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Design, analysis and performance evaluation of F-PI controller based on analytical structure developed using Gaussian membership functions

[1] A.D. Sonar (Limgaokar),[2] R.H. Chile and [3] B.M. Patre

[1] *Department of Instrumentation Engineering, Dr. D.Y.Patil Institute of Technology,Pimpri,Pune-411 018, India.*
[2,3] *Department of Instrumentation Engineering, S.G.G.S. Institute of Engineering and Technology,*
Vishnupuri, Nanded 431 606, India.
E-mail: E-mail: [1]arundsonar21@gmail.com, [2] *rhchile@sggs.ac.in*,[3]*bmpatre@sggs.ac.in*

ABSTRACT

This paper presents a method of development of formula based fuzzy proportional-integral (F-PI) controller using Gaussian membership functions (GMFs). Though very popular in fuzzy literature, GMFs are very rarely used in designing formula based fuzzy controller (FBFC) in contrast to triangular and trapezoidal membership functions. FBFC involves obtaining the analytical structure of F-PI controller to overcome the limitations of traditional fuzzy controllers. The controller thus has analytical structure capable of achieving some significant enhancement in transient response specifications over system under control. The formulae thus obtained, can be viably applied in real time control circumstances. Thus, the controller proposed here is discrete interpretation of the conventional PI controller. The control simulations were carried out for set point tracking and disturbance rejection (regulation) to assess the transient execution of the proposed controller. The relative stability of the controller is confined through computer simulations. The proposed controller ensures better performance execution when tested on complex systems. The similar structure using Triangular membership functions is also compared with the Gaussian one. The performance of the controller in setpoint tracking regulation is evaluated. The error metrics IE, IAE and ISE are also obtained to substantiate the effectiveness of the proposed controller.

Keywords: *PI controller, fuzzy PI Controller, formula based fuzzy controller (FBFC), Gaussian membership functions (GMF)*

1. INTRODUCTION

Despite of huge research and large number of various solutions proposed, big portion of the modern control systems still utilize customary PID controllers, due their nominal effort, economical upkeep, ease in operation and viability for general forms. The ordinary controllers can't give an overall answer for all control issues, especially when the processes involved are, complex, time varying, having delays, nonlinearities, and poor dynamics. At the point when the procedure turns out to be too complicated, it is probably not going to be effectively controlled by regular methodologies [1,2]. Fuzzy Logic Controllers (FLC) on the other hand can efficiently control the complex and difficult-to-model processes [3]. It has got developed as a standout amongst the most dynamic and useful research regions in the fuzzy control premise, thus they have been effectively connected for control of different physical processes. Likewise, use of fuzzy logic controllers (FLC's) has increased far reaching applications worldwide and have turned out to be economically savvy approach to take care of testing reasonable issues with narrowed time [4,5]. FLC's thus are considerably nearer to human thinking and regular dialect than the conventional logical systems [6,7]. The performance of PI-type gain FLCs is known to be quite satisfactory for linear first-order systems [8]. A model based fuzzy PD controller can be effectively used to control the speed of the turbine and hence the alternator by adjusting the percentage opening of the fuel feed system valve [9].

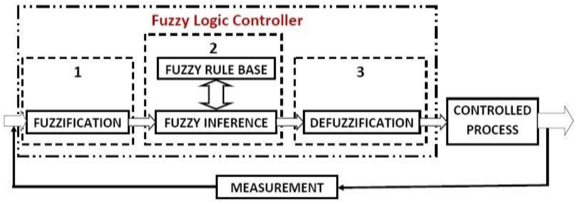

Fig. 1. Basic Fuzzy Logic Controller

Though FLCs were applied successfully for control of various processes, its mathematical structure was unknown. Deriving the underlying structure of FLCs became essential due to two reasons, first, once the FLC is constructed the meaningful analytical analysis and design cannot be obtained. Second, it is very difficult to predict whether fuzzy controller can provide an approximation solution to any continuous non-linear control problems with the accuracy that one desires. The analytical structures of simplest Takagi-Sugeno fuzzy two-term controllers [10,11], Fuzzy PI and fuzzy PD controllers can take care of complexities in the systems in much superior way to their conventional counterpart[12],[13]. Accessibility of scientific model of FLC and their exact comprehension are in a general sense imperative for orderly examination and combi- nation of fuzzy control framework [14]. Because of exploratory approach of fuzzy logic, it plays a critical role in upgrading of traditional controllers. The FBFC results into the fuzzy control law, which has analytical formulas, and hence controller architects can be adequate to represent FBFC in real time systems [15].

The shape of membership function plays key role in the design of fuzzy controller. Large amount of studies is focused on triangular/trapezoidal membership functions because of their idealized properties [16]. The GMFs are quite popular in the fuzzy logic literature. The GMFs have smooth and continuous derivatives which makes the mathematical analysis of it more tractable and simpler than any other type of membership functions. Representation of GMFs is also simple as it only needs two parameters, whereas other membership functions need more parameters to represent. The reduced number of parameters results into reduced Degree of Freedom (DOF) and hence gives a more robust fuzzy controller. GMFs guarantee a continuous control surface regardless of the type-reduction and de fuzzification method used. Experimental results show that when the rule base is small GMFs are faster [17]. Further, from statistical point of view Gaussian membership function can better fit one's imagination. The thought process of human being is logically characterized as normal distribution. Analytical structures of fuzzy controllers are required to be known for precisely understand why and how fuzzy controllers work [18]. Furthermore fuzzy controllers in real-time control often apply the Gaussian membership function [19,20]. Study on fuzzy controller using Gaussian membership function has noticeable importance. Therefore, the essential goal of this paper is to un- cover the scientific model of straightforward F-PI controller utilizing GMFs and demonstrate its adequacy over conventional PI controller, F-PI controller utilizing triangular membership functions as well. The out- comes displayed in this paper are critical and helpful to the control group.

2. THE TYPICAL FUZZY PI CONTROLLER

The design of basic fuzzy logic controller has three stages namely, an input stage; fuzzification (1), a processing stage; rule evaluation (2) and the output stage; defuzzification (3) as shown in Figure 1. The proposed F-PI controller has two inputs and one output. The two input variables are error and error rate (i.e. change of error) of system output with respect to set point. They are calculated as follows:

$$\left.\begin{aligned} e(nT) &= SP(nT) - y(nT) \\ r(nT) &= e(nT) - e(nT-T) \end{aligned}\right\} \quad (1)$$

where; n is positive integer, T is sampling period and SP is set point. $e(nT), r(nT)$ and $y(nT)$ are error, error rate and process output respectively. Each input is thus fuzzified into two fuzzy variables namely Positive Big (PB) and Negative Big (NB). The analytical structure of simplest F-PI controller is discussed below.

The discrete-time version of classical PI controller is,

$$uPI(nT) = Kp.r(nT) + Kr.e(nT) \quad (2)$$

where; $r(nT)$ is the error rate and $\Delta uPI(nT)$ is the incremental control output is based on Eq. (2). The error and error rate are the inputs to the F-PI controller to get the corresponding output $\Delta uPI(nT)$. Further, in order to prove the effectiveness of Gaussian membership functions in design of a fuzzy controller, we have chosen Gaussian membership functions in contrast with traditional membership functions such as Triangular, Trapezoidal. The GMF can be expressed in general by equation 3, as shown below,

$$f(x, c, \sigma) = exp^{-(x-c)^2/(2.\sigma^2)} \quad (3)$$

where; 'σ' determines the shape of the curve (curvature) and 'c' locates the center of the curve, respectively.

The two Gaussian membership functions have the centers at '-L 'and 'L' respectively with 'σ' value is chosen as 'L/1.15', to achieve 50% overlaps with neighboring membership function as per general design guidelines of FLC's These membership functions are usually defined over the range (-∞ to ∞), where; the range [-L, L] indicates the range with design parameter L, as shown in Figure 2 and Figure 3. The out- put singleton membership functions used are as shown in Figure 4. The controller structure has been derived using control rules expressed in Table 1, and Zadeh Fuzzy logic AND with 'Centroid Defuzzifier' in evaluating the output of rules. The mathematical representation of membership functions for both Gaussian as well as Triangular is defined as given in Table 2 and Table 3.

The output is calculated using centroid Defuzzifier defined by equation 4;

$$\Delta u(nT) = \frac{\sum_{i=1}^{4} \Delta ui.\mu i}{\sum_{i=1}^{4} \mu i} \quad (4)$$

The new output of F-PI controller at $(n+1)T$ is given by,

$$u(n+1)T = u(nT) + \Delta u(nT) \quad (5)$$

Table 1: Rule Base Table

Rule	$e(nT)$	$r(nT)$	$\Delta u(nT)$
R1	NB	NB	ONB
R2	NB	PB	OZ
R3	PB	NB	OZ
R4	PB	PB	OPB

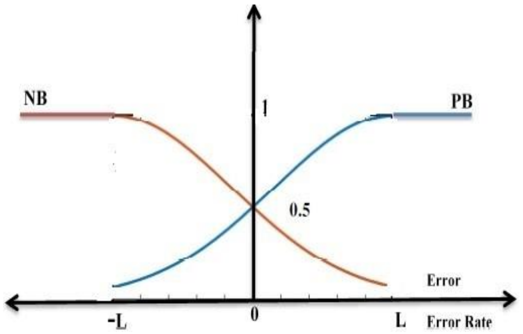

Fig. 2. Input Gaussian Membership Function

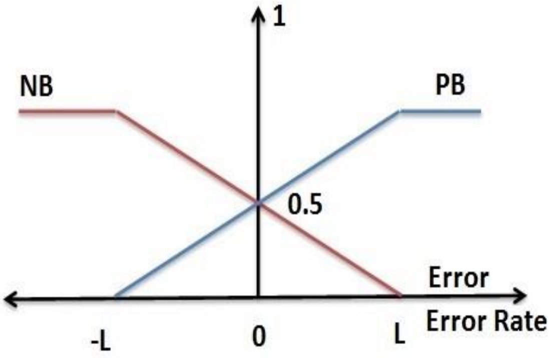

Fig. 3. Input Triangular Membership Function

3. DERIVATION OF ANALYTICAL STRUCTURE

The basic structure of F-PI controller has simple analytical formulas obtained by considering two Gaussian fuzzy sets on each input variable and three singleton fuzzy sets on output variable. The stepwise procedure for obtaining the formula is given below,

- Define the Universe of Discourse (UoD) L.
- Calculate $e(nT)$ and $r(nT)$ nth sampling instant using equation 1.
- Multiply it with respective gains ke and ker, which becomes $Ke(nT), Kr(nT)$ where, $ke(nT) = ke.e(nT)$ and $Kr(nT) = ker.r(nT)$.
- Evaluate the respective membership values eNB, ePB, rNB and rPB for each of them using equations given in Table 2.
- Apply the rules from rule base given in table 1, in the form of 'if - then - else' and use Zadeh 'MIN' operator.
- Evaluate the formula using 'Centroid Defuzzifier' given by equation 4.

Table 2: Gaussian Membership Function Definition

-	Error	Error Rate
Negative	$\boldsymbol{eNB = exp^{-\left(\frac{(Ke+L)^2}{2(L/1.15)^2}\right)}}$	$\boldsymbol{rNB = exp^{-\left(\frac{(Kr+L)^2}{2(L/1.15)^2}\right)}}$
Positive	$\boldsymbol{ePB = exp^{-\left(\frac{(Ke-L)^2}{2(L/1.15)^2}\right)}}$	$\boldsymbol{rPB = exp^{-\left(\frac{(Kr-L)^2}{2(L/1.15)^2}\right)}}$

Table 3: Triangular Membership Function Definition

-	Error	Error Rate
Negative	$\boldsymbol{eNB} = -\frac{1}{2L}Ke + \frac{1}{2}$	$\boldsymbol{rNB} = -\frac{1}{2L}Kr + \frac{1}{2}$
Positive	$\boldsymbol{ePB} = \frac{1}{2L}Ke + \frac{1}{2}$	$\boldsymbol{rPB} = \frac{1}{2L}Kr + \frac{1}{2}$

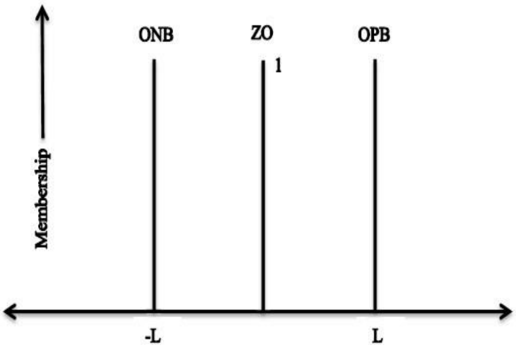

Fig. 4. Output fuzzy Membership Functions

Thus, the analytical structure using the assumptions stated in section 2 for various Input Combination (IC) regions shown in Figure 5 and Figure 6, is given in Table 4, Table 5 and Table 6 respectively. This is the generalized structure and it is applicable to Triangular membership functions also. There are such 44 different formulae; representing each IC region and acting as variable gains for the proposed controller. The flow chart given in Figure 6 illustrates the exact working of the proposed F-PI controller.

4. COMPUTER SIMULATIONS

In order to illustrate the effectiveness of the proposed F-PI controller, computer simulations were per formed on various complex processes such as Second Order Process with Dead Time (SOPDT), Conical Tank System and Non-Minimum Phase System. These simulations are performed for set-point tracking and for disturbance rejection at a certain time interval so as to confirm the transient behavior of the above mentioned process. The conventional PI controller is tuned using traditional Ziegler-Nichols tuning method. The different fuzzy constants used in the proposed controller are tuned manually. The comparison has been made between analytical F-PI controller designed using Gaussian input membership functions, Triangular input membership functions with conventional PI controller. In order to depict the improvement in performance; the parametric comparison along with the performance indices is also given in Table 6.

Table 4: Formulae for Region 1, 2

Cell No	Region 1	Cell No	Region 2
11,12,13,14	$\frac{L \times (rPB - eNB)}{2(eNB) + 1}$	21,22,27,28	$\frac{L \times (rPB - eNB)}{2(eNB) + 1}$
15,16,17,18	$\frac{L \times (rPB - eNB)}{2(rPB) + 1}$	23,24,25,26	$\frac{L \times (ePB - rNB)}{2(rNB) + 1}$

Table 5: Formulae for Region 3, 4

Cell No	Region 3	Cell No	Region 4
31,32,33,34	$\frac{L \times (ePB - rNB)}{2(rNB) + 1}$	41,42,47,48	$\frac{L \times (rPB - eNB)}{2(rPB) + 1}$
35,36,37,38	$\frac{L \times (ePB - rNB)}{2(ePB) + 1}$	43,44,45,46	$\frac{L \times (ePB - rNB)}{2(ePB) + 1}$

Table 6: Formulae for Region 5, 6

Cell No	Region 5	Cell No	Region 6
51,52	$L \times rPB$	61	L
53,54	$L \times ePB$	62	0
55,56	$-L \times rNB$	63	-L
57,58	$-L \times eNB$	64	0

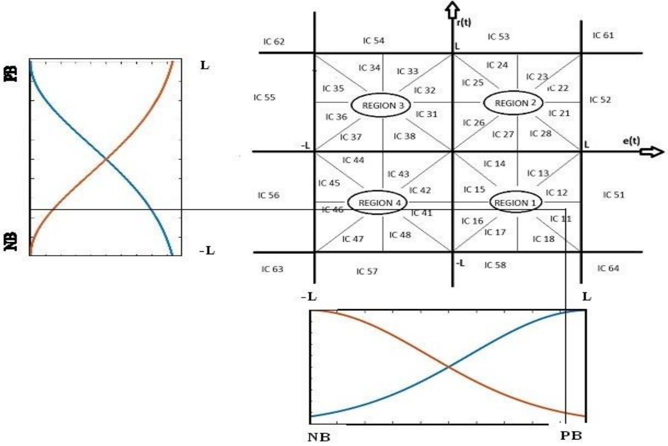

Fig. 5. Distribution of regions with Gaussian Membership Functions

4.1 Second Order Process with dead Time (SOPDT)

Dead time, transportation lag, time delays are very common in industrial process; hence the plant model SOPDT is considered for illustration of controller performance. The model transfer function is given by,

$$Gp1(s) = \frac{e^{-6s}}{2s^2 + 3s + 1} \tag{6}$$

from figure 7 it can be noted that, for SOPDT process, proposed F-PI Controller using Gaussian MF's shows slightly better performance than F-PI Controller using Triangular MF's and Conventional PI controller as well.

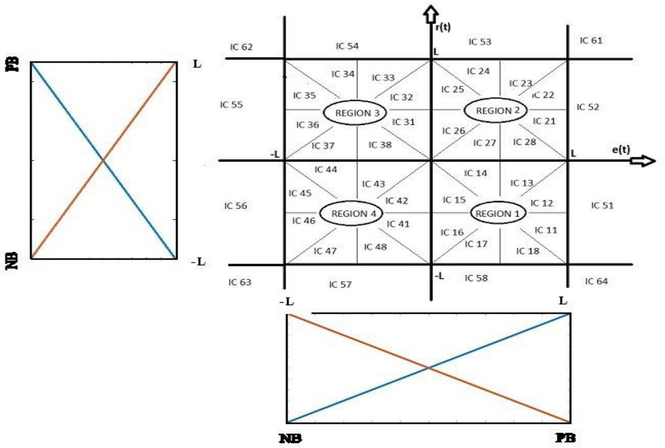

Fig. 6. Distribution of regions with Triangular Membership Functions

4.2 Conical Tank System

Benchmark problems of three tank water level control [21], interacting and Non-interacting tank level control, Conical tank level control, continuously stirred tank (CST) process [22] etc. have always attracted the researchers to prove the effectiveness of their proposed control structures. Here Conical Tank System is a nonlinear system which is broad at upper end and becomes narrow at lower end is considered for illustration. These two tanks are non-interacting tanks. They are connected in series signifying second order system. Figure 8 shows the physical arrangement of noninteracting conical tank system. The inlet flow of the tank 1 is F_{in1}. H_1 represents the total height and h1 represents the actual level of the tank 1. Similarly, the inlet flow of the tank 2 is represented by Fin2 and the outlet flow from tank 2 is F_{out}. H_2 represents the height and h_2 represents the level of the tank 2. MV_1, MV_2 and MV_3 represent the rotameters attached to the tanks. The specifications of the system considered while deriving the transfer function are as below [3].

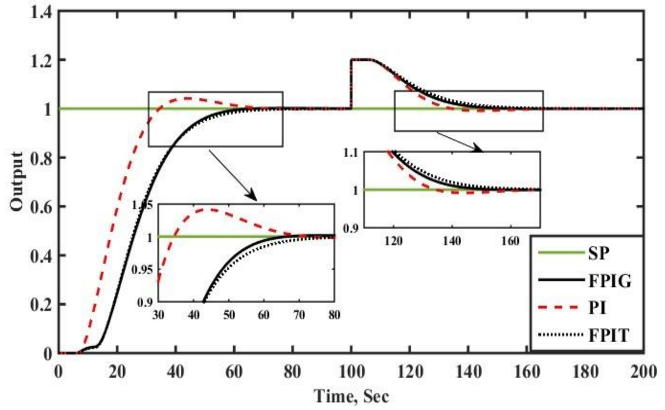

Fig. 7. The Controller Response for Second Order Process with dead Time

– R, Top radius of the Conical tank = 17 cm.
– H, Maximum height of the tank 1 and tank 2 = 70 cm.
– $Fin1$ and $Fin2$, Maximum inflow for tank 1 and tank 2 = 500 LPH.
– $Cv1$ and $Cv3$, Valve coefficient of $Mv1$and $Mv3$= 14 (1 inch).
– $Cv2$ = Valve coefficient $Mv2$ = 11(3/4 inch).

thus, final transfer function of conical tank system becomes,

$$Gp2(s) = \frac{0.0207}{626.5352s^2 + 50.2932s + 1} \tag{7}$$

The system performance to set-point tracking and disturbance rejection are shown in figure 9 and figure 10 respectively.

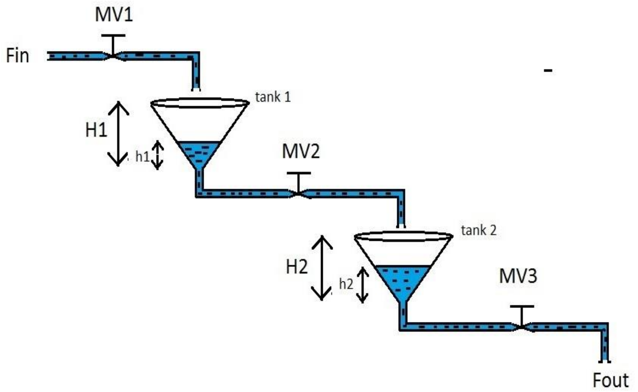

Fig. 8. Schematic Representation of Conical Tank System

4.3 Non-Minimum Phase or Inverse Response Process

In process industry, many processes like drum boiler, distillation column etc. exhibit inverse response behavior i.e. when a step is given, initially they show the response opposite to outcome. This is due to the odd number of right-half-plane zeros. Control of such processes becomes challenging. Such systems are also known as Non-minimum phase systems. Non-minimum phase systems are slow in response because of their inverse behavior at the start of the response.

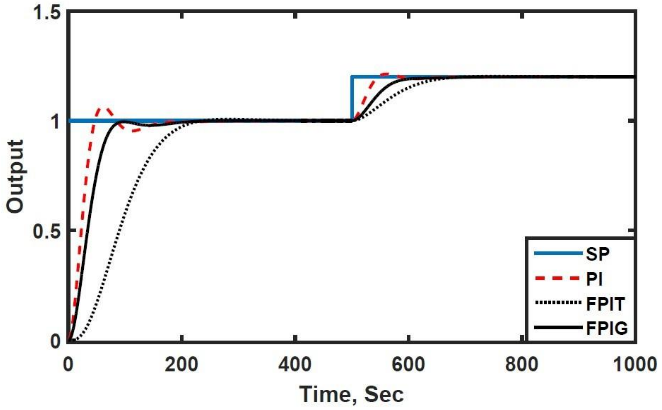

Fig. 9. Set point Tracking Response of Conical Tank System

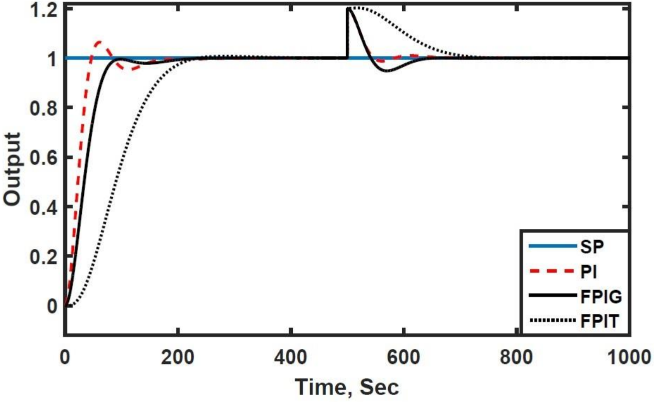

Fig. 10. Disturbance Rejection Response of Conical Tank System

The model transfer function of such a system is given by,

$$Gp3(s) = \frac{-1.4s^2 + 1}{s^3 + 3s^3 + 3s + 1} \tag{8}$$

Figure 11 and figure 12, shows the controller performance to set-point tracking and disturbance rejection mode respectively.

4.4 Heat Exchanger System

Figure 13 shows the physical structure of Heat Exchanger (HE) system designed and manufactured in the process laboratory. Model of the system was identified using 'ident' toolbox of MATLAB. The transfer function model was estimated using the toolbox. Equation 9, gives estimated model of the heat exchanger system,

$$Gp4(s) = \frac{0.06474s \ + \ 0.000517}{s^2 + 0.02383s + 5.78e^{-05}} \tag{9}$$

The F-PI controllers (Gaussian and Triangular MF) so developed are applied to the process model, obtained by data driven model identification technique. The response of the system to conventional PI controller and F-PI Controller using Gaussian input membership functions (FBFC-G) along with the F-PI controller using triangular ones (FBFC-T) is shown in the figure 14. The transient response specifications of all the four models are collectively given in Table 6 for comparative analysis. It can be noticed that the pro- posed F-PI controller shows superior performance as compared with its conventional counterpart.

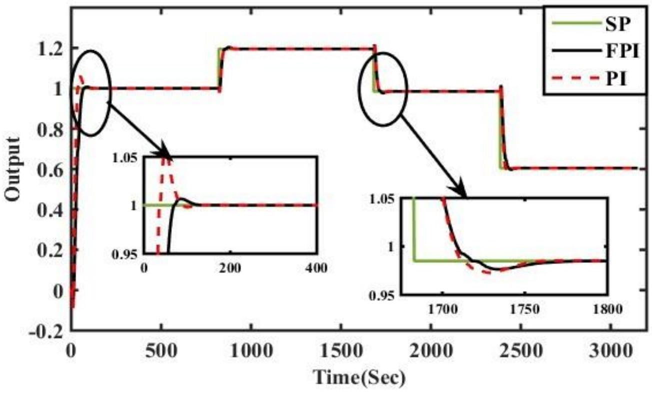

Fig. 11. Set point Tracking Response of Non-Minimum Phase System

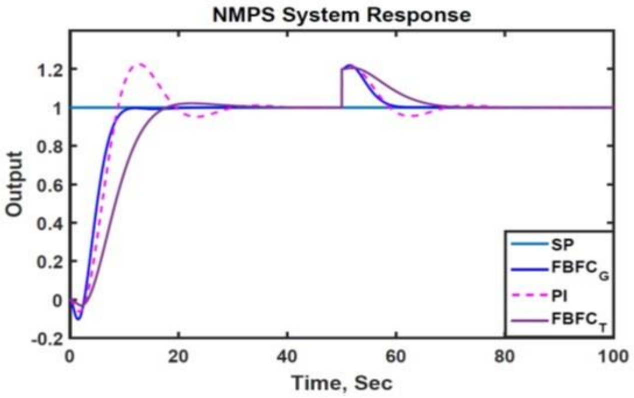

Fig. 12. Controllers' Response to Disturbance against Non-Minimum Phase System

5. STABILITY ANALYSIS

In this section, the relative stability of the controller is confined through computer simulation based on the research reported by Kim and Tahk [23,24]. For stability study, the block $K.e^{-sTd}$ is added just before actuator. where, K is gain multiplying factor and T_d is time delay for system being unstable. If the system shows GM > 0, the close loop system is stable, GM > 6, we can double the gain without the system being unstable and PM > 30, the system is stable. The case study, of the Non-Minimum phase system, $Gp(s) = \frac{-1.4s^2+1}{s^3+3s^3+3s+1}$, for increasing gain the system started oscillating at an additional gain of 2.64 and Similarly keeping K=1, with total 8 samples delay @ 2.5ms/sample, the system started oscillating at 97.85Hz after 44.38 Sec. This gives the GM = 8.4 dB, and PM = 587.1 deg. The results are consistent for other systems as well.

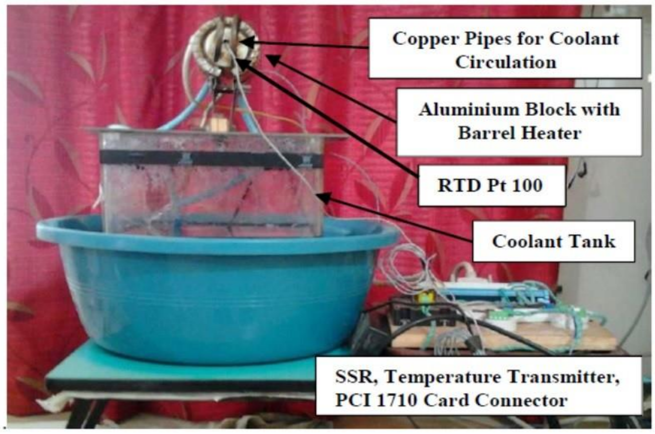

Fig. 13. The Actual Experimental Set-up.

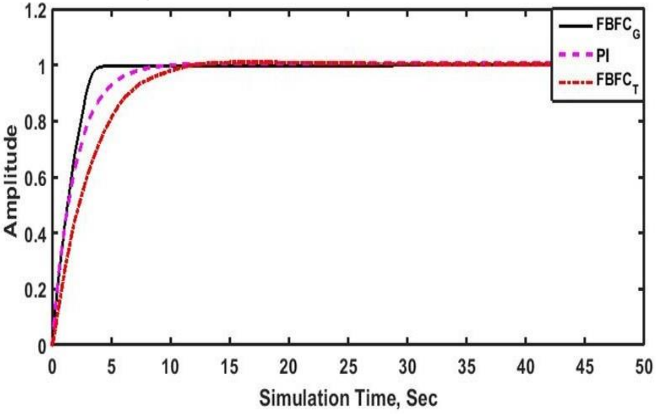

Fig. 14. Step Response of the Heater Exchanger System

6. CONCLUSION

In this paper, a proposed approach of deriving analytical structures for F-PI Controller using Gaussian membership functions (GMFs) was presented. Further the adequacy of the proposed method over F-PI controller utilizing triangular membership function the controller is derived to control the nonlinear processes. It is important to mention that the proposed controller has the characteristics of a nonlinear controller with time varying gains. It could be noted that the proposed controller can successfully be applied to systems such as SOPDT, Conical Tank System and non-minimum phase with careful tuning of fuzzy parameters. It is further observed that controller is much suitable for the systems whose dynamics is not known or poorly known. To verify the usefulness and effectiveness of the proposed controller computer simulations on above mentioned systems were carried out. Since the control law has analytical form and the fuzzy rules are also small, the controller can be effectively implemented in real time with a very less computational burden. Finally, when compared with F-PI controller using triangular input fuzzy membership functions, the proposed structure using Gaussian membership function exhibits superior performance. As a future work, we plan to derive the analytical structure of F-PI controller with hybrid input membership functions like 2 Gaussian and 1

Triangular (2G1T) or 2 Triangular and 1 Gaussian (2T1G) and test its effectiveness.

Table 6: Transient response specifications for unit step change in set point

Sr. No	System Transfer Function	Controller Type	Rise Time t_r (s)	Settling Time t_S (s)	Overshoot (%)	IE	IAE	ISE
1	G_P 1	**PI**	13.73	51.20	5.78	11.64	17.86	10.18
		F-PI	21.16	64.67	2.49	10.25	15.17	10.57
	% Change		35	-20.82	56.99	11.94	15.06	-3.68
2	G_P 2	**PI**	3.13	27.09	5.97	24.78	27.81	16.91
		F-PI	6.92	26.90	0.90	53.84	60.63	36.28
	% Change		54.76	19.00	84.92	-53.97	-54.13	-53.39
3	G_P 3	**PI**	43.73	299.13	22.49	4.83	7.85	5.48
		F-PI	38.08	174.65	0.35	6.02	6.034	4.91
	% Change		-12.92	41.61	98	-19.76	23.13	10.40
4	G_P 4	**PI**	7.48	26.47	0.11	1.41	2.36	0.96
		F-PI	4.32	15.49	0.04	1.47	1.50	0.90
	% Change		-35	41.48	56.99	-4.08	36.44	6.25

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AUTHOR PROFILES

Arun D. Sonar (Limgaokar) completed his BE and ME from S.G.G.S Institute of Engineering & Technology, Vishnupuri, Nanded in 1994 and 1998 respectively. He is pursuing Ph.D in Instrumentation Engineering Department at S.G.G.S Institute of Engineering & Technology, Nanded. He has published eight papers in National and International Journals. He is life member of professional bodies like ISOI, ISTE and SSI. His areas of interest are Process Control, Fuzzy Logic, Real time Process Control and Biomedical. Presently working as an Associate Professor in Instrumentation Engineering Department at Dr. D. Y. Patil Institute Technology, Pimpri, Pune-18 Conferences. He was member BOS in Mechatronics for Savitribai Phule Pune University, Pune. He is Fellow of Institution of Engineers (India), India.

Rajan H. Chile completed his BE and ME from S.G.G.S Institute of Technology, Vishnupuri, Nanded in 1987 and 1992 respectively. He received his Ph.D form University of Roorkee (Now IIT, Roorkee) in the year 1999. He has published 100 plus research papers in National and International Journals and Conferences. He is a recipient of Late Padmashree S.M. alias Annasaheb Beharay Ideal Teacher award. He is member BOS at Shivaji University Kolhapur and Solapur University, Solapur. He is a life member of professional bodies like ISTE, ISOI etc. His areas of interest are Process Control, Advance Process Control, Control Engineering, Adaptive control and its applications to Process Industries. Presently working as Professor in Instrumentation Engineering Department at S.G.G.S Institute of Technology, Vishnupuri, Nanded.

B. M. Patre completed his BE and ME from S.G.G.S Institute of Technology, Vishnupuri, Nanded in 1986 and 1990 respectively. He received his Ph.D form IIT, Bombay in the year 1998. He has published more than 100 research papers in National and International Journals and Conferences. He has 03 Books and 04 Book chapters to his credit. He was Governing Council Member, Instrument Society of India, Bangalore during 2010-2012. He is Fellow of Institution of Engineers (India), Member of IEEE (USA), Member of IET (formerly IEE), Member of Institution of Electronics and Telecommunication Engineers (MIETE), New Delhi. Life Member of Indian Society for Technical Education (LMISTE), New Delhi, Life Member of Instrument Society of India, Member of International Association of Engineers (IAENG). He is member BOS at North Maharashtra University, Jalgaon. He is regular reviewer of many referred international journals of IEEE, IETE, ISA, Elsevier, Springer, Taylor and Francis etc. His areas of interest are Process Control, Advance Process Control, Control Engineering, Sliding mode control etc. Presently working as Professor in Instrumentation Engineering Department at S.G.G.S Institute of Technology, Vishnupuri, Nanded.