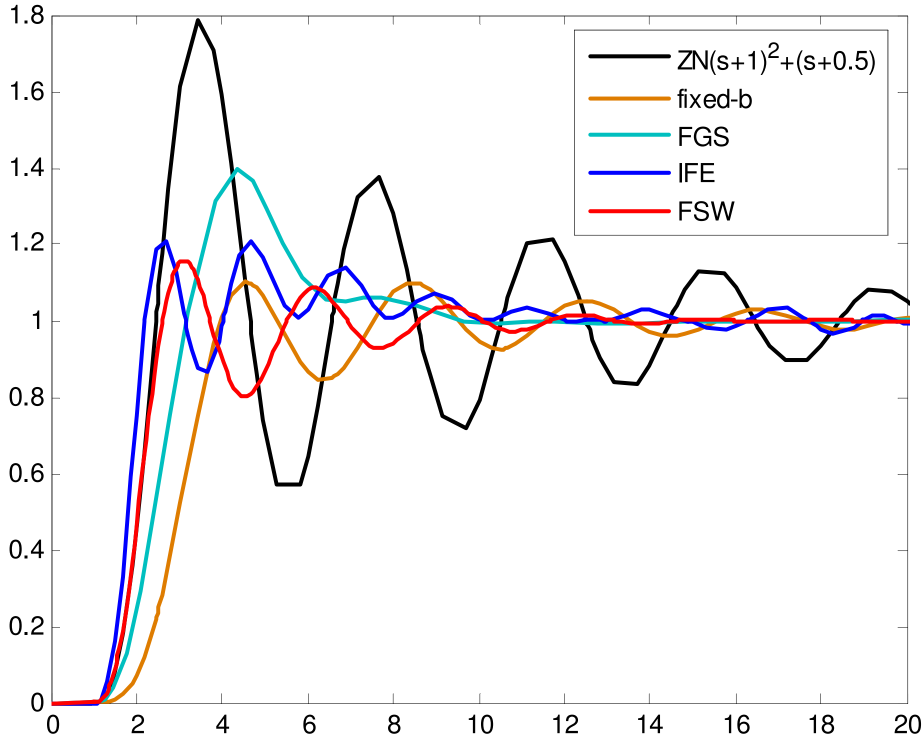


Figure 5.24 Output Responses for the System G1 with Parameter Changes

The simulation results show that systems with fuzzy tuning mechanism have less sensitivity to parameter changes during the operating time. Settling time, rise time and IAE values are better than of the fixed parameter tuning methods. Fuzzy tuning mechanism does not only improve the performance of the output signal, but also provides robustness to the systems.

5.2.2.Second Order Plus Time Delay System

For system G_2, a fuzzy tuned system and conventional PID controlled system is compared. The simulation results are shown in Figure 5.25.

$$G_2(s) = \frac{e^{-0.5s}}{(0.5s+1)(s+1)} \tag{5.11}$$

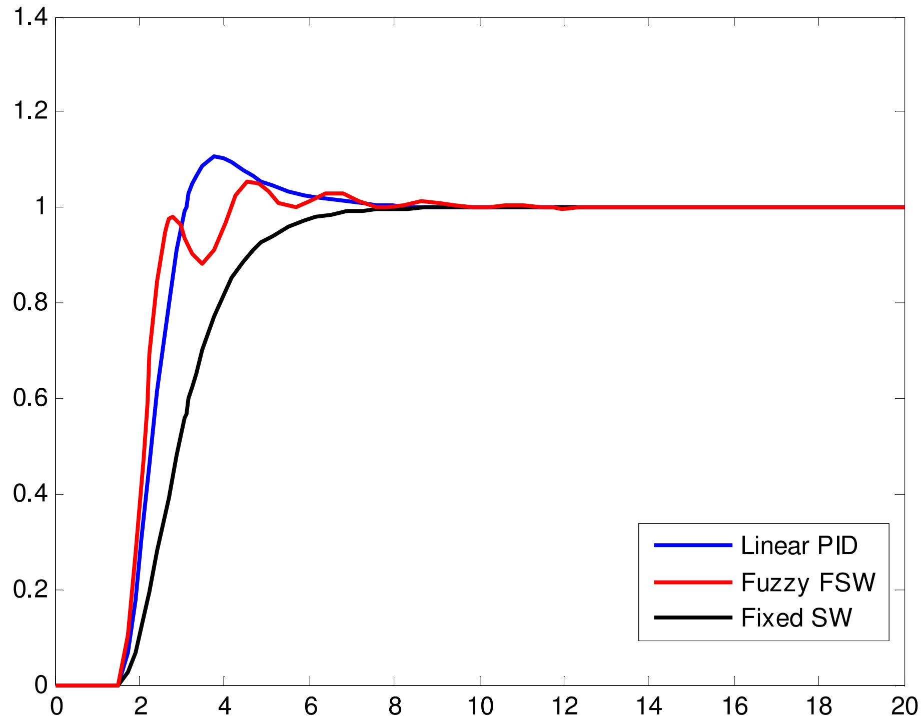


Figure 5.25 Output Signal of SOPTD System Controlled By PID- Fixed Set-Point Weighting and Fuzzy Tuning Mechanism

For system G_2, PID controller tuned by Ziegler-Nichols tuning method, fixed and fuzzy set-point weighting methods are simulated. As a result output signal of system that is tuned by fuzzy mechanism perform better result Table 5.3.

Table 5.3 Performance Criterions for system G_2

	PID	Fixed Setpoint Weighting	Fuzzy Setpoint Weighting
IAE	1,52	2,15	1,30
ITAE	3,20	5,05	2,79
ISE	1,10	1,57	0,95
ITSE	1,79	3,01	1,45

5.2.3.Nonlinear plant

These fuzzy tuning mechanisms are applied to a nonlinear system [15]. It is investigated that the advantages of adding a fuzzy logic supervisor to the standard PID controller to improve performance. Assigning PID parameter tuning is generally difficult to nonlinear systems. By the help of fuzzy mechanism, better performance is obtained.

$$\frac{d^2y}{dt^2} + \frac{dy}{dt} + \frac{1}{4}y^2 = u(t-L) \qquad (5.12)$$

PID parameters are tune by trial and error method or resembling a linear system.

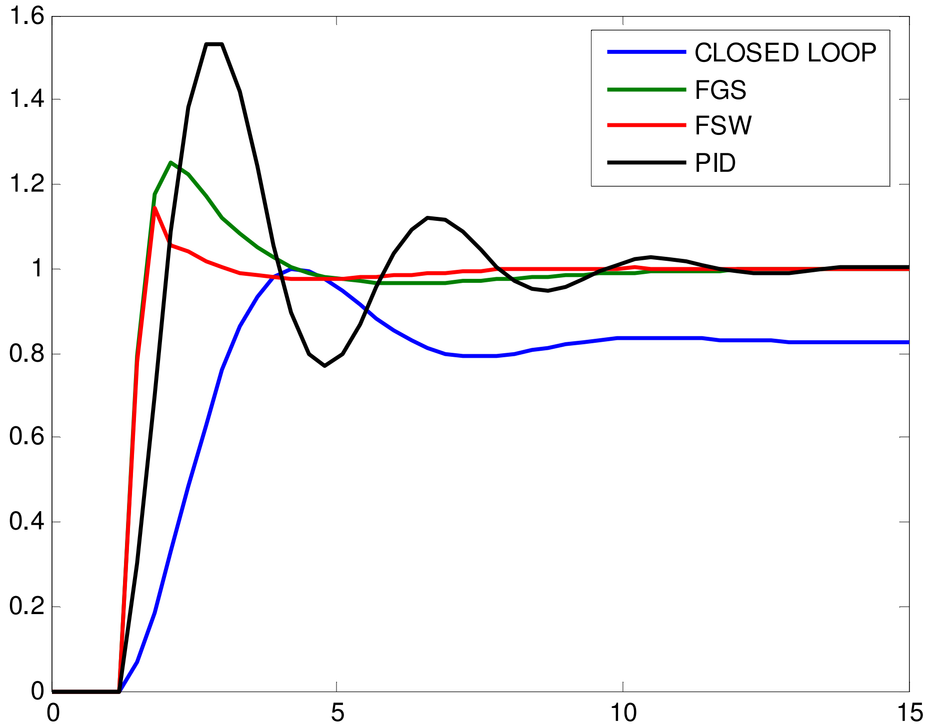


Figure 5.26 Comparison of Output Signals of Nonlinear System With Fuzzy Tuning Mechanism

Fuzzy systems are independent form the plant parameters. Therefore, exact PID parameter values are not needed to get acceptable output result. With the help of property of fuzzy mechanism, even nonlinear plants can be controlled successfully.

5.3. Nonlinear PID controllers

After evaluating the performances of self-tuning fuzzy methods, nonlinear PID controllers' performances can be examined. First method is Shinskey's nonlinear controller. The control law is already stated in chapter 4.1. In simulations are done by changing the nonlinearity constant L. As L approaches to 0, the controller becomes highly nonlinear. When L is equal to 1, controller becomes the linear classical PID.

5.3.1.Third Order System

Comparison of the outputs of G_1 (s) (5.1) is illustrated in **Figure 5.27**.

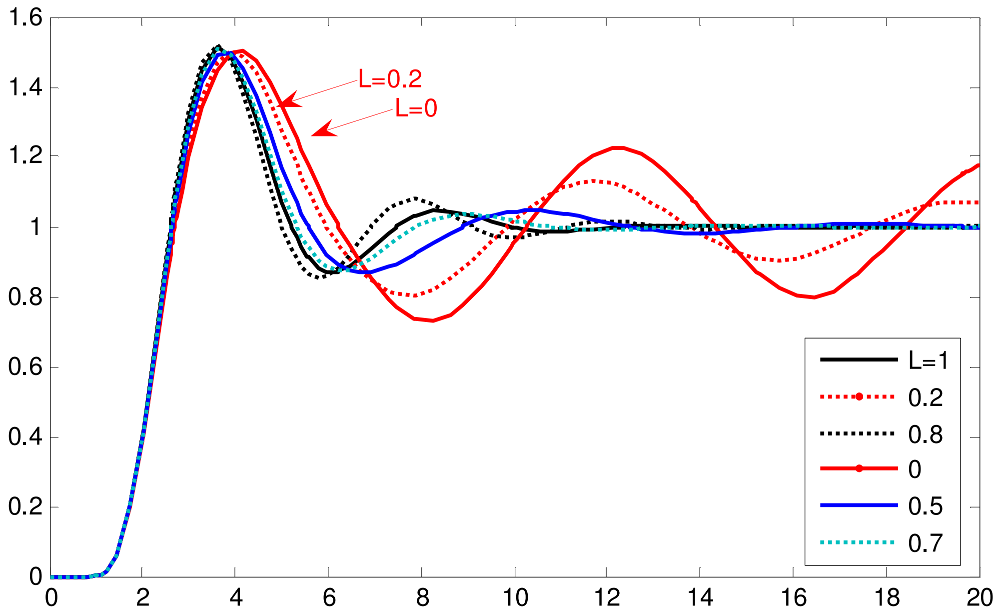


Figure 5.27 Output Values for the system G_1 for Incremental Values of Nonlinearity Constant L (0, 0.2, 0.5, 0.7, 0.8, 1)

Table 5.4 Performance Criterions for the system G_1

	NPID						FLC		
	ZN	ZN-b	L=0	L=0.2	L=0.5	L=0.7	FGS	IFE	FSW
IAE	2,20	1.20	7,34	3,93	2,42	3,93	2,13	1,77	1,31
ITAE	7,44	2,24	142,46	41,14	9,57	41,14	6,66	14,60	2,62
ISE	1,20	1.20	2,08	1,41	1,24	1,41	1,28	0,80	0,89
ITSE	2,60	2,24	21,98	4,92	2,89	4,92	2,44	1,49	1,38

When controller highly nonlinear (i.e. L=0), system acts oscillatory output. Nonlinear PID controller did not generate better result for systems G_1.

Other nonlinear PID method; nonlinear PID based on the nonlinear norm transform is declared in chapters 4.2 and 4.3. An exponential transform of the system error is given to the system as error. In the following simulations, α =0.6 is applied to the system to form a NNTPID controller. NNTPID controller has same α values for P, I and D controllers. Difference of the improved version is α value of integral controller is different than P and D controllers. α_i has been taken bigger than 1; specifically 1/0.6 [13]. The output signals are demonstrated in Figure 5.28

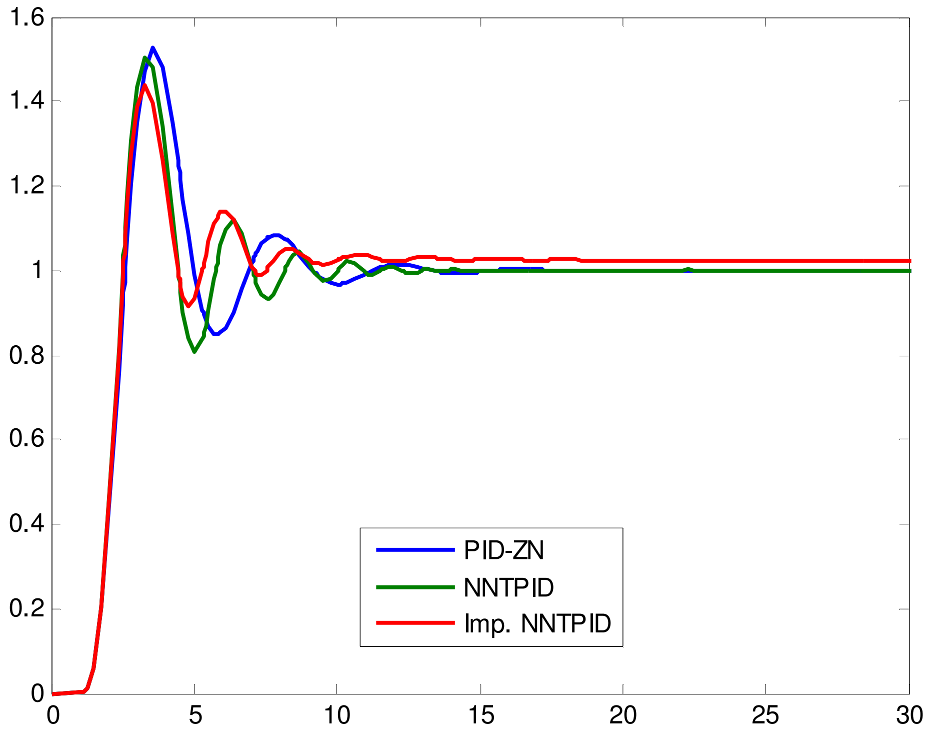


Figure 5.28 Output Signals of NNTPID Controllers and Linear PID Controller

By increasing α_i, the output signal is faster to converge to reference value, but steady state output error become larger. There is no obvious improvement on the performance with NNTPID. On the other hand, improved NNTPID can reduce the rise time and overshoot.

Another modification is made to NNTPID controller. After evaluating the effects of the norm value α, apply different α values to different controllers. Therefore after several simulations, better performance is achieved by adjusting norm as $\alpha_P = 1$, $\alpha_i = 0.6$ and $\alpha_D = 0.2$.

Table 5.5 Performance Criterions for NNTPID methods

	NNTPID	Improved NNTPID	Proposed NNTPID
IAE	2,10	2,67	1,67
ITAE	7,17	28,72	5,33
ISE	1,14	1,06	0,99
ITSE	2,38	2,46	1,77

This modification provides better performance than other two methods with respect to rise time, settling time and percent overshoot and other performance criterions.

Namely, overshoot is decreased by %10 and settling time is also significantly decreased. In order to achieve better output responses, norm values may be changed during operation.

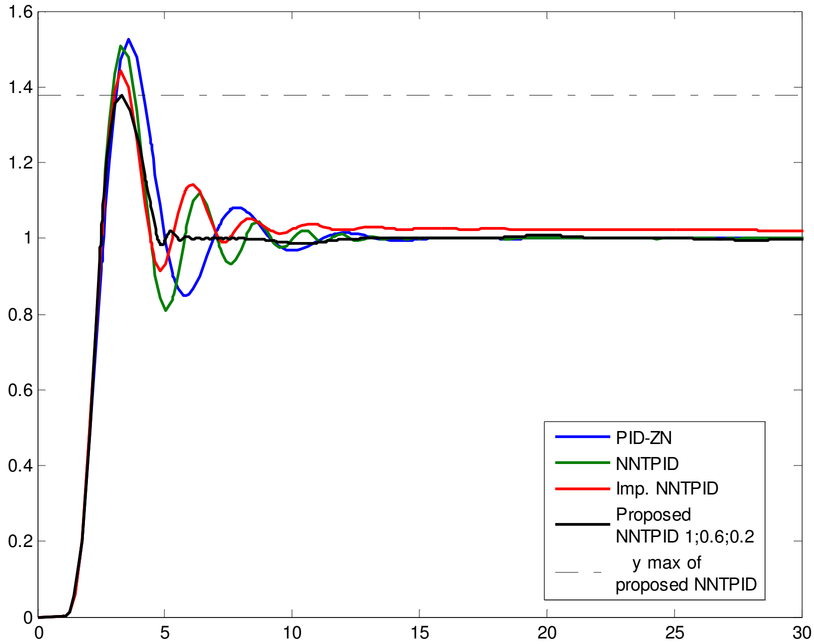


Figure 5.29 Comparison of Output Signals Derived from NNTPID Methods

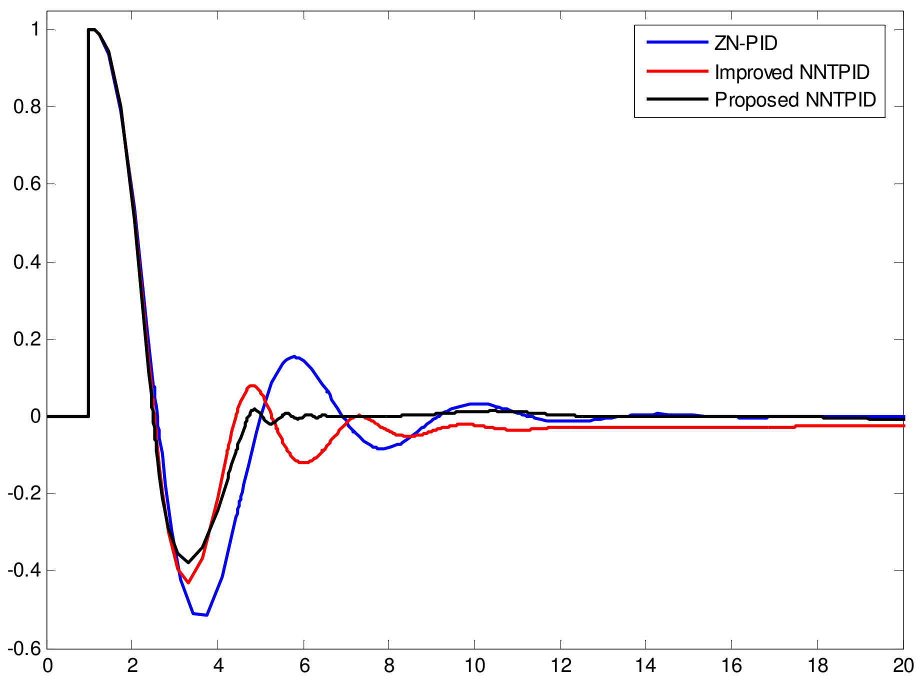


Figure 5.30 Comparison of Output Error Derived From NNTPID Methods

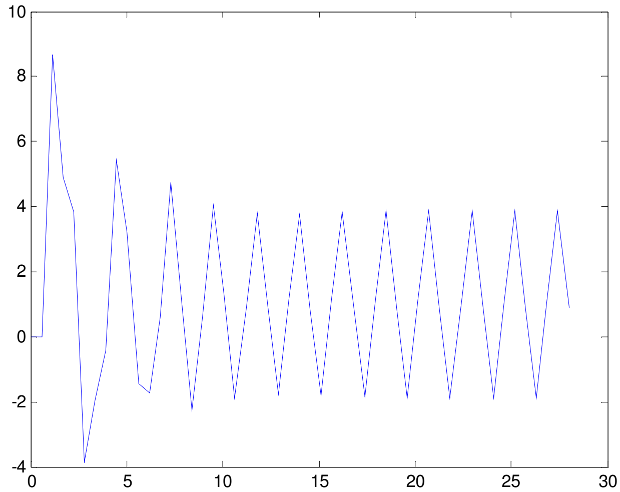


Figure 5.31 Control Signal of NNTPID Controller

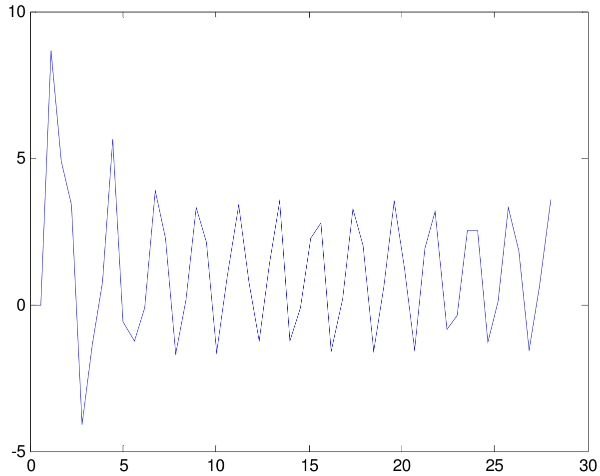


Figure 5.32 Control Signal of Improved NNTPID Controller

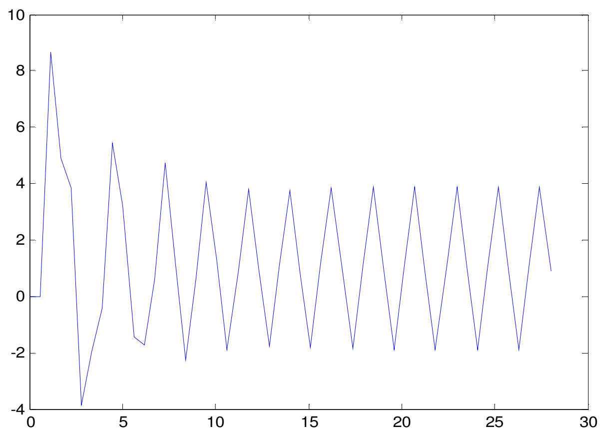


Figure 5.33 Control Signal of Proposed NNTPID Controller

5.3.2.Second Order Plus Time Delay (SOPTD)

Nonlinear PID controllers are also implemented to the second order plus time delay system $G_2(s)$.

$$G_2(s) = \frac{e^{-0.5s}}{(0.5s+1)(s+1)} \tag{5.13}$$

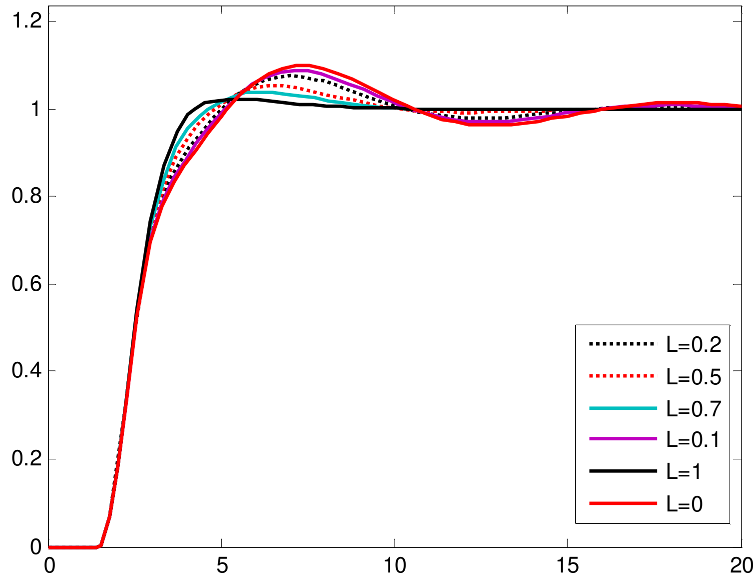


Figure 5.34 Shinskey's Nonlinear PID Controlled System Outputs

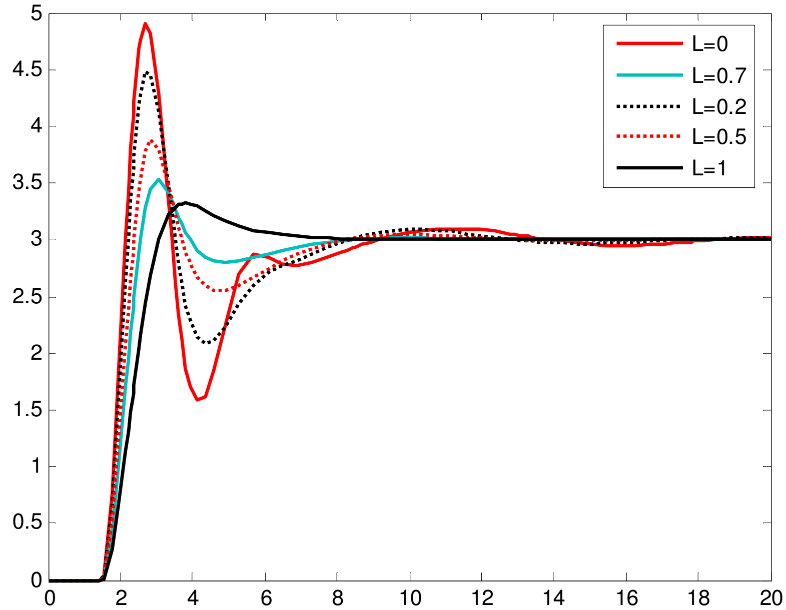


Figure 5.35 Output Response for an Step Input >1

Highly nonlinear PID controller can cause the system small oscillations, increase rise time and settling time. Linear PID controller gives better results. But for step input higher than 1 , when the system error is bigger than, because of the property of the error squared controller, the effect of the error become higher in control law. The controller becomes more sensitive to error. As a result, the rise time turns out to be shorter whereas the settling time becomes longer. When the nonlinearity degree is near 0.7, optimum result can be obtained. The nonlinearity degree can be manipulated over the control action, so better control signal may be achieved.

5.3.3.Nonlinear Plant

System 3 is a nonlinear system. Nonlinear PID controller is applied to the system (5.13)

$$\frac{d^2y}{dt^2}+\frac{dy}{dt}+\frac{1}{4}y^2=u(t-L) \qquad \textbf{(5.14)}$$

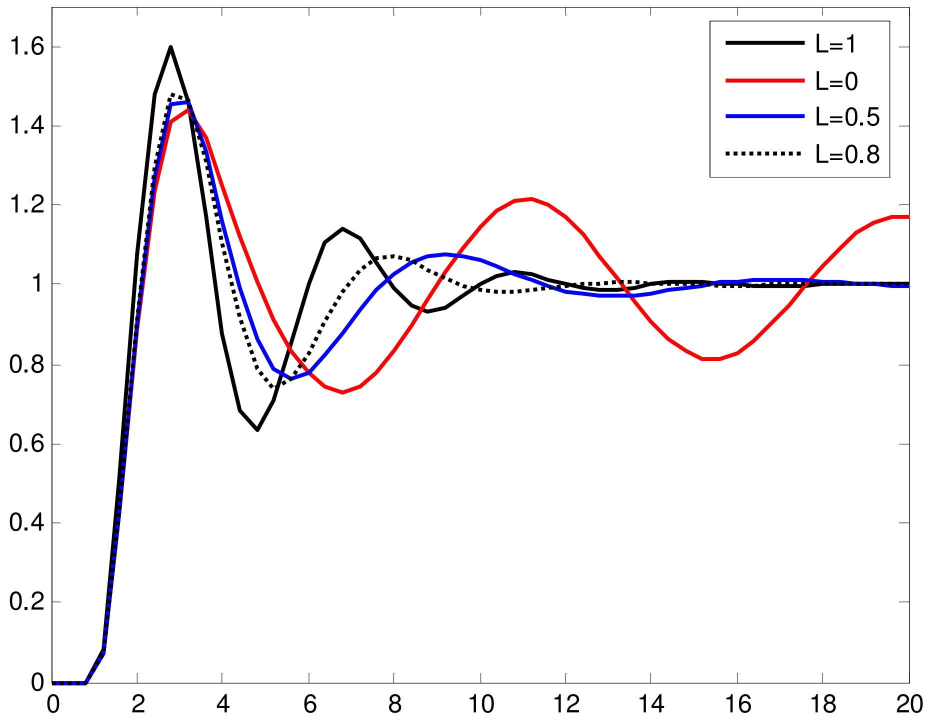


Figure 5.36 Output Values Obtained by Using Shinskey's Nonlinear PID Method

Control Rules are defined with respect to the effect of nonlinearity constant L. For example, for small values of L , rise time is small on the other hand, settling time is longer. big values of L (i.e. near 1) settling time is shorter, percent overshoot is smaller.

1. If the error Positive and the change of error is Negative , then L is Small
2. If the error Positive and the change of error is Positive , then L is Big
3. If the error Negative and the change of error is Positive, then L is Small
4. If the error Negative and the change of error is Negative , then L is Big
5. o/w L is B

Table 5.6 Rule Base defined for Nonlinear Controller

		Change in error		
		N	Z	P
error	N	B	B	S
	Z	B	B	B
	P	S	B	B

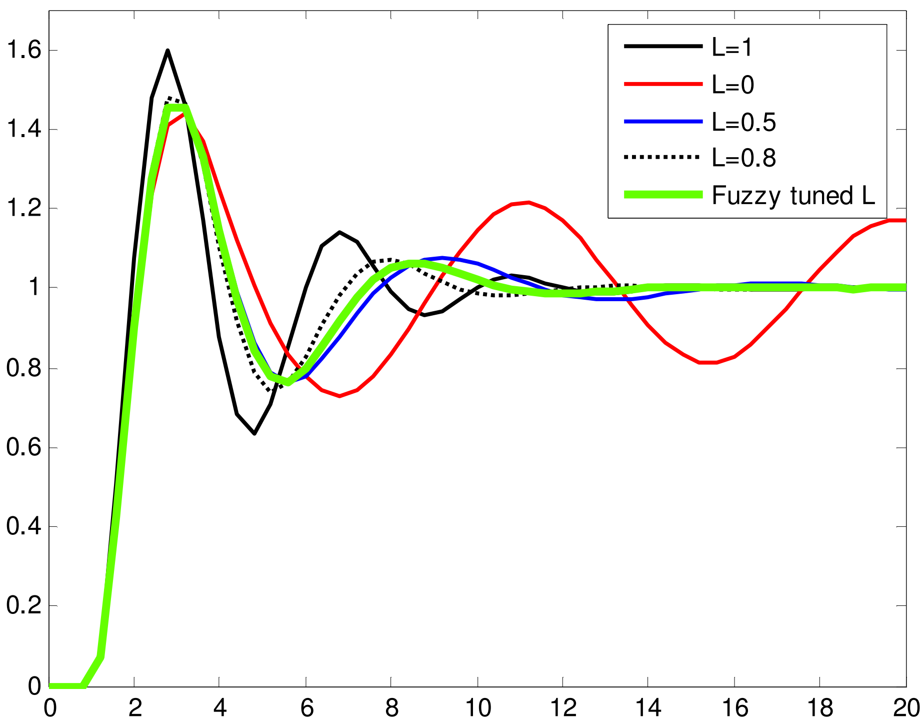


Figure 5.37 Output Values Obtained by Using Shinskey's Nonlinear PID Method with L Values is Tuned by Fuzzy Controller.

The advantageous of the different L values at different stages of the output is evaluated and control rules are assigned. An optimum output signal is achieved concerning the rise time, settling time and overshoot.

6. CONCLUSION

The purpose of this thesis is to improve the performance of conventional PID controllers, research on . First approach is to make a combination of conventional PID control and fuzzy control. Fuzzy controller is used to tune PID controllers that are already specified by classical tuning procedures. Second approach is implementing nonlinear PID controllers. Because fuzzy controllers have nonlinear properties, the performance of other nonlinear PID controllers is investigated.

This study is mainly composed of three parts; first part is introducing the classical tuning methods and fuzzy tuning PID methods, second part is introducing nonlinear PID controllers and comparing with the conventional PID controller and third part is comparing the performance of fuzzy tuning methods and nonlinear PID controllers with classical parameter tuning methods. In addition, robustness of these methods is evaluated.

In first part, conventional tuning methods which are Ziegler-Nichols, Cohen-Coon, and IMC control and fuzzy tuning methods which are incremental fuzzy expert PID , fuzzy tuning of set-point weighting and fuzzy gain scheduling are introduced. Fuzzy tuning algorithm is applied to the systems of which the PID controller parameters are tuned by one of the conventional methods. Generally, Ziegler-Nichols method is used.

It is observed that Ziegler –Nichols method is resulted larger maximum overshoot and longer settling time. On the contrary, the output signals produced by the method of self-tuning PID controller with fuzzy control mechanism indicate that the systems have the performances of the smaller maximum overshoot, very small oscillation, shorter rise time, and the acceptable settling time. Particularly, incremental fuzzy expert PID (IFE) and fuzzy tuning of set-point weighting methods (FSW) have better performance in all cases.

In second part, two types of nonlinear PID controllers are introduced. First method is proposed by Shinskey. This nonlinear PID controller is basically error-squared controller. Performance of this controller gets better by adjusting the nonlinearity degree (L). Highly nonlinear PID controller is not desirable. Generally, linear PID controller gives better result for linear systems. For nonlinear system G_3, when L is near 0.7, as L decreases, overshoot decreases on the other hand settling time and rise time increases. Therefore a fuzzy controller is implemented to tune the nonlinearity constant L according to the system error and change of error. Considerably good output result has been achieved. Second method is nonlinear PID control based on norm transformation. Exponential transform is applied to the error to make the controller more sensitive to small errors. In addition, modified version of this controller is introduced. The difference is changing the effect of the integral controller to add more intelligence. This method could not give significant improvement. Additional modification is done by examining the output characteristics; increase the effect of I and D control. By this modification, better output results are achieved in point of rise time, settling time and other performance criterions.

We also examined the robustness of these methods; the responses to the parameter changes are simulated. Fuzzy tuned systems have higher robustness characteristics. Namely, robustness, stability, and IAE values are best in fuzzy set-point weighting tuning method (FSW).

As a conclusion, nonlinear PID controllers' performances are restricted by the types of the systems. Fuzzy controller can be applied to linear and nonlinear systems. Although some improvements are achieved with nonlinear PID controller, fuzzy controllers satisfy many aspects of control performances.

Fuzzy control schemes have performed better actions in all conditions. Nonlinearity property and independency from system parameters make fuzzy controllers essential in industrial applications. The another advantage of the fuzzy control methods is that it can be implemented quite easily by adding to current hardware PID controllers a microprocessor component that carries out the extra computation.

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ÖZGEÇMİŞ

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