Modeling and Controller Design Using ANFIS Method for Non-Linear Liquid Level System

G. Shahgholian and A. Movahedi

Abstract—**In this paper, it will be shown that ANFIS network is capable of identification of non-linear systems. Also, the fuzzy logic can simply control the system. The mentioned non-linear system is a control system of the liquid level which can be modeled by use of ANFIS network. After modeling stage, a fuzzy controller will be designed in order to achieve a desired liquid level. It will be proved that a fuzzy input-output controller acts like a PD controller. A PI controller will be added to the system in order to remove the steady-state error. Finally, we will design a fuzzy PID controller.**

Index Terms— **Fuzzy PID Controller, ANFIS method, liquid level, non-linear.**

I. Introduction

Designing a mathematical model for a system may be complicated and time taking. In some cases, by taking some hypotheses such as methods of making linear into consideration, a simplified model of the system is considered. These facts lead us to the further application and development of neural networks and fuzzy logic. Applicability of fuzzy controls is explained in [1, 2] and fuzzy controllers are shown in [3-7].

An effective method to design the grey prediction PID controller for PSS is proposed in [8], which requires only a few desired state variables, such as torque angles and rotor speeds. To improve the dynamic response, regulation precision and robustness of the closed-loop system, a model reference fuzzy adaptive PID control for industrial processes is proposed in [9], which the control law consists of two parts, PID controller and fuzzy logic controller. In [10], in terms of a class of steam generator water level control systems, two PI controller systems, and performance assessment methods for the nuclear power plant with stable and unstable zeros are developed at specific power level. The Kalman filter fuzzy adaptive PID control method in order to realize the in-line adjustment of PID parameters and to weaken the effect of random disturbances and measure noises is presented in [11].

We follow two main objectives in this paper. The first stage is identification of the system with the contribution of ANFIS network as well as presentation of system capabilities of identification of non-linear systems. The second stage is designing a fuzzy controller for the system identified in the previous stage. In this paper, the neural networks and fuzzy logic are synthesized to control a non-linear system. Before use of this technique, making this system linear was required to control the system, however, by use of system identification technique, we can control the non-linear system with the contribution of neural network and without need of making the system linear.

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II. Control System

Fuzzy logic proposes a proper method to control non-linear systems regarding human knowledge and experience and by use of rules. It is necessary to select the proper membership functions. The neural networks are very beneficiary, since they produce a sorting mechanism and can fit to the environmental changes. It causes this system to be able to learn. Using these specifications and synthesis of neural networks and the fuzzy logic presents a strength model which is called as ANFIS network. This model is described in [12, 13]. This model has been already used in estimation of functions, identification of errors, etc. In this paper, the structure of ANFIS network will be used in the dynamic model. In fact, the input-output set is used in this method to design the controllers. This method is explained in [14-16]. After modeling stage, by control of input, a fuzzy controller is designed to retain the liquid level as desired. The input-output treatment of the fuzzy controller designed for the non-linear system of liquid level will be studied here as well. It seems firstly that use of PD controllers is an appropriate method for controlling this non-linear system, but finally a PID controller will be designed to increase the efficiency and improve the system operation. In fact, a PD controller has the steady-state error and a PI controller is used to remove the steady-state error. Therefore, the designed controller is produced by synthesis of PI and PD controllers. Use of this controller causes the speed to increase, overshoots to decrease and finally leads in a decrease of the time of achieving a static status.

III. System Model

The structure of the ANFIS network is shown in the Fig. 1. ANFIS model can design and determine the fuzzy system parameters based on the sample of the input and output of the system. Consequently, we can design a self-educating fuzzy system. The structure of ANFIS model can be divided to five layers. The first layer: in this layer, the number of membership of the input nodes is determined.

$$Z_{ij} = \mu_i(X_j, \theta_i) \tag{1}$$

In equation (1), we have: $i=1,2,\ldots, M_{num}$ and $j=1,2,\ldots, I_{num}$. M_{num} represents the number of membership function and I_{num} is the number of input variable. $\mu(0)$ represents the generalized membership function. Usually, the triangle, trapezoidal, Gaussian and bell-shaped membership functions are applied. The second layer: each node output represents a firing strength of a rule.

$$W_k = \prod Z_{ij}, i = 1,2,\ldots,R_{num} \tag{2}$$

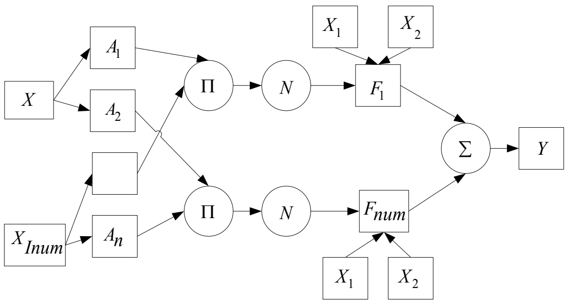

Fig. 1. Structure of ANFIS network

R_{num} is the number of fuzzy rules. The Third layer: normalized incentive intensity is the ratio of the rule's incentive intensity and the sum of all of the rule's incentive intensity.

$$\overline{W}_k = W_k \Big/ \sum_{j=1}^{R_{num}} W_j, k = 1,2,\ldots,R_{num} \tag{3}$$

The fourth layer: fuzzy rule's conclusion, which is accurate output.

$$f_i = P_{i1}X_1 + P_{i2}X_2 + \ldots + P_{ij}X_i + r_i \tag{4}$$
$$i = 1,2,\ldots,R_{num}, j = I_{num}$$

The fifth layer: is the general output of the network as follows.

$$Y = \sum_{i=1}^{R_{num}} \overline{W}^T F \tag{5}$$

The Fg. 2 shows the liquid level system in which Q_{in} and Q_{out} are respectively the maximum of the flow rate of the input and output liquid in m^3/s. q_{in} is the flow rate of the controlled input liquid and is defined as follows:

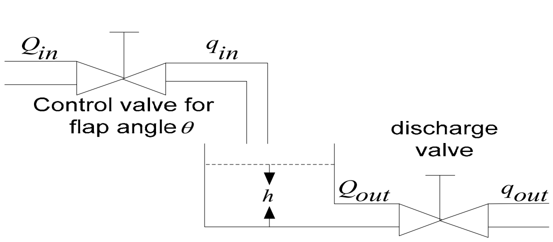

Fig. 2. Liquid level system

$$q_{in} = Q_{in}\sin(\theta(t)), \ \theta(t) \in [0, \frac{\pi}{2}] \tag{6}$$

In the equation (6), Q_{in} is the flow rate of the input liquid and is equal to 0.15 m^3/s. q_{out} represents the flow rate of output liquid and is defined as follows. ($q_{out}=Q_{out}$ is hypothesized since there is no control).

$$q_{out} = a_{out}\sqrt{2gh(t)} \tag{7}$$

In the equation (7), $g=9.81 m/s^2$ and a_{out} is the surface area of the outlet and is equal to 0.013 m^2. The output variable which is liquid level is defined as follows.

$$h(t) = h(0) + \frac{1}{A}\int_0^t (q_{in}(\tau) - q_{out}(\tau))d\tau \tag{8}$$

In the equation (8), A is the surface area of the bottom of the tank and is equal to 1 m^2 and its primary height is zero. The angle of input tap represents the excitation signal which changes between zero and $\pi/2$ rad and is created by sum of two sinusoidal signals.

IV. PID FUZZY CONTROLLER

In the complicated systems whose understanding is dependent on human reasoning, decision-making and inferences, fuzzy logic is an effective instrument. The fuzzy controller is composed of knowledge base, logical decision making, fuzzification interface, defuzzification interface. Analysis of the fuzzy control of the systems has been explained in [17, 18] and the PID controllers' applicability has been explained in [19, 20]. We hypothesize the controller with two inputs and one output. The inputs are error (e) and the change rate of error (de/dt). Linguistic values of inputs are defined by A_i and A_j. The rule of fuzzy controller is as follows.

If e is A_i and de/dt is A_j then u is u_{ij}.

All of the linguistic values of e and de/dt are shown with the triangle membership functions in the Fig. 3.

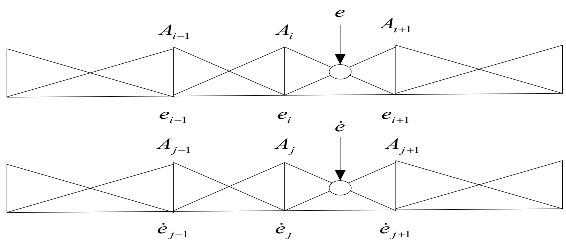

Fig. 3. Membership functions of A_i and A_j

Each node in the plan of e and de/dt presented in Fig. 4 shows that the controller output is a non-linear function.

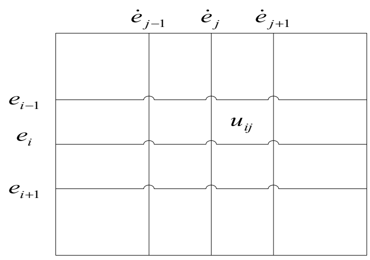

Fig. 4. The structure of the network in the ($e - \dot{e}$) plan

The relationship between the input-output in designing the controllers to control the non-linear model is like following.

$$u = f(e,\dot{e},t) = u_{ij} \tag{9}$$

If we hypothesize the equation (9) is linear,

$$\partial u = [\frac{\partial f}{\partial e}]\partial e + [\frac{\partial f}{\partial \dot{e}}]\partial \dot{e} = \frac{u_{(i+1)j} - u_{ij}}{e_{i+1} - e_i}\partial e + \frac{u_{i(j+1)} - u_{ij}}{\dot{e}_{j+1} - \dot{e}_j}\partial \dot{e} \tag{10}$$

In equation (10), we have:

$$\partial \mathrm{e} = \mathrm{e} - \mathrm{e_i}, \partial \dot{\mathrm{e}} = \dot{\mathrm{e}} - \dot{\mathrm{e}}_\mathrm{j}, \partial \mathrm{u} = \mathrm{u} - \mathrm{u_{ij}}$$

Therefore the following equation is obtained.

$$u = [u_{ij} - \frac{u_{(i+1)j} - u_{ij}}{e_{i+1} - e_i}e_i - \frac{u_{i(j+1)} - u_{ij}}{\dot{e}_{j+1} - \dot{e}_j}\dot{e}_j] + \frac{u_{(i+1)j} - u_{ij}}{e_{i+1} - e_i}e + \frac{u_{i(j+1)} - u_{ij}}{\dot{e}_{j+1} - \dot{e}_j}\dot{e} \tag{11}$$

Equation (11) can be written like that as follows.

$$u = A + Pe + D\dot{e} \tag{12}$$

In equation (12), we have:

$$A = u_{ij} - Pe_i - D\dot{e}_j \tag{13}$$

$$P = \frac{u_{(i+1)j} - u_{ij}}{e_{i+1} - e_i} \tag{14}$$

$$D = \frac{u_{i(j+1)} - u_{ij}}{\dot{e}_{j+1} - \dot{e}_j} \tag{15}$$

Consequently, the fuzzy controller behaves like a PD controller. Also to remove steady-state error, we use the PI controller. As a result, a fuzzy PID controller is designed which is shown in Fig. 5.

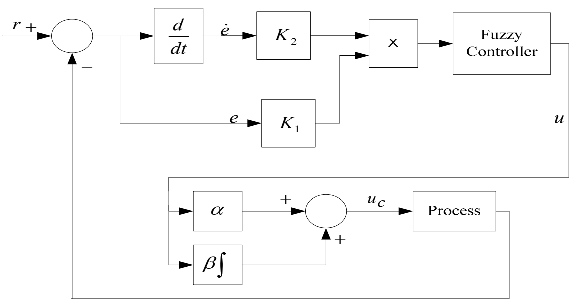

Fig. 5. The structure of PID controller

In Fig. 5, α is the weight of PD controller and β is the weight of PI controller. The output of equation (12) in the controller can be considered as follows.

$$u_c = \alpha A + \beta At + (\alpha K_1 P + \beta K_2 D)e + \beta K_1 P \int edt + \alpha K_2 D\dot{e} \tag{16}$$

V. Simulation Results

In this section simulation results of ANFIS model proposed for tank system of the liquid level and the related control is described. A data set of the inputs related to the changes in control valve's flap angle θ in the interval between zero (in which there is no flow) and $\pi/2$ rad (full flow) for 2500 sample is shown in the Fig. 6. The inputs data are entered into the system and the output of the system of the liquid level is calculated with the unit of meter which is drawn for 2500 samples in Fig. 7. In the modeling stage input data of the previous stage and the output data to approach to input-output relation of the system are applied. Data vector can be considered as follows.

In fuzzy inference, a specialists who knows completely the modeled system should determine the number of rules, but in the modeling technique with the ANFIS model, there are no expert opinion and the number of membership functions of each variable is determined based on a trial and error basis, which is similar to determining the number of hidden layers and nodes in neural networks. Here the system of multiple inputs-one output is transformed to the system of two inputs-one output.

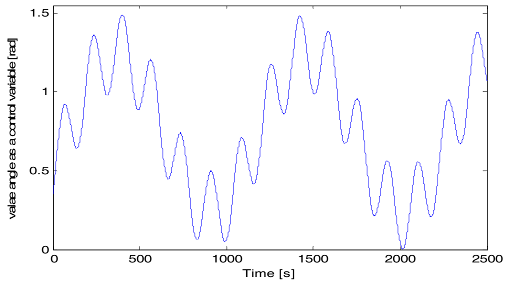

Fig. 6. Presentation of the changes in the angle of control of the input signal (θ) based on rad

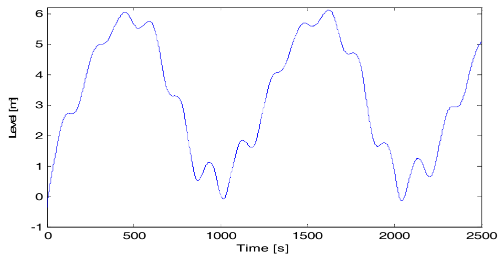

Fig. 7. Output of system of liquid level based on meters

$$\varphi = [u(t-1), y(t-1)] \tag{17}$$

Each input variable is shown with five membership functions which produce 25 rules. Often, the ANFIS systems are used with a fuzzy system of TakagiSugeno-Kang (TSK) in the form of the structure of progressing grids. The data of input- output is processed by the ANFIS model and a proposed model is presented for this system. Fuzzification interface operations are accomplished in there stages of comparison, decoding and coordination to get the desired output. The applied rules for the fuzzy PID controllers are shown in the Table I.

In table I, N is negative, P is positive, L is large, M is medium, S is small and ZR is zero. The membership functions of error (e), change rate of error (de/dt) and control signal, shown in Fig. 8. The membership functions are selected among the triangular membership functions.

TABLE I. RULES OF FUZZY PID CONTROLLER

e \ $\dot{e}$	**PL**	**PM**	**PS**	**ZR**	**NL**	**NM**	**NS**
PL	PL	PL	PL	PL	ZR	PS	PM
PM	PL	PL	PL	PM	NS	ZR	PS
PS	PL	PL	PM	PS	NM	NS	ZR
ZR	PL	PM	PS	ZR	NL	NM	NS
NS	PM	PS	ZR	NS	NL	NL	NM
NM	PS	ZR	NS	NM	NL	NL	NL
NL	ZR	NS	NM	NL	NL	ZL	NL

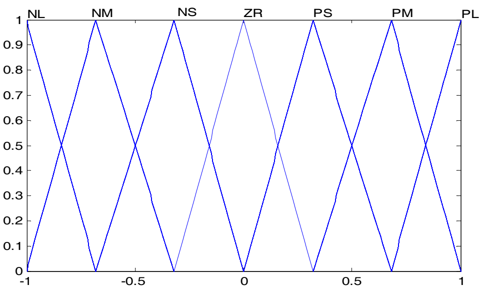

Fig. 8. The membership functions of u and e_i and de_j/dt

In Fig. 9, we consider a fuzzy PD controller for the output system. As it is shown in Fig. 9, the applied fuzzy PD controller has the steady-state error. Now, in Fig. 10, we consider the fuzzy PI controller for the system's output.

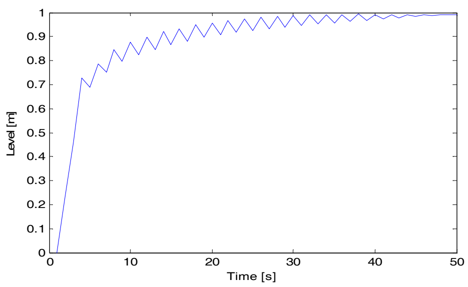

Fig. 9. The response of ANFIS model to the fuzzy PD controller

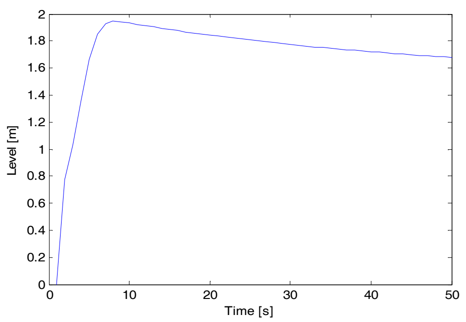

Fig. 10. The response of ANFIS model to the fuzzy PI controller

In Fig. 10, overshoot of the system is about 92% which is a high amount. Therefore, regarding figures 9 and 10, we conclude that the best controller is made by synthesizing the PI and PD controllers. So, the fuzzy PID controller is used for the non-linear system of the liquid level. The Figs. 11-13 shows the response of ANFIS model and the Fig. 14 presents the response of the mathematic model to the fuzzy PID controller with different weights of α and β and K_1=12 and K_2=0.3.

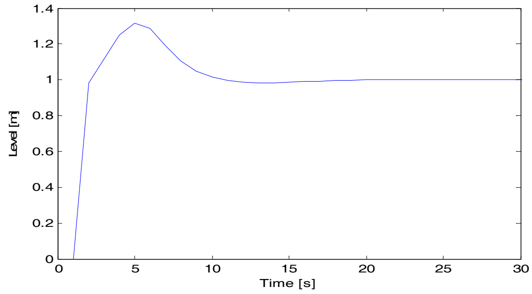

Fig. 11. Response of ANFIS model to controller for α=0.9 and β=0.12

In Fig. 11, the overshoot is about 35% and the settling time is about 18 seconds. In Fig. 12, by doubling the weight of integral and increase of the weight of the derivative by 54%, a faster response with lower overshoots could be got.

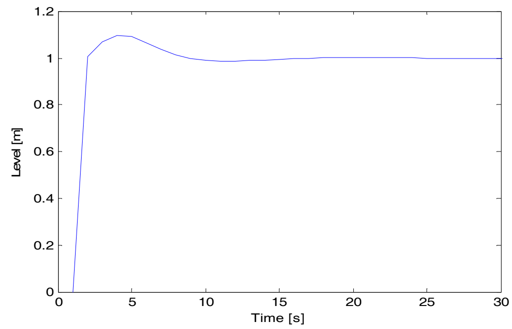

Fig. 12. Response of ANFIS model to the controller for α=1.39 and β=0.24

In Fig. 12, the overshoot is about 15% and the settling time is about 12 seconds. By gradual increase in the weight of derivative, the settling time and the overshoot decreases and we can reach the overshoot less than 10%.

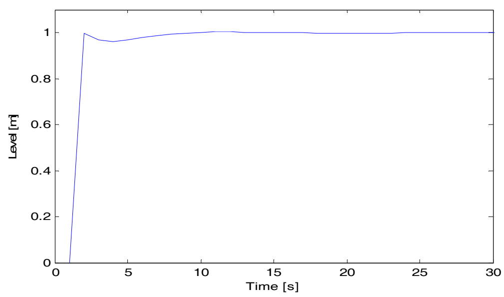

Fig. 13. Response of ANFIS model to the controller for α=2.24 and β=0.24

In the Fig.13 the overshoot is about 10% and the settling time is about 8 seconds. As it is shown in the fig. 13, by increase in the weight of derivative, the settling time and the overshoot is decreased compared to those shown in Figs. 11 and 12. If we don't use the ANFIS method for making the system linear and if we make the mathematical equations of the system as linear, the Fig. 13 is as follows.

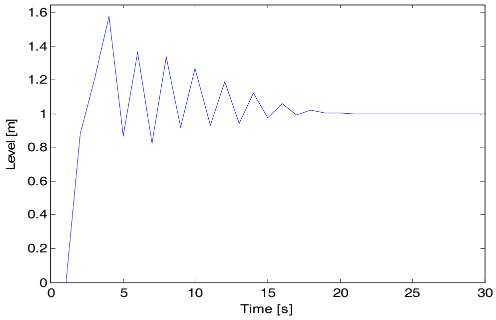

Fig. 14. Response of the mathematical model to the controller for α=2.24 and β=0.24

As it is shown in the Fig. 14, the system has the primary oscillations and the overshoot is about 60% and the settling time is about 20 seconds which shows a remarkable increase compared to the Fig. 13 with the ANFIAS model. Regarding the conclusions, the fuzzy PID controller with the ANFIS model which is proposed in this paper has acted well.

VI. Conclusion

In recent two decades, the fuzzy controllers have been applied successfully in controlling different systems. These controllers have been produced based on the human logic and thinking and they make attempt to treat like a specialized human who controls a system. If there is a strong non-linear system, we cannot get the desired response by the usual PID controller but by a fuzzy controller the desired response can be achieved.

In this paper, the fuzzy PID controller has been used to maintain the liquid level at the desired height. Additionally, the old methods of examining the non-linear systems are complicated and time taking. We can analyze the non-linear system by use of ANFIS model in neural network without making the system linear.

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