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Fuzzy and Taguchi based Fuzzy Optimization of Performance Criteria of the Process Control Systems

Fatih Kara[1], Vedat Arda Küçük*[1], Barış Şimşek[1]

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Abstract: This paper proposes a Taguchi based Fuzzy and Fuzzy PID application using MATLAB® version 2015a to assess and optimize of process control performance criteria of liquid level and flow rate control system. When the main effect graphs for the liquid level and flow rate control system are evaluated, it was seen that the change in the membership function is the most effective factor on the process control performance. It can be said that the Gaussian membership function provides the lowest mean and standard deviation in the offset value. Improvement rates for "overshoot", "rise time", "first peak time", "%95 setting time, "%99 setting time", "mean" and "the standard deviation of the offset values" are %50, %50, %55, %77, %64, %5, %63 for flow rate control system; %50, %49, %55, %43, %48, %4, %63 for liquid level control system in order. In comparison with the classical PID method, in the Fuzzy PID method, the improvement is calculated as 54% in the average of the offset value and 99% in the standard deviation.

Keywords: *Fuzzy PID, Fuzzy Logic, Taguchi Optimization, Process control, Design of Experiments, DoE*

1. Introduction

This Proportional–integral–derivative control (PID control) is a reliable, efficient control method and it is one of the most preferred control strategy in the industrial applications [1]. PID control has wide range of applications. It is used to control the hypnosis depth in anesthesia [2] the temperature in friction stir welding process [3], the dynamic behavior of heat exchanger [4], the temperature of a solar furnace [5], vibration in a building structure [6], chamber pressure in a coke furnace [7], temperature in a surfactant reactor [8], power in lead cooled fast reactor [9], power in perturbed pressurized heavy water reactor [10]. The PID control is widely used due to the low hardware costs. Time-varying and non-linear effects can lead to failure in PID control performance [11]. Fuzzy Logic is one of the techniques used to eliminate this disadvantage of PID controllers [12]. Fuzzy PID methods are used in various control applications ranging from single-input single-output systems to multi-input multi-output systems such as optoelectronic stabilization platforms [13], robotic manipulators [14], air handling units [15], docking maneuver of two spacecraft [16], steam turbines [17], ball-beam systems [18], and temperature of the heating furnaces [19]. Studies involving the application of Fuzzy PID method are usually determination of PID parameters in the form of membership functions [20, 21]. Experimental design and Taguchi designs are often used for increasing the level of process robustness, performing statistical analysis of the criteria that represent process efficiency, determining effective factors on the selected responses, and determining the most appropriate factor levels to optimize the selected criteria. Taguchi design is not practiced with Fuzzy PID control techniques.

This paper proposes a systematic methodology contains Taguchi design based Fuzzy, PID and Fuzzy PID (FPID) tools to evaluate and optimize the laboratory scale liquid level (LLCS) and flow rate control systems (FRCS). This study includes three novelties as listed below:

a. Taguchi design based Fuzzy, PID and Fuzzy PID tools have been applied to the commonly used control systems such as LLCS and FRCS for the first time in the literature.
b. Control performance the Fuzzy, PID and Fuzzy PID tools have statistically compared for the first time in the literature.
c. The difference in membership functions which has affected on the process control performance criteria have been analysed using Taguchi method.

2. Materials and Method

2.1. Materials

LLCS consists of differential pressure sensor, recorder, controller, pneumatic proportional valve, control buttons, on-off valves (Figure 1). The height of the test cylinder is 75 cm. Liquid level in the test cylinder was measured with Differential pressure sensor; which measures the pressure difference between the high and low pressure inputs, giving a result of 4-20mA or 0-10V. There are three channels in the recorder, "Level", "Valve Position" and "Valve Reference". The PID controller; regulates proportional valve either with P, PI or PID modes. P,I, and D parameter values of the controller can be assigned manually or automatically calculated by the PID controller's Auto-Tune feature. Pneumatic proportional valve was used in the liquid level control system as the last control element. In the flow rate control system, unlike the liquid level control system, the electric proportional valve is used as the last control element. Pneumatic proportional valve and electric proportional valve consists of a positioner, actuator and 1 inch global valve.

[1] *Çankırı Karatekin University, Faculty of Engineering, Department of Chemical Engineering, Çankırı– 18100, TURKEY*
* *Corresponding Author: Email: ardakucuk@karatekin.edu.tr*

Fig. 1. a) LLCS, b) differential pressure sensor, c) recorder, d) process controller and e) FRCS

2.2. Taguchi Based Fuzzy Logic

Number The Taguchi method is an experimental design technique that uses orthogonal matrices as experimental design matrices and takes into account only linear effects. Performing the experiments with the experimental design method allows to use the statistical methods to analyse the experimental results. In this study, the membership functions of input and output parameters were determined by fuzzy logic and the rules for fuzzy logic were written by Taguchi experiment design. Fuzzy rules, ("IF-THEN" statements) were used to model the system status. The method adopted in this article is summarized as follows. First, the input variables are divided into a number of subgroups by the simple trapezoidal type fuzzy membership functions of the according to the Taguchi orthogonal arrays. Responses representing process control performance are divided into a number of subgroups with simple trapezoidal fuzzy membership functions. An example is given to better illustrate the method used in this study. For example, there are two input variables X1, very small and small fuzzy sub-sets, and two sub-sets, X2, medium and large, can be written as some rules. *If R1, X1 is "too small" and X2 is "medium" THEN Y1*

2.3. Taguchi Based Fuzzy PID Control

Basically, a process can be expressed by the following first-order process model [11];

$$G_P = \frac{K}{\tau s+1} \quad (1)$$

Matlab® version 2015a was used to determine the PID (Proportional gain, integral gain, derivative gain is tuning parameter which is symbolized as K_c, τ_I and τ_D) parameters in the experimental matrix created by the optimum Taguchi design [22]. The Fuzzy PID (FPID) process control diagram of the liquid level system using the Matlab Simulink tool is shown below (Figure 2).

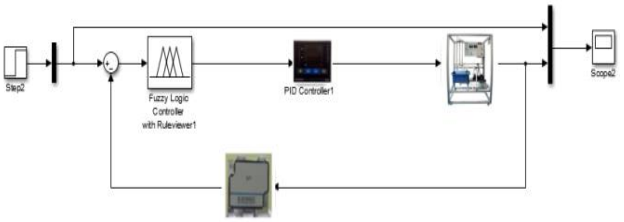

Fig. 2. FPID control system diagram

FPID is basically an application for blurring PID parameters [11, 23]

3. Methodology

In order to compare the performances of the PID, Fuzzy and FPID control strategies in the liquid level and flow rate control system, the following steps were followed (Figure 3)

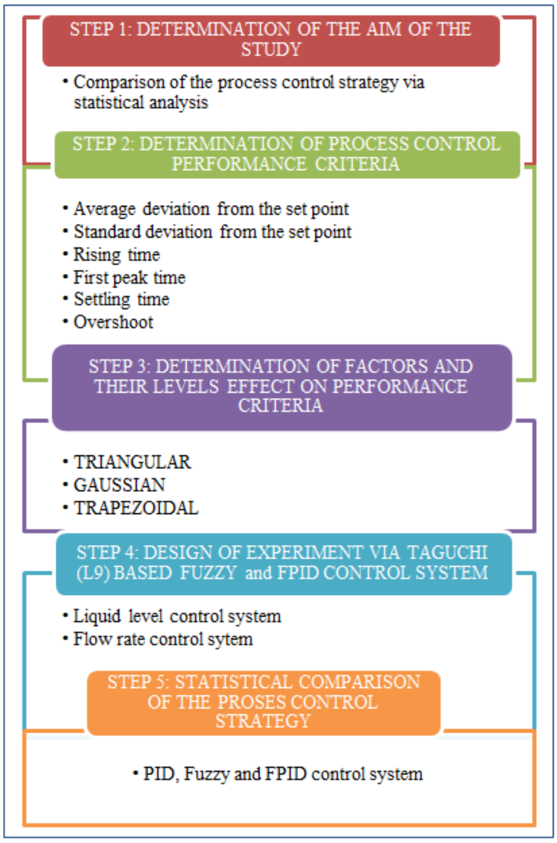

Fig. 3. Proposed methodology

4. Factors and Responses

4.1. Performance Criteria

The performance criteria of the PID, Fuzzy and FPID control strategies in the liquid level and flow rate control system are shown in Table 1. Minimization of all responses is preferred.

Table 1. Performance Criteria

Quality Feature	Sign	Definition
1	R1	Overshoot
2	R2	Rise time (s)
3	R3	First Peak Time (s)
4	R4	Setting time (s) 95%
5	R5	Setting time (s) 99%
6	R6	Mean of the offset values (cm)
7	R7	Variance of the offset values (cm^2)

4.2. Determination of factors and their levels

Three factors "Level", "Rate", "Valve" are characterized as A, B, C and their three levels are given in Table 2. The factors in this study are liquid level in the tank, change of the liquid in the tank and valve position which is the output controller [23]

Table 2. Factor levels for response surface methodology.

	1	2	3
A (LEVEL)	TRIMF	TRAPMF	GAUSSMF
B (RATE)	TRIMF	TRAPMF	GAUSSMF
C (VALVE)	TRIMF	TRAPMF	GAUSSMF

5. Building Fuzzy Logic Controller

5.1. FIS editor

Mamdani type fuzzy inference system was used in this study for building the predicting process control performance criteria (Figure 4).

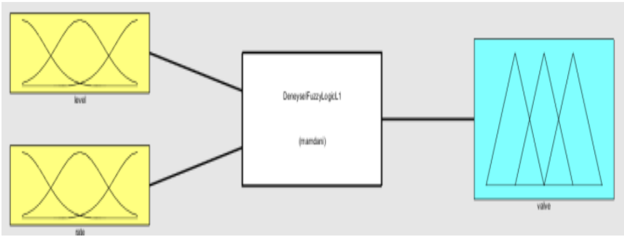

Fig. 4. Mamdani type fuzzy inference

In the proposed method, the factors defining the performance criteria are treated as fuzzy variables. Level and rate was selected as input variables, valve is also selected as output variables. These variables are divided into a number of subsets with simple triangular, trapezoidal and Gaussian membership functions. According to first run, membership functions chosen for level, rate and valve were given in Figure 5, Figure 6, Figure 7 respectively.

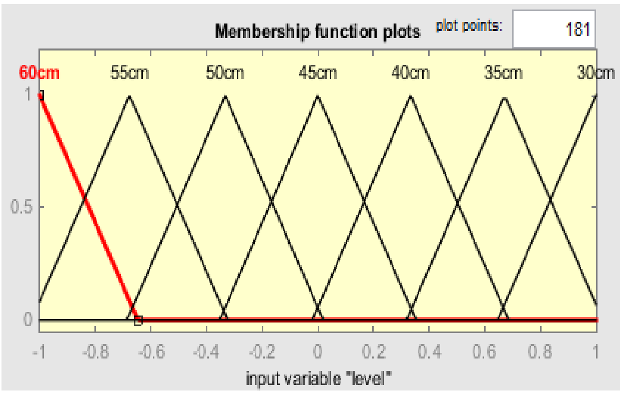

Fig. 5. Membership function plot of "level"

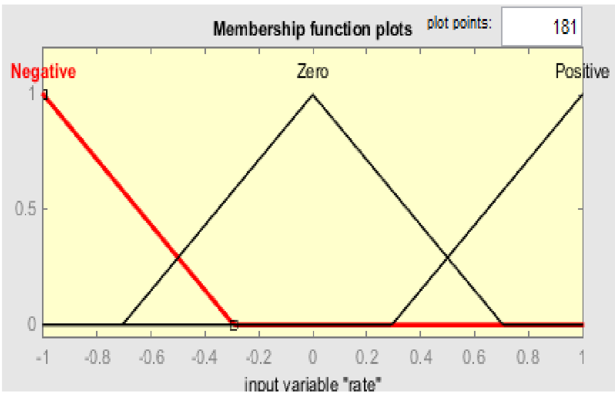

Fig. 6. Membership function plot of "rate"

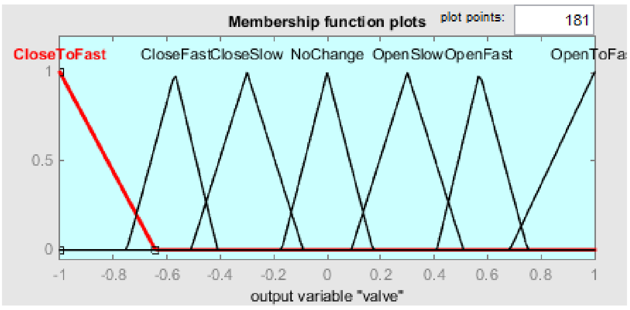

Fig. 7. Membership function plot of "valve"

Twenty one rules were written into the Matlab Fuzzy Rule Editor (Figure 8) considering the results of the experiments and the fuzzy model was completed.

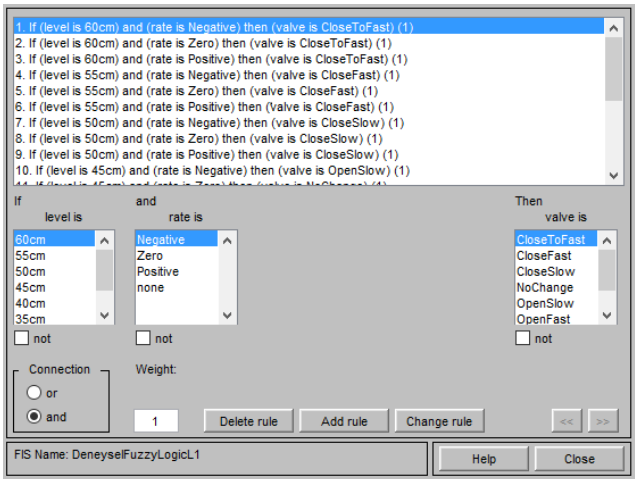

Fig. 8. Matlab Fuzzy Rule Editor and Fuzzy Rules

5.2. Simulink Models

The simulation models constructed for the liquid level and flow rate control systems are shown in Figure 9 and Figure 10. Process models were determined using experimental modeling. The final control element and the measurement element transfer function were set to 1/s and 1, respectively.

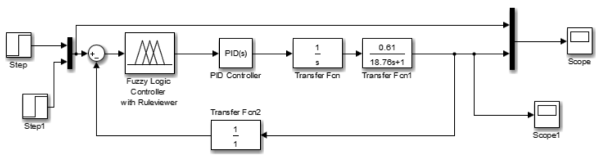

Fig. 9. MLLCS Simulink Diagram

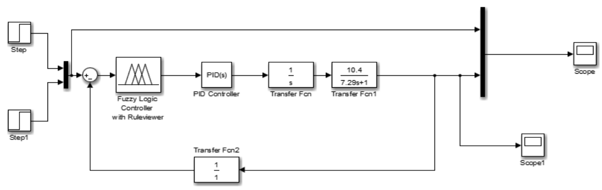

Fig. 10. FRCS Diagram

6. Optimization

In this study a L_9 Taguchi orthogonal array was selected for experimental runs. In Table 3, columns 2–4 represent the three control factors and their levels.

Table 3. L_9 Taguchi Experimental Matrix

No	A (LEVEL)	B (RATE)	C (VALVE)
L1	TRIMF	TRIMF	TRIMF
L2	TRIMF	TRAPMF	TRAPMF
L3	TRIMF	GAUSSMF	GAUSSMF
L4	TRAPMF	TRIMF	TRAPMF
L5	TRAPMF	TRAPMF	GAUSSMF
L6	TRAPMF	GAUSSMF	TRIMF
L7	GAUSSMF	TRIMF	GAUSSMF
L8	GAUSSMF	TRAPMF	TRIMF
L9	GAUSSMF	GAUSSMF	TRAPMF

The experimental results obtained from Matlab Simulink using the fuzzy and FPID control strategies are shown in Figure 11 (FRCS) and Figure 12 (LLCS).

No	R1	R2	R3	R4	R5	R6	R7
FFR1*	82.47	2.48	3.82	39.77	76.88	1.04	0.29
FFR2	82.49	2.47	3.81	41.71	64.44	1.04	0.29
FFR3	80.72	2.55	3.88	39.95	63.93	1.06	0.28
FFR4	100.9	2.31	3.64	106.98	821.00	1.07	0.39
FFR5	108.1	2.27	3.53	806.00	1204.00	1.04	0.32
FFR6	83.58	2.46	3.82	950.00	1375.00	1.04	0.27
FFR7	80.73	2.56	3.92	42.00	66.49	1.07	0.29
FFR8	82.73	2.48	3.84	43.95	71.59	1.05	0.34
FFR9	84.05	2.47	3.84	42.58	65.10	1.07	0.33
FPFR1**	20,89	21,58	44,00	75,07	82,00	1,07	0,08
FPFR2	19,88	20,63	44,00	71,24	78,92	1,06	0,07
FPFR3	24,10	22,85	49,80	81,63	87,28	1,06	0,08
FPFR4	20,49	20,83	40,00	96,00	405,00	1,10	0,06
FPFR5	20,37	21,41	40,00	93,55	380,00	1,08	0,05
FPFR6	11,88	10,93	18,00	746,00	1311,00	1,06	0,02
FPFR7	10,23	11,43	20,00	42,55	74,00	1,03	0,03
FPFR8	10,79	11,67	22,00	44,00	74,00	1,03	0,03
FPFR9[1]	10,35	10,87	20,00	42,77	74,00	1,03	0,03

*FFR: Fuzzy for flow rate control system
**FPFR: Fuzzy PID for flow rate control system
[1]Optimum experiment for flow rate control system

Fig. 11. Performance criteria FRCS.

No	R1	R2	R3	R4	R5	R6	R7
FLL1*	60.82	11.47	20.31	94.00	150.00	1.09	0.24
FLL2	60.72	11.41	20.00	106.00	160.00	1.10	0.24
FLL3	59.42	12.05	20.75	95.23	150.53	1.06	0.21
FLL4	61.34	11.23	19.67	122.59	382.00	1.13	0.25
FLL5	60.22	11.69	20.00	121.12	403.00	1.15	0.25
FLL6	61.61	11.35	19.70	125.10	426.00	1.13	0.25
FLL7	59.23	12.09	20.87	98.00	163.71	1.07	0.23
FLL8	60.68	11.49	20.00	112.00	162.00	1.14	0.26
FLL9	62.35	11.43	20.00	98.14	164.65	1.10	0.24
FPLL1**	20.89	53.95	112.00	190.00	208.00	1.08	0.08
FPLL2	19.96	51.51	108.00	182.00	211.17	1.07	0.07
FPLL3	24.10	57.22	126.00	208.49	223.01	1.08	0.08
FPLL4	21.79	55.63	110.00	232.00	411.00	1.12	0.06
FPLL5	21.53	56.00	108.00	227.55	388.00	1.08	0.06
FPLL6	61.61	100.00	19.70	125.10	896.00	11.23	0.85
FPLL7	10.25	27.84	52.00	108.00	188.00	1.04	0.03
FPLL8	10.80	28.85	54.00	112.00	190.00	1.04	0.03
FPLL9[2]	10.35	27.04	50.00	107.47	190.00	1.04	0.03

*FLL: Fuzzy for liquid level control system
**FPLL: Fuzzy PID for liquid level control system
[2]Optimum experiment for liquid level control system

Fig. 12. Performance criteria LLCS.

Optimum experiment runs were determined with the TOPSIS method, for flow rate and liquid level system found as FPFR9 and FPLL9. The response of the system (LLCS and FRCS) to the one unit step effect is shown in Figure 13 and Figure 14.

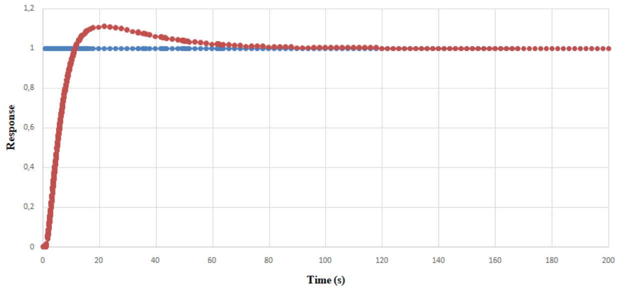

Fig. 13. System response of LLCS

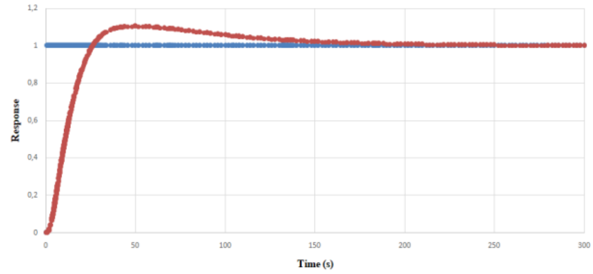

Fig. 14. System response of FRCS

7. Discussion

7.1. Effects of Factors

When the main effect graphs for the flow rate control system are evaluated, it was seen that the change in the membership function is the most effective factor on the FRCS process control performance. It can be said that the Gaussian membership function provides the lowest mean and standard deviation in the offset value (Figure 15-18).

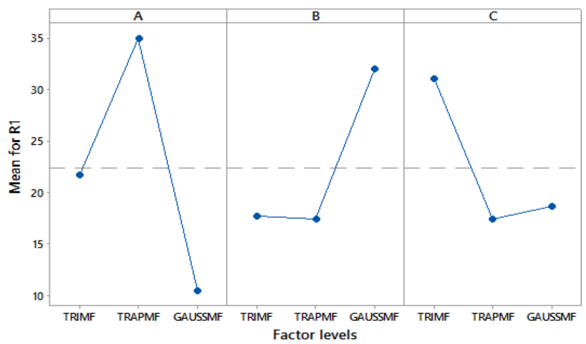

Fig. 15. Main effect plot of R1 (LLCS)

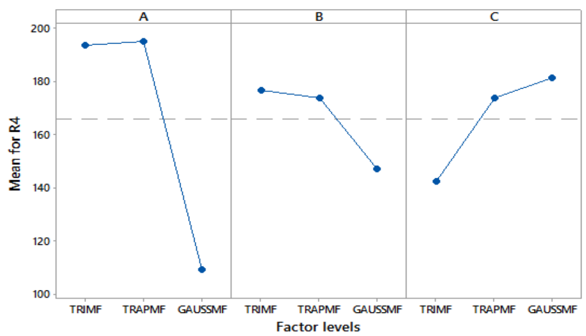

Fig. 16. Main effect plot of R4 (LLCS)

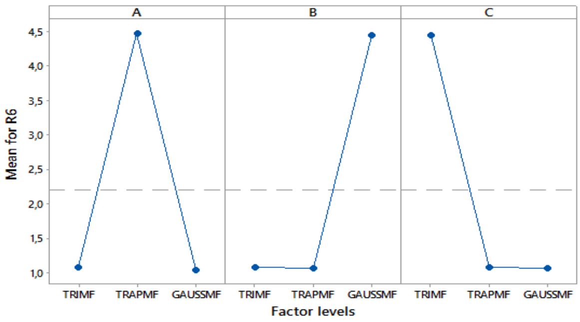

Fig. 17. Main effect plot of R6 (LLCS)

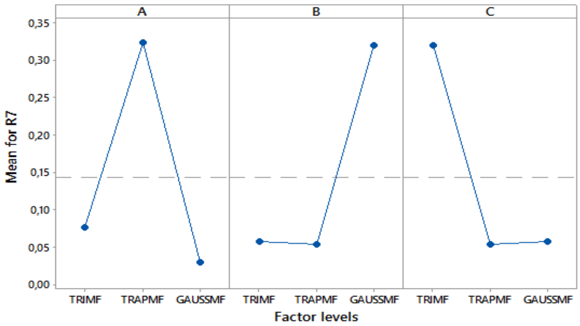

Fig. 18. Main effect plot of R7 (LLCS)

When the main effect graphs for the liquid level control system are evaluated, it was seen that the change in the membership function is the most effective factor on the LLCS process control performance. It can be said that the Gaussian membership function provides the lowest mean and standard deviation in the offset value (Figure 19-22).

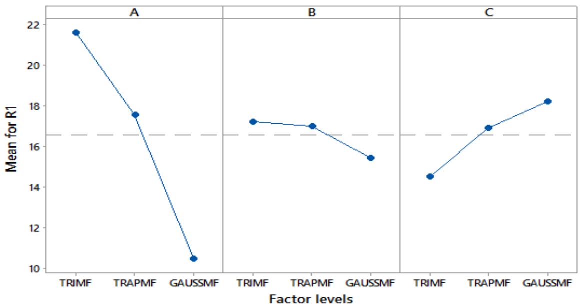

Fig. 19. Main effect plot of R1 (FRCS)

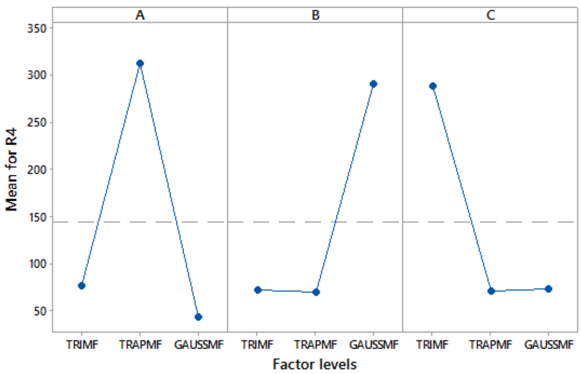

Fig. 20. Main effect plot of R4 (FRCS)

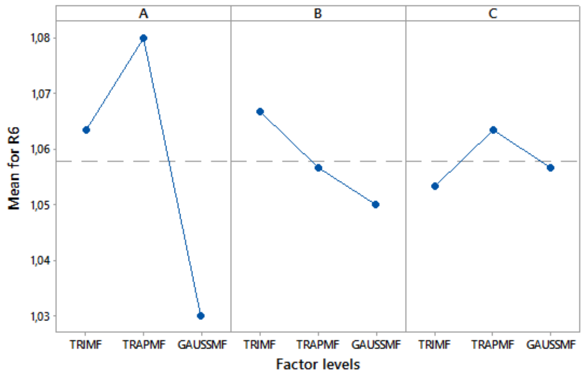

Fig. 21. Main effect plot of R6 (FRCS)

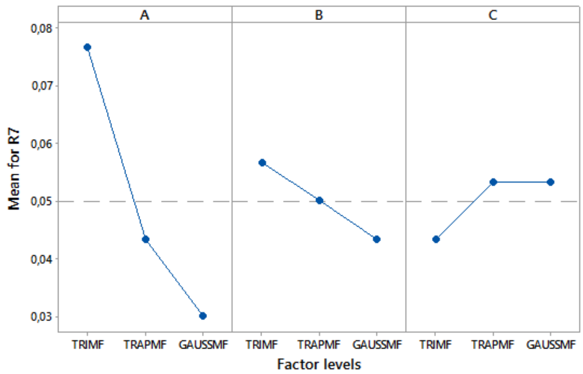

Fig. 22. Main effect plot of R7 (FRCS)

7.2. Improvement Rates

FPR1 and FPLL1 would be selected in the FPID method if the experimental design approach is not used. For this reason, the improvement rates are calculated according to FPR1 and FPLL1 where the experimental design is not performed. Improvement rates for “overshoot”, “rise time”, “first peak time”, “%95 setting time”, “%99 setting time”, “mean” and “the standard deviation of the offset values” are %50, %50, %55, %77, %64, %6, %63 for FRCS; %50, %49, %55, %43, %48, %4, %63 for LLCS in order. Improvement rates can be seen at Figure 23.

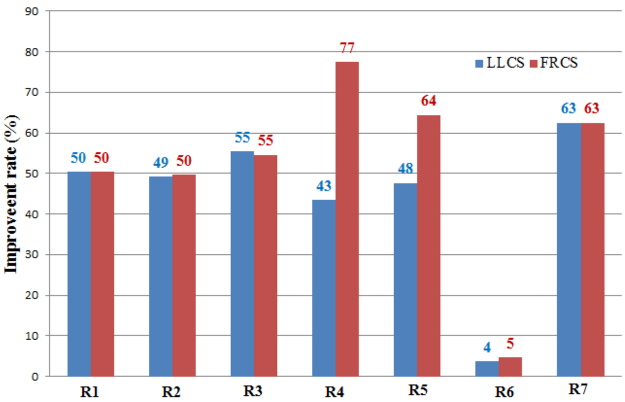

Fig. 23. Improvements rates

7.3. Comparison with PID controller

In comparison with the classical PID method, in the FPID method, the improvement is calculated as 54% in the average of the offset value and 99% in the standard deviation. These results clearly demonstrate the success of the fuzzy method in process control

(Figure 24).

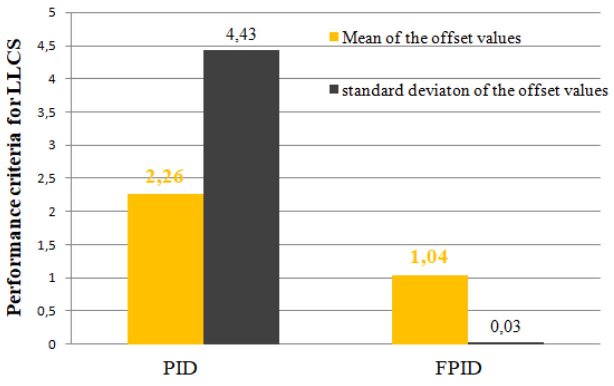

Fig. 24. Improvement rates of controllers

8. Conclusion

In this study; process control performance criteria for the widely used FRCS and LLCS systems were determined by the experimental design method. A total of thirteen factors, each with three levels, were identified. Orthogonal array (a semi-factorial array) L_9 (3^3) was used in the experiments. The results obtained at the end of the study can be summarized as follows:

1. In comparison with traditional PID methods, the improvement rates of the fuzzy control methods (FPID) were found to be 54% in the average offset values and 99% in the standard deviation.
2. In comparison with the initial state where the experimental design is not performed very high improvement rates were obtained.
3. It is seen that the change in membership function is the most effective factor on process control performance both for LLCS and FRCS
4. It can be said that the Gaussian membership function provides the lowest mean and standard deviation in the offset value.
5. It has been determined that FPID is more effective than conventional PID control methods and fuzzy methods.

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