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Robust Control of Heat Exchangers

Anna Vasičkaninová*, Monika Bakošová

Institute of Information Engineering, Automation and Mathematics, Faculty of Chemical and Food Technology
Slovak University of Technology in Bratislava
Radlinského 9, 812 37 Bratislava, Slovakia
anna.vasickaninova@stuba.sk

This work deals with the design and application of a neuro-fuzzy controller to a heat exchanger and with possibilities to use the coefficient diagram method for heat exchanger control. The heat exchanger is a tubular one and it is used for pre-heating of kerosene by hot water. The heat exchanger can be represented as a system with interval parametric uncertainty.

Fuzzy logic control has emerged as one of the most fruitful areas in fuzzy set theory, and many practical applications in both industry and household appliances, as well as studies on the theory itself, have been reported in many works.

Coefficient Diagram Method gives control systems that are very stable and robust, system responses without overshoot and very small settling time. The controller design by coefficient diagram method is based on the choice of the coefficients of the characteristic polynomial of the closed loop system according to the convenient performance criteria such as equivalent time constant, stability indices, and stability limits.

Most processes are nonlinear, and their control is a difficult yet important problem. The heat exchanger is an example one such nonlinear process. In the presented paper, the performance of set point tracking and disturbance rejection in two controller methods is investigated. Initially, the third order plus dead time model of the process was obtained. Then, the neuro-fuzzy controller and controller using the coefficient diagram method were designed. Finally, the performances of the two controllers are compared.

The simulations of control were done in Matlab/Simulink environment. The presented experimental results show applicability of mentioned approaches to safer control of nonlinear process. The control response obtained by CDM controller has smaller overshoots. On the other side, the use of the neuro-fuzzy controller led to smaller consumption of the heating medium.

1. Introduction

Fuzzy control has long been applied to industry with several important results. Originally introduced as model-free control design approach, model-based fuzzy control has gained widespread significance. Fuzzy control has proven to be a successful control approach to many complex nonlinear systems or even nonanalytic ones. It has been suggested as an alternative approach to conventional control techniques in many situations (Salmasi, 2007; Maidi et al., 2008; Hladek et al., 2009; Wakabayashi et al., 2009). Fuzzy logic controllers have been implemented successfully in a variety of applications (Hayward and Davidson, 2003; Peri and Simon 2005; Galluzzo and Cosenza 2011). Clustering algorithms are used extensively not only to organize and categorize data, but are also useful for data compression and model construction. The idea of data grouping, or clustering, is simple in its nature and is close to the human way of thinking (Premalatha and Natarajan, 2010).

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Coefficient Diagram Method (CDM) is the one of the most effective control design methods. CDM is introduced by Shunji Manabe in 1991. In this method, characteristic polynomial and controller are simultaneously designed. A semi-log diagram is used as the main tool to analyse stability, speed of response and robustness features of a control system. The controller design method is described in detail in (Manabe, 1998), including historical background, comparison with other control theories, mathematical relations and design procedure. An improved and simplified literature for CDM is presented in (Koksal and Hamamci, 2004). The CDM design method can be used very effectively in many applications (Lee et al., 2005, Öcal et al., 2008).
Heat exchangers are key devices used in a wide variety of industrial applications. Control of a heat exchanger is a complex process due to its non-linear behaviour and complexity caused by many phenomena such as leakage, friction, temperature-dependent flow properties, contact resistance, unknown fluid properties, etc. (Janna, 2009; Al-Mutairi 2010; Panjeshahi et al., 2010; Pan et al., 2011). Therefore, fuzzy and neuro-fuzzy controllers can be a better alternative to the PID control, although many industrial applications use PID control to maintain constant process variables.

2. Process description

Consider a co-current tubular heat exchanger (Vasičkaninová et al., 2010; Vasičkaninová et al., 2011), where kerosene is heated by hot water through a copper tube. The controlled variable is the outlet kerosene temperature T_{1out}. Among the input variables, the water flow rate $q_3(t)$ is selected as the control variable. The tubes are described by a linear coordinate z, which measures the distance of a generic section from the inlet. The fluids move in a plug velocity profile and the kerosene, tube and water temperatures $T_1(z,t)$, $T_2(z,t)$ and $T_3(z,t)$ are functions of the axial coordinate z and the time t. The kerosene, water and tube material densities ρ_i as well as the specific heat capacities C_{Pi}, i = 1, 2, 3, are assumed to be constant. The simplified nonlinear dynamic mathematical model of the heat exchanger is described by three partial differential equations (Vasičkaninová et al., 2010; Vasičkaninová et al., 2011). Parameters and steady-state inputs of the heat exchanger are enumerated in Table 1, where the superscript s denotes the steady state and the subscript in denotes the inlet, D is the tube diameter, ρ is the density, C_P is the specific heat capacity, α *is* the heat transfer coefficient, q is the volumetric flow rate.

Table 1: Heat exchanger parameters and inputs

Variable	Unit	Value	Variable	Unit	Value
N		5	ρ_3	kgm^{-3}	1000
L	m	10	C_{P1}	$Jkg^{-1}K^{-1}$	2100
D_3	m	0.05	C_{P2}	$Jkg^{-1}K^{-1}$	418
D_{12}	m	0.025	C_{P3}	$Jkg^{-1}K^{-1}$	4186
D_{23}	m	0.028	q_1	m^3s^{-1}	3.7723×10^{-4}
α_{12}	$Js^{-1}m^{-2}K^{-1}$	750	q_{3in}^{s}	m^3s^{-1}	1.1111×10^{-4}
α_{23}	$Js^{-1}m^{-2}K^{-1}$	1480	T_{1in}^{s}	K	308.52
ρ_1	kgm^{-3}	810	T_{2in}^{s}	K	317.76
ρ_2	kgm^{-3}	8960	T_{3in}^{s}	K	324.82

For the identification, following step changes of the inlet mass flow-rate of heating water were generated at the time t = 0: ±15 %, ±30 %, ±50 %. Step responses of the outlet temperature are shown in Figure 1. According to these step changes, the heat exchanger is a time-delay nonlinear system with asymmetric dynamics. The model was identified using the Strejc method from the step in the form of the n^{th} order plus time delay transfer function:

$$S = \frac{K}{\left(\tau s + 1\right)^{n}}^{-Ds} \tag{1}$$

Because the heat exchanger can be represented also as a system with interval parametric uncertainty, for various step responses were obtained intervals for values of the gain K, the time constant τ, the time delay D, the system order n=3 (Table 2). The mean values of the parameters are considered to be nominal.

Table 2: Identification of the process dynamics

τ_{min}	τ_{max}	τ_{mean}	K_{min}	K_{max}	K_{mean}	D_{min}	D_{max}	D_{mean}
15	26	19.33	3.734×10^4	7.8407×10^4	5.4136×10^4	0.24	2.00	0.91

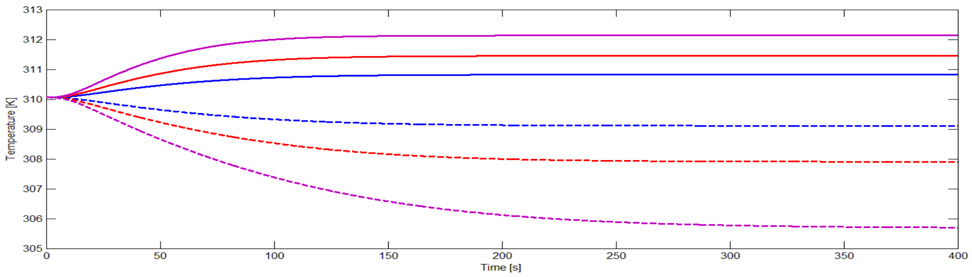

Figure 1: Step response of the outlet temperature on the step changes of the control input, where input change +15 % is represented by blue solid line, -15 % is represented by blue dashed line, +30 % is represented by red solid line, -30 % is represented by red dashed line, +50 % is represented by magenta solid line, -50 % is represented by magenta dashed line.

3. Control of the heat exchanger

PID controllers described by the transfer function

$$C = k_p \left(1 + \frac{1}{t_i s} + t_d s \right) \tag{2}$$

with k_p the proportional gain, t_i the integral time and t_d the derivative time, were tuned using Cohen-Coon method (Ogunnaike and Ray, 1994). The controllers parameters were designed for the models, described by the minimal, mean (nominal) and maximal values of identified parameters.

3.1 Fuzzy PD+I controller

Fuzzy PID controllers are physically related to classical PID controller with three input terms: error, integral error, and derivative error. A rule base with three inputs easily becomes rather big and rules concerning the integral action are troublesome. Therefore it is common to separate the integral action. Fuzzy controller was implemented as fuzzy PD + I controller.

Experimental simulations of control with all designed PID controllers were used for obtaining the data sets of e, de/dt, and u that were needed for the neuro-fuzzy controller design with the Takagi-Sugeno-type fuzzy inference system, generated using subtractive clustering in the form:

If e is A_i and de is B_i Then $f_i = p_i\, e + q_i\, de + r_i$, i=1, ... 3 (3)

where e is the control error, p_i, q_i, r_i are consequent parameters, $q_3(t)$ is the calculated control input. The symmetric Gaussian function (*gaussmf* in MATLAB) is used for the fuzzification of inputs and it depends on two parameters σ and c (Vasičkaninová et al., 2010). The parameters σ and c for *gaussmf* are listed in the Table 3. The consequent parameters in the control input rule (3) are listed in Table 4.

Table 3: Parameters of the Gaussian membership functions

e		de	
σ_i	c_i	σ_i	c_i
0.28	-0.046	0.18	0.00033
0.28	0.181	0.18	0.0108
0.28	-0.177	0.18	-0.0246

Table 4: Consequent parameters

p_i	q_i	r_i
5.5×10^{-4}	7.2×10^{-3}	6.0×10^{-4}
2.5×10^{-5}	-7.5×10^{-5}	2.8×10^{-4}
-3.5×10^{-4}	-8.4×10^{-4}	-2.7×10^{-4}

I controller was used in the form as follows from (2) with $I= k_p/t_i = 2.9\times10^{-6}$.

3.2 Coefficient Diagram Method

The CDM is one of the methods of a controller design using polynomial approach. The standard block diagram of the CDM for SISO systems is shown in Figure 2. Here, $W(s)$, $Y(s)$, $U(s)$ and $N(s)$ represent reference input, system output, control signal, and disturbance signal, respectively. $A_P(s)$, $B_P(s)$ are polynomials of the system to be controlled, $A_C(s)$, $B_C(s)$, $F(s)$ are controller polynomials.

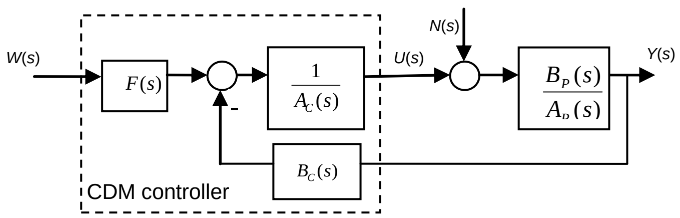

Figure 2: Standard block diagram of CDM control system

The CDM is a technique to arrange the poles of a closed loop transfer function, in order to get wanted response in the time domain. The arrangement of a suitable pole is get using to design parameters, the equivalent time constant τ_e, the stability index γ_i, and the stability limit γ_i^* (Manabe, 1998).

The equivalent time constant can be taken as τ_e = 28. It is advised to choose the stability indices in form γ_i = [2.2 3.6 0.53 20.2859], here γ_4 is enumerated. The stability limits are computed (Manabe, 1998) to be γ_i^* = [0.2778 2.3413 0.3271 1.8868].

It is considered that there is a step disturbance affecting the system. Thus, let the structure of the controller be chosen with l_0 = 0 as follows: The CDM controller polynomials and the characteristic polynomial (5) are found for nominal values of identification parameters as

$$\frac{B_C(s)}{A_C(s)} = \frac{k_2 s^2 + k_1 s + k_0}{l_2 s^2 + l_1 s} = \frac{5.4\times10^{-3} s^2 + 4.9682\times10^{-4} s + 1.8472\times10^{-5}}{0.3826 s^2 + 1.1042 s} \tag{4}$$

$F(s)$ is obtained in order to eliminate possible steady-state error in the response of the closed-loop system: $k_0 = 1.8472\times10^{-5}$

$$P(s) = 27634 s^5 + 84039 s^4 + 12599 s^3 + 3564 s^2 + 28 s + 1 \tag{5}$$

Simulation results obtained using designed neuro-fuzzy controller and CDM controller are shown in Figures 3, 4. Figure 3 presents the simulation results of the control of the heat exchanger in the task of

set point tracking and in the case when disturbances affect the controlled process. The set point changes from 313.15 K to 312.15 K at 400 s and then to 313.65 K at 800 s. Disturbances were represented by water temperature changes from 348.15 K to 344.15 K at 200 s, from 344.15 K to 351.15 K at 600 s and to 346.15 K at 1000 s. The comparison of the controller outputs is shown in Figure 4. The energy consumption is measured by the total amount of hot water consumed during the control process, smaller energy consumption is assured using neuro-fuzzy controller.
The control response obtained by CDM controller has smaller overshoots, but longer settling times. The simulation results were compared also using IAE (integral absolute value of error) and ISE (integral squared value of error) criteria (Ogunnaike and Ray, 1994). The IAE and ISE values and the consumption of the heating medium are given in Table 5.

Table 5: Values of IAE and ISE and hot water consumption V

controller	IAE	ISE	V [m^3]
fuzzy PD+I	311	290	0.2789
CDM	217	331	0.2828

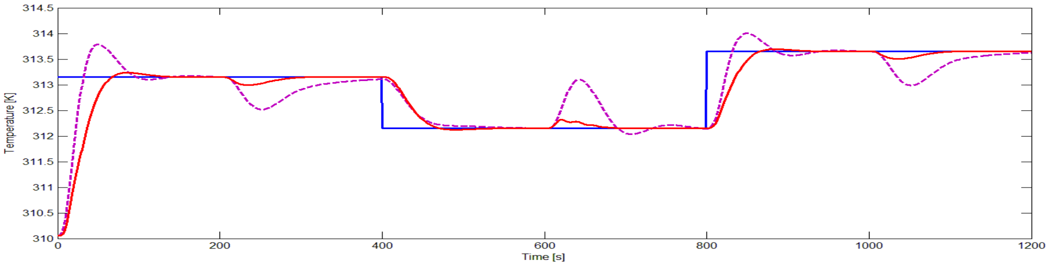

Figure 3: Comparison of the outlet kerosene temperature, where reference is represented by blue solid line, fuzzy PD+I control is represented by magenta dashed line, CDM control is represented by red solid line

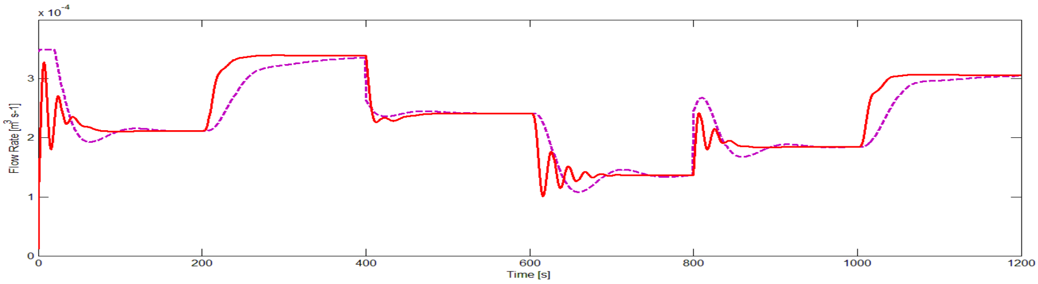

Figure 4: Comparison of the water flow rate, where fuzzy PD+I control is represented by magenta dashed line, CDM control is represented by red solid line

4. Conclusion

In this paper, the performances of two controllers, neuro-fuzzy PD+I controller and CDM controller, were investigated on the nonlinear heat exchanger. Simulation results obtained using designed controllers were measured calculating integral performance indexes IAE and ISE. The control response obtained by CDM controller has smaller overshoots and so smaller value IAE. The use of the neuro-fuzzy controller led to smaller consumption of the heating medium.
Te CDM design procedure is easily understandable. Therefore, the coefficients of the CDM controller polynomials can be determined more easily than those of the neuro-fuzzy or other types of controller.

The advantage of the fuzzy approach is that it is not linear-model-based strategy.
The simulation results confirm that designed robust controllers propose the possibilities for successful control of heat exchangers.

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