Fuzzy Control of a Heat Exchanger

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***Abstract* - This paper investigates the design method of a fuzzy logic control system for a heat exchanger. A proportional-integrative (PI) controller, tuned using Ziegler-Nichols method, will provide the starting point in the development of the Fuzzy Logic Controller (FLC). First an initial linear FLC is designed which is equivalent to the conventional PI controller, and provides the same performances. Then, by making the FLC nonlinear and by fine tuning it the design stage is completed. To verify the effectiveness of the design procedure, modeling and simulations are done using Matlab-Simulink.**

Keywords- fuzzy control, heat exchanger

I. INTRODUCTION

Heat exchangers are widely used in many industrial applications for exchanging or transmitting heat between various stages in a plant operation. Control of a heat exchanger is a complex process due to its non-linear behavior and complexity caused by many phenomena such as leakage, friction, temperature dependent flow properties, contact resistance, unknown fluid properties, etc.[12,14]. However, most of the time such plants are already controlled by conventional PID (or its derivates) controllers with satisfactory results [6,10,12,14]. Since a PID approach is most of the time available, it could be used in the design stage of fuzzy-PID controllers that are able to perform the same task, as the conventional controllers, and also improve the general performance of the closed loop system, due to their specific structure [4].

FLCs are in essence nonlinear controllers and tuning them proves most of the time difficult. However, their components can be modeled in such a way that they are able to generate the characteristic of all known conventional controllers, including the PID [3,4]. This is a consequence of the fact that fuzzy systems are universal approximators [8,13].

This paper examines the design methodology of a FLC used to regulate the temperature of a chemical reactor through a heat exchanger. The plant model provided in [10] is used as a test bed for the presented algorithms. Based on a fuzzy-PD controller developed in a previous work [3,4] for the control of an unstable electromagnetic levitation device with very fast dynamics, the authors apply the same design method to control a plant with a complete different dynamic behavior, characterized by slow response with time delay.

The design method used to obtain the FLC in this paper follows the next steps:

- a PID-type controller is tuned using Ziegler-Nichols method;
- the equation of the discrete time version of that controller is re-organized so that a PD component is isolated, which is then replaced by an equivalent linear fuzzy logic system;
- by performing heuristic changes to the linear fuzzy logic system, the resulting FLC is made nonlinear and the overall behavior of the closed loop system is improved.

II. CONVENTIONAL CONTROL

A. *The heat-exchanger process*

Consider the heat exchanger shown in Fig. 1. The top inlet delivers fluid to be mixed in the tank. To regulate the temperature of the tank fluid to a desired set point, the amount of steam supplied to the heat exchanger is modified via its control valve. Variations in the temperature of the inlet flow are the main source of disturbances in this process [10,12].

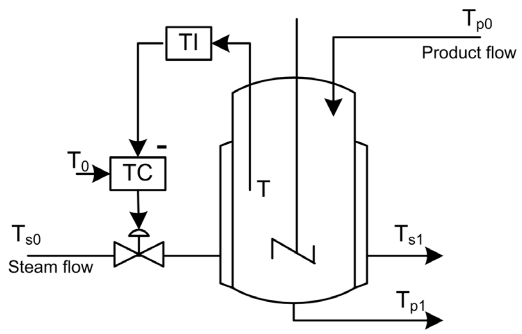

Figure 1. Reactor with heat exchanger

To derive a first-order-plus-deadtime model of the heat exchanger characteristics, a step change in valve voltage V is produced and the effect on the tank temperature T is recorded over time.

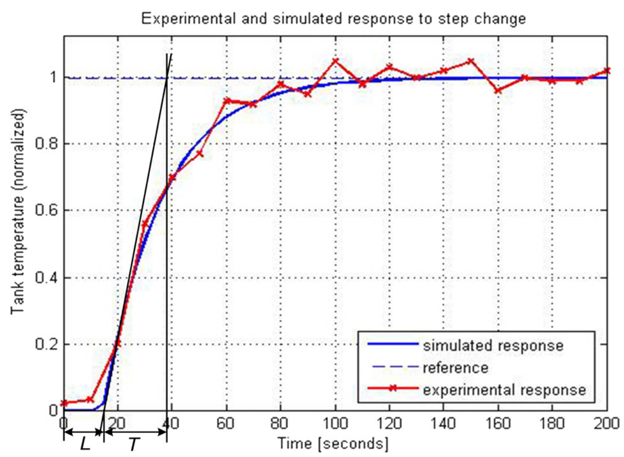

Figure 2. Plant step response

The measured response in normalized units is shown in Fig. 2. The constants in equation (1) can be determined from the step response of the process. If a tangent is drawn at the inflection point of the reaction curve, then the slope of the line is R=1/T, where T denotes the system's time constant, and the intersection of the tangent line with the time axis identifies the time delay L [6].

This type of response shown in Fig. 2 is typical of a first order system with transportation delay, and can be approximated by the step response of:

$$H(s) = \frac{e^{-Ls}}{Ts+1} \tag{1}$$

where L=14.7s and T=21.3s.

B. Design of the controller

The transfer function in (1) models the way a change in the voltage V driving the steam valve opening affects the tank temperature T.

Based on this model and by using Ziegler-Nichols tuning method a proportional-integrative (PI) controller can be derived for the plant, with the following parameters:

$$C(s) = K_C\left(1 + \frac{1}{T_i s}\right) \tag{2}$$

where, the proportional gain K_C and the integral time T_i are computed as follows:

$$\begin{aligned} K_C &= \frac{0.9T}{L} = 1.3 \\ T_i &= 3.3L = 48.5 \end{aligned} \tag{3}$$

Since FLCs require most of the time a digital implementation, the continuous time controller in (2) is digitized with a sampling rate T_s=1s. The resulting discrete time version of the PI controller is given in equation (4)

$$u_n = K_C\left(e_n + \frac{1}{T_i}\sum_{j=1}^{n} e_j T_s\right) \tag{4}$$

where u_n is the output of the controller and e_n is the tracking error.

By considering the incremental version of the discrete time PI controller, equation (4) can be re-written in the form shown in (5)

$$u_n = u_{n-1} + \Delta u_n \tag{5}$$

where Δu_n denotes a PD component:

$$\Delta u_n = K'_P\left(e_n + T'_D\frac{e_n - e_{n-1}}{T_S}\right) \tag{6}$$

and parameters K'_P, T'_D are computed based on K_C, T_i and have the following values:

$$\begin{aligned} K'_P &= \frac{K_C T_S}{T_i} = 0.027 \\ T'_D &= T_i = 48.5 \end{aligned} \tag{7}$$

III. DESIGN OF THE FUZZY CONTROL SYSTEM

A. Design procedure for a linear fuzzy system

Having designed the conventional discrete time controller, an equivalent FLC for the plant can be obtained, by replacing in equation (5) the PD component (6) with a linear fuzzy system [3,4,9].

Generally, fuzzy systems are non-linear systems, having three known sources of nonlinearity: the rule base, the inference engine and the defuzzification method.

It is possible to create a linear fuzzy control structure which acts like the summation in a PD controller, by adequately modeling the system's components. The resulting fuzzy system is a piecewise linear controller similar to the classical proportional derivative (PD) controller [2].

In order to achieve this linear behavior several constraints should be considered:

- for the fuzzification process use symmetric triangular membership functions, overlapped at 50%. A large enough domain should be considered to cover all possible variations of the input parameters;
- use the algebraic product for the *and* connective;
- use singleton membership functions for the output variable, with the position determined by the sum of the peak values of the input sets;
- use the centre of gravity (COG) defuzzification method;
- use a rule base that covers all possible combinations of fuzzy sets for the two input variables [2,3,4,7,9].

With these choices the control surface (input-output mapping) of the fuzzy system degenerates into a plane [7].

Fig. 3 shows the general structure of the considered PDFLC.

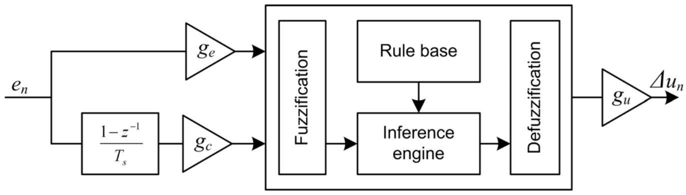

Figure 3. The fuzzy PD system

This system uses the error e_n between the setpoint and the controlled value, and the change in error $c_n=(e_n-e_{n-1})/T_s$ (derivative of the error) as input variables and the variation in command Δu_n as output variable. Three scaling gains, denoted by g_e, g_c and g_u, are assigned for these variables. These gains are used for tuning the response and for scaling the signals onto their universe of discourse to exploit it better.

The other components of the system were designed according to the specifications. That is: each universe of discourse for the input variables was uniformly covered by 5 fuzzy sets denoted by NB, NS, Z, PS and PB. Their corresponding membership functions were triangular in shape, symmetric and two by two the adjacent sets overlap at 50%. For the output variable, nine singletons were used.

Fig. 4 shows the choice for the controller's membership functions.

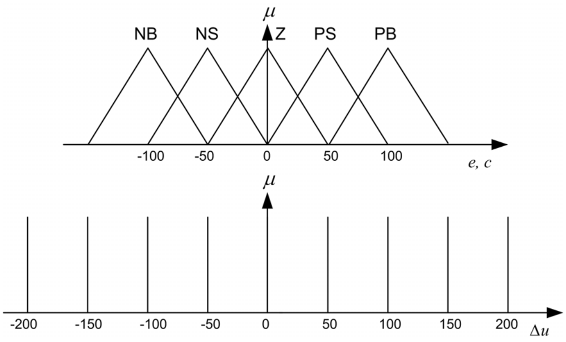

Figure 4. Membership functions and domain for the fuzzy variables in the case of the linear fuzzy system

The rule base which determines the linear behavior of the fuzzy system is summarized in Table I. The rule base is made up of IF-THEN type rules. As seen, their consequences are chosen as the sum of the centers of the input membership functions and cover all possible combinations.

TABLE I. RULE TABLE FOR THE FUZZY-PD CONTROLLER

output: Δu		**input: e**				
		NB	NS	Z	PS	PB
input: c	NB	-200	-150	-100	-50	0
	NS	-150	-100	-50	0	50
	Z	-100	-50	0	50	100
	PS	-50	0	50	100	150
	PB	0	50	100	150	200

Fig. 5 shows the control surface generated by the linear fuzzy system. This system, together with the associated scaling gains will replace the PD component in the final design of the controller.

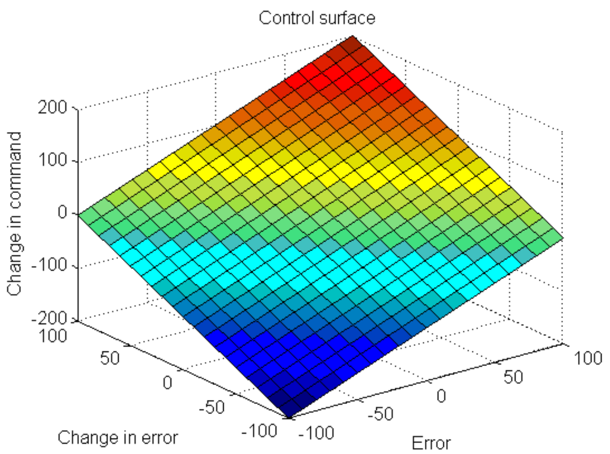

Figure 5. Control surface for the linear fuzzy system

The next step of the design requires a way to determine a relationship between the scaling gains of the fuzzy system (g_e, g_c and g_u) and the tuning parameters of the conventional controller (K_C, T_i) developed earlier.

Since in the final controller, the PD component (6) will be replaced by the linear fuzzy system, finding a relationship between the scaling gains and parameters K'_P, T'_D is more suitable.

Usually a fuzzy system performs a nonlinear input-output mapping, as shown in equation (8), where f represents a nonlinear function.

$$\Delta u_n = f(g_e \cdot e_n, g_c \cdot c_n) \tag{8}$$

Using the linear approximation for *f*:

$$f = g_e \cdot e_n + g_c \cdot c_n \tag{9}$$

equation (8) becomes:

$$\Delta u_n = g_u \cdot (g_e \cdot e_n + g_c \cdot c_n) \tag{10}$$

$$\Delta u_n = g_e \cdot g_u \cdot \left(e_n + \frac{g_c}{g_e} \cdot \frac{e_n - e_{n-1}}{T_s} \right) \tag{11}$$

which is very similar in form to equation (6).

By identifying the terms in equations (11) and (6), the gains of the fuzzy system can be determined based on the following relations [3,4]:

$$g_e \cdot g_u = K'_P \tag{12}$$

$$\frac{g_c}{g_e} = T'_D \tag{13}$$

With the specified design constraints and by choosing the values for the gains according to equation (14), the linear fuzzy system becomes equivalent to the PD component in equation (6), and the resulting fuzzy PI controller, behaves the same way as the conventional PI controller in equation (5).

$$\begin{aligned} g_e &= 0.1 \\ g_c &= 4.85 \\ g_u &= 0.27 \end{aligned} \tag{14}$$

B. The non-linear controller

To finalize the design procedure, the linear fuzzy system developed in paragraph A is made nonlinear. The transformation involves several changes to the structure of the fuzzy system, such as: changing the shape of the membership functions for the inputs and the output, changing the fuzzy operators used, modifying the gains, adopting different inference or defuzzification strategies, changing the rule base etc. All changes in the controller's structure were done heuristically in order to gradually improve the overall performances of the closed loop system and were analyzed by means of digital simulation.

The following changes were performed:

- the size of the universe of discourse was reduced to cover the variations of the error and change-in-error and the activation of all the rules
- the shapes of the membership functions were changed as shown in Fig. 6. Saturation of the input variables was considered by using S and Z membership functions at the edges of the domain. At the same time, different

shapes of membership functions were analyzed (e.g. gauss, non-symmetrical triangular functions etc.)

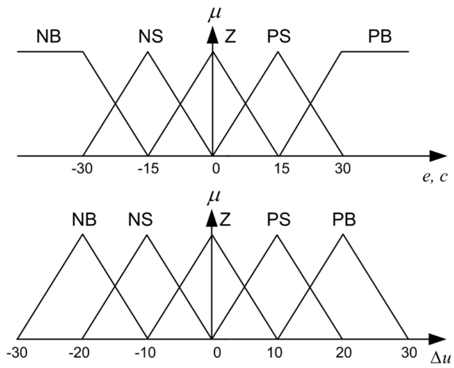

Figure 6. Membership functions and domain for the fuzzy variables in the case of the nonlinear fuzzy system

- the Mamdani inference system was used.
- a rule table (Table II) specific to a PD FLC system [1,2,3,4,11] was considered for the fuzzy component of the controller

TABLE II. RULE TABLE FOR THE NONLINEAR FUZZY-PD CONTROLLER

output: Δu		input: e				
		NB	NS	Z	PS	PB
input: c	NB	NB	NB	NB	NS	Z
	NS	NB	NB	NS	Z	PS
	Z	NB	NS	Z	PS	PB
	PS	NS	Z	PS	PB	PB
	PB	Z	PS	PB	PB	PB

- finally, the values of the scaling gains were modified to improve the system's response

The resulting control surface, generated by the modified (nonlinear) fuzzy system, is shown in Fig. 7.

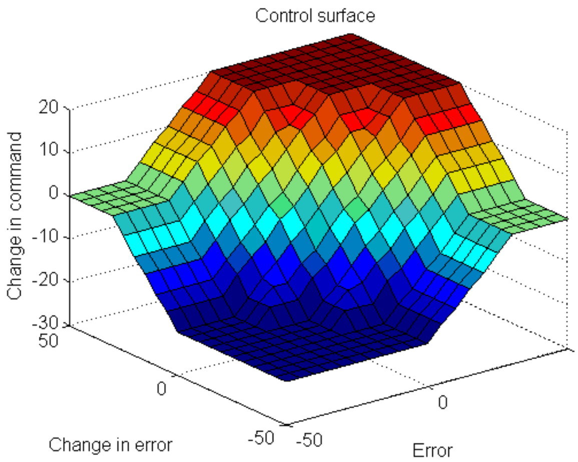

Figure 7. Control surface for the nonlinear fuzzy system

The final structure of the nonlinear fuzzy PI controller for the heat exchanger plant is given by equation (5), where Δu_n is the output of the nonlinear fuzzy system, specified by equation (8). In this case f represents the nonlinear function resulted by considering the changes mentioned in this paragraph and having the scaling gains as specified by equation (15).

$$\begin{aligned} g_e &= 20 \\ g_c &= 485 \\ g_u &= 0.0035 \end{aligned} \tag{15}$$

IV. SIMULATION RESULTS

This section presents results obtained by simulation using the presented control structures for the control of a heat exchanger.

Following the design strategy mentioned in the previous paragraphs a Simulink model was designed for the fuzzy based controller. Its structure is presented in Fig. 8.

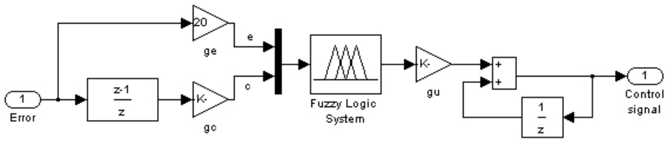

Figure 8. Simulink model of the FLC

The feedback control loop was tested based on the Simulink model shown in Fig. 9. This model is an adapted version of the one presented in [10], to accommodate the control algorithms developed in this paper.

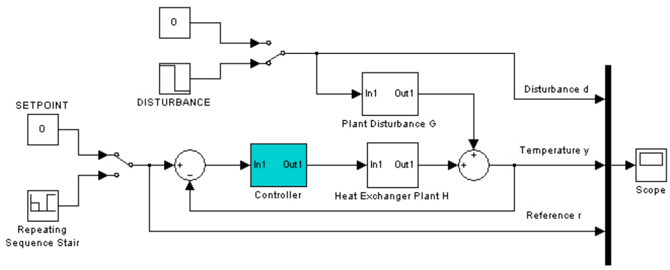

Figure 9. Simulink model of the feedback control loop

The model consists of three main blocks: the controller, the heat exchanger defined by equation (1), the model of the inflow disturbance shown in equation (16).

$$G(s) = \frac{1}{25s+1} e^{-35s} \tag{16}$$

The transfer function in (16) models the way a change in the inflow temperature affects the tank temperature T [10].

Several control algorithms can be selected to be implemented by the controller block in the model from Fig. 9. These are: conventional PI control (see equations (2) and (5)), linear and nonlinear Fuzzy Control (see Section III).

Simulation results obtained using the designed fuzzy controllers and the conventional PI controller are shown in Figs. 10 and 11.

Fig. 10 compares the controlled output in the task of set point tracking, in the absence of disturbance. The set point changes in steps at time 200s and at 400s.

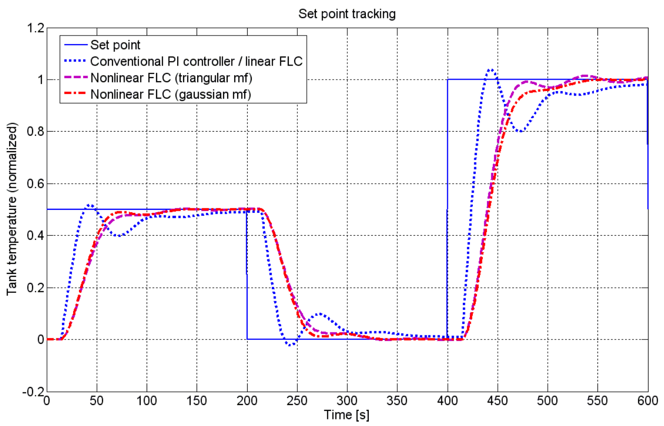

Figure 10. System response (normalized tank temperature) for set point tracking

Fig. 11 shows the simulation results for the disturbance rejection. Disturbances were represented by a step change / drop in the inlet water temperature.

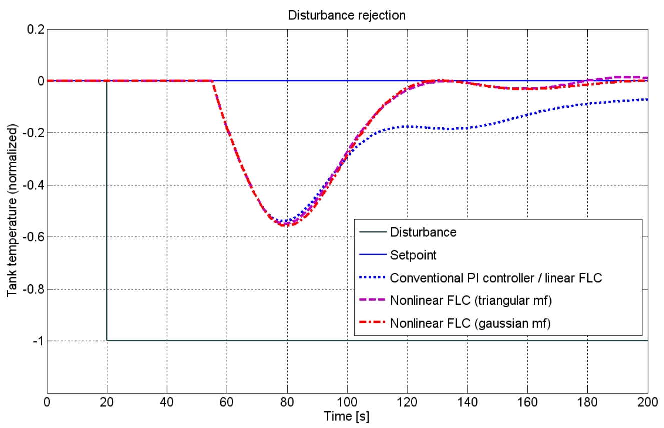

Figure 11. System response (normalized tank temperature) for disturbance rejection

The results show that the linear fuzzy controller exhibits a behavior which is identical to that of the conventional PI controller. This linear fuzzy controller represented the starting point in the design of the nonlinear fuzzy controller, whose final structure determines a better response: it has virtually no overshoot and the settling time is shorter.

V. Conclusion

This paper presents the application of a simple method for developing a fuzzy controller to a heat exchanger. Whenever a PID type controller is possible, or already implemented, it can provide the basis for the development of a fuzzy logic controller.

The simulations confirm that fuzzy control is one of the possibilities for successful control of heat exchangers. The linear fuzzy controller can be made to perform exactly like the crisp PI controller, while the nonlinear implementation of the fuzzy controller can be gradually improved in order to perform better. The comparison to the classical PI control strategy demonstrates the superiority of the proposed nonlinear fuzzy controller. Since the conventional PI controller is a special case of the fuzzy controller, it is true to say that the later performs at least as well.

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