International Journal of Latest Research in Science and Technology ISSN (Online):2278-5299
Volume 2, Issue 6: Page No.1-5 ,November-December 2013
https://www.mnkpublication.com/journal/ijlrst/index.php

FUZZY CONTROL OF A NON-LINEAR SYSTEM WITH INVERSE RESPONSE: VAN DE VUSSE REACTION

[1]Hugo Ojeda-Elizarras, [1]Rafael Maya-Yescas, [2]Salvador Hernández Castro, [2]Juan Gabriel Segovia Hernández and [1]Agustin Jaime Castro-Montoya
[1]Facultad de Ingeniería Química, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, México
[2]Departamento de Ingeniería Química, Universidad de Guanajuato, Guanajuato, México

Abstract-The main issue of this paper is a fuzzy logic design controller, which is applied to a non-linear process with inverse response as the Van de Vusse reactor. This kind of process offer difficulties in the application of conventional feedback loop control. The Van de Vusse reactor had the interesting characteristics of right-half plane zeros (inverse response) under certain operating conditions. Simple fuzzy proportional control strategy is presented for non-linear IR system. The approach is compared with the conventional P, PI and PID algorithms tuning with the classical Ziegler-Nichols rules. The performance of the strategies were evaluate by the MATLAB-Simulink-Fuzzy Logic software, the results show the effectiveness of the strategy proposed allowing to obtain a better performance with a simple control scheme.

Keywords: Fuzzy controller, Inverse response, Van de Vusse

I. INTRODUCTION

Inverse response (IR) behavior appears when the initial response of the output variable is in the opposite direction to the steady-state value. This behavior occurs in several systems in chemical process industry, such as distillation columns and drum boilers [1], [2], [3]. Inverse response occurs when the process transfer function has an odd number of zeros in the open right half plane (RHP) [4]. This process characteristic affects the achievable closed-loop performance because the controller operates on wrong sign information in the initial time of the transient state. This fact introduces limitations of achievable output performance. Different control configurations are found in the literature and can be classified into two categories, the first one uses proportional-integral-derivative (PID) controller with many kinds of tuning methods [5]. The good results obtained are due to a positive feature of the derivative action in trying to correct the wrong direction of the system`s response [6]. However, performance of the PID control usually degrades to keep the stability margin. In the second category, inverse response compensators which increase the complexity of the control structure are used. In addition, performance is affected by model/plant mismatches. The first inverse response compensator was presented in [7]. But it is an empirical method and it can not provide satisfactory performance. The Internal Model Control (IMC) [8] can also be fit in this category. A similar approach based on modern H∞ control theory was presented in [4]. Luyben [9] proposed a new tuning method in which the PI tuning constants are presented as functions of the positive zero and the dead time D. Although, the setting of this method gives large oscillatory and overshoot. To resolve this problem, Chien et al [10] proposed a tuning method deriving from a direct synthesis controller design method (DCS). However, the parameter is not convenient for tuning in practice. In this paper, a simple fuzzy control is proposed to control non-linear inverse response processes. This fuzzy controller can give acceptable performance compared with linear PID approaches. In section II, the conditions of yielding IR processes are introduced. The case of study and the design controller are presented in section III. Simulation of close-loop responses is illustrated in section IV. General conclusions are drawn in section V.

II. OPEN-LOOP CHARACTERISTICS OF IR PROCESSES

Physically, the processes exhibit inverse response mainly because of the conflict of two first-order systems with opposite effects, as illustrated in Fig. 1a. The transfer function of the overall response is described as:

$$y(s) = y_1(s) - y_2(s) = \frac{K_1}{\tau_1 s + 1} - \frac{K_2}{\tau_2 s + 1} \qquad (1)$$

K_1, K_2 are respectively proportional gain of the two first-order systems and τ_1, τ_2 are time constants. All of them are positive constants.
or:

$$y(s) = \frac{K_1\tau_2 - K_2\tau_1) + (K_1 - K_2)}{(\tau_1 s + 1)(\tau_2 s + 1)} \qquad (2)$$

Publication History
Manuscript Received : 19 November 2013
Manuscript Accepted : 25 November 2013
Revision Received : 28 November 2013
Manuscript Published : 31 December 2013

$$y(s) = K_P \frac{-\alpha s + 1}{(\tau_1 s + 1)(\tau_2 s + 1)} \qquad (3)$$

With:

$$K_P = K_1 - K_2 > 0\,;\, \alpha = \frac{(\mathrm{K}_2\tau_1 \text{ - } \mathrm{K}_1\tau_2)}{K_1 - K_2} \qquad (4)$$

IR appears when the slower process has higher gain; that is, the condition for IR is:

$$\frac{\tau_1}{\tau_2} = \frac{K_1}{K_2} > 1; \alpha > 0 \qquad (5)$$

The open-loop responses to a step input are reported in Fig. 1b for different values of α, it is evident that difficulties associated with the control increase with α (the corresponding RHP zero approaches the origin).

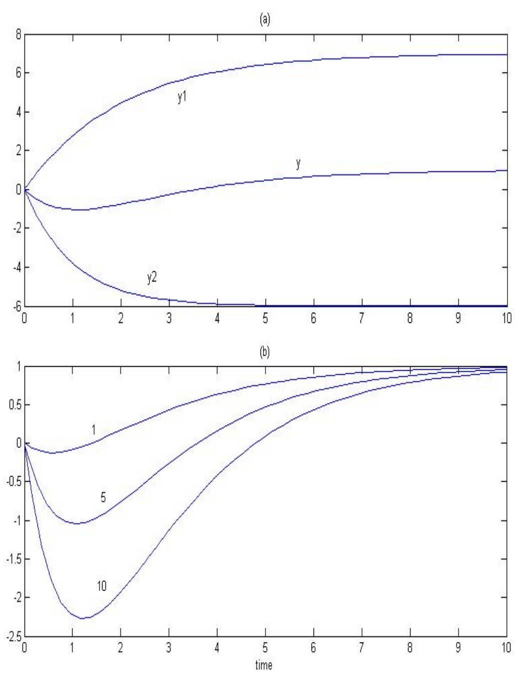


Fig. 1 Open-loop step response for an IR process: (a) individual first-order components (y1, y2) and overall component (y); (b) effect of increasing values of the parameter α = 1, 5, 10.

III. CASE OF STUDY

In many chemical processes, the main reaction that yields the desirable product is accompanied by consecutive and parallel reactions that produce unwanted byproducts. An example of a general reaction scheme of this type was used by Kantor [11] to discuss the applicability of extended linearization techniques to the control of reactions in continuous stirred tank reactors. The same reaction mechanism was used by Engell and Klatt [12] to design a gain scheduling controller. This scheme reaction was presented by Van de Vusse [13]:

$$\mathrm{A} \xrightarrow{\mathrm{k_1}} \mathrm{B} \xrightarrow{\mathrm{k_2}} C \qquad (6)$$

$$2\mathrm{A} \xrightarrow{\mathrm{k_3}} \mathrm{D} \qquad (7)$$

Where A is the reactant, B the desirable product, C and D are the unwanted by-products. In general, reaction rates k_2 y k_3 smaller than k_1 are sought choosing appropriate catalyst and reaction conditions. If this is not possible, the concentration of B can be controlled by the inflow to the reactor and/or the reactor temperature. In this work, it is assumed that the continuous stirred tank reactor shown in Fig. 2 is operating at isothermal and isochoric conditions with constant reaction rate parameters as well. Therefore, an energy balance is not necessary. The process considered here involves the production of cyclopentenol (B) form cyclopentadiene (A) by acid-catalyzed electrophilic addition of water in dilute solution. Due to the strong reactivity of reactants A B, dicyclopentadiene (D) is produced by a Diels-Alder reaction as a side product and cyclopentanediol (C) is generated as a consecutive product adding another water molecule [12]. The complete reaction scheme is:

$$\mathrm{C_5H_6} \xrightarrow{+H_2O/H+} C_5H_7OH \xrightarrow{+H_2O/H+} C_5H_8(OH)_2 \qquad (8)$$

$$2\mathrm{C_5H_6} \longrightarrow C_{10}H_{12} \qquad (9)$$

The Van de Vusse reactor had input multiple and right-half plane zeros (inverse response) characteristics. The dynamics of the reactor can be described by the following set of differential equations. In the following development, it is assumed that the feed stream only contains component A.

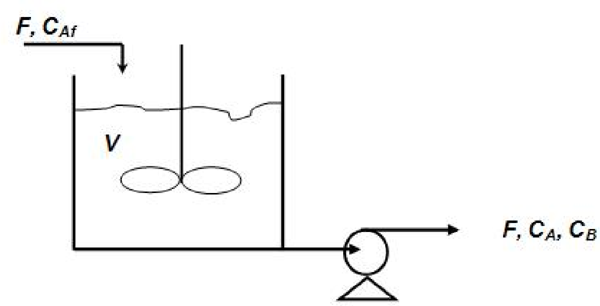


Fig. 2 Continuous stirred tank reactor (CSTR

III.1 MATHEMATICAL MODEL OF VAN DE VUSSE REACTOR

Overall material balance (assuming constant density and constant volume):

$$\frac{\mathrm{dV}}{\mathrm{dt}} = 0 \quad \text{and} \quad F = F_i \qquad (10)$$

Component *A* Balance:

$$\frac{d(VC_A)}{dt} = F(C_{Af} - C_A) - Vk_1C_A - Vk_3C_A^2 \qquad (11)$$

since *V* is constant:

$$\frac{d(C_A)}{dt} = \frac{F}{V}(C_{Af} - C_A) - k_1C_A - k_3C_A^2 \qquad (12)$$

Component *B* Balance, similarly, we can write:

$$\frac{d(C_B)}{dt} = -\frac{F}{V}C_B + k_1C_A - k_2C_B \qquad (13)$$

Component *C* Balance:

$$\frac{d(C_C)}{dt} = -\frac{F}{V}C_C + k_2C_B \qquad (14)$$

Component *D* Balance:

$$\frac{d(C_D)}{dt} = -\frac{F}{V}C_D + \frac{1}{2}k_3C_A^2 \qquad (15)$$

Equations (10) and (11) do not depend on C_C or C_D. If we only concerned about C_A and C_B, we only need to solve that equations.

Consider that F/V is the input variable of interest. In the reaction engineering literature, F/V is known as the “space velocity” and V/F as the “residence time”.

III.2 OPERATING CONDITIONS

Different steady-state operating points are studied. Considering Table 1 conditions with k_1=5/6 min^{-1}, k_2=5/3min^{-1}, k_3=1/6 mol/min. Set 1 illustrates inverse response behavior while set 2 does not.

Table 1 Steady-state concentrations for the Van de Vusse reactor.

	Set 1	**Set 2**
Dilution rate,F_s/V	4/7 min^{-1}	2.8744min^{-1}
C_{As}	3mol/liter	6.0870mol/liter
C_{Bs}	1.117mol/liter	1.117mol/liter
C_{Afs}	10mol/liter	10mol/liter

Since the objective of the process is to maximize the production of B, the response of the B concentration is more important than the changes input. It is interesting to note how the system response changes under certain operating conditions. Note that sets 1 and 2 are based on the same component B concentration. Case 1 exhibits inverse response, while case 2 does not. The different types of behavior are shown in the Figure 3. The Fig. 3a is typical of a system with a positive gain and inverse response whereas Fig. 3b characterizes a system with a negative gain. In this case, the process does not exhibit inverse response.

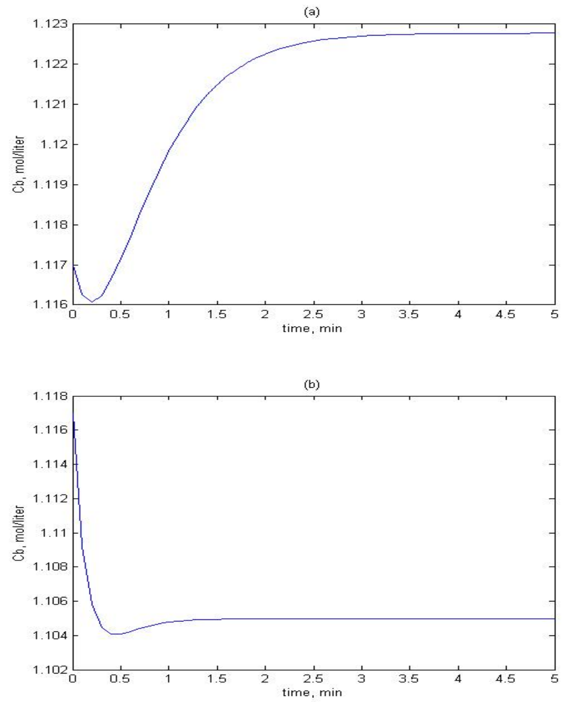


Fig. 3 Open-loop response for the Van de Vusse reactor: (a) small step change (0.01) in space velocity, case 1 conditions; (b) response to a small step change in space velocity (0.1), case 2 conditions.

III.3 FUZZY CONTROLLER DESIGN

The design of the fuzzy P controller for the concentration of B (product of interest) is based on conventional unity feedback control and it is compared with P, PI, PID type controllers. The manipulated variable is the dilution rate F/V. The conventional unity feedback control is illustrated in Fig. 4. The development of the fuzzy controllers is divided into three parts, namely fuzzyfication, determination of a control rule base, and defuzzyfication. In the left side of Fig. 5, the input membership function fuzzifies the input variable *e* of the fuzzy P controller, and the membership function for the output signal u is on the right side.

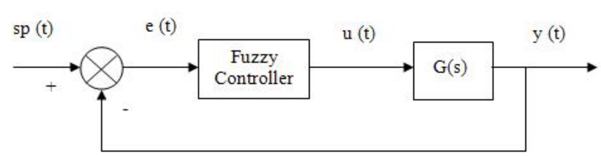


Fig. 4 Unit feedback control scheme

For design purposes, the process input and output ranges are varied, the number of fuzzy sets, the overlap between sets, such as the shape of membership functions to assess the best parameters combination according to closed-loop performance, finding the fuzzy controller proposed.

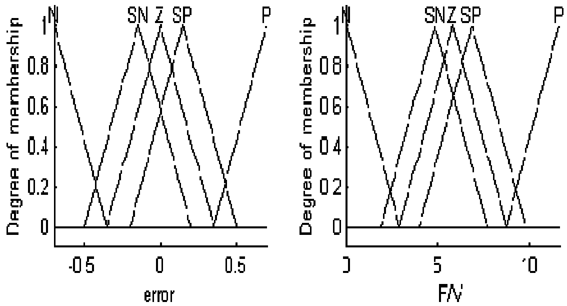


Fig. 5. Fuzzy sets for input left, (Cb error) and output, right (F/V).

The selection of the control rules is based on the changes of error, that it is equal to the difference between the reference (set-point) and the measured value of the controlled variable, generating a control signal. The rule-base for the fuzzy P controller was constructed as follows:

1. IF error is N THEN the dilution rate (F/V) is N.
2. IF error is SN THEN the dilution rate (F/V) is SN.
3. IF error is Z THEN the dilution rate (F/V) is Z.
4. IF error is SP THEN the dilution rate (F/V) is SP.
5. IF error is P THEN the dilution rate (F/V) is P.

where N (negative), SN (semi-negative), Z (zero), SP (semi-positive) and P (positive), are linguistic variables.

IV. SIMULATION OF CLOSED-LOOP RESPONSE

The fuzzy P (proportional) controller used, consisted in five fuzzy sets input and fuzzy sets output using triangular membership functions with the configuration shown in Fig. 5. The fuzzy inference process of fuzzy controller is based on the Mamdani method and the centroid method as desfuzzyfucation process. The calculated P, PI and PID controller parameters for the conventional controllers are given in Table 2 (Ziegler-Nichols settings). The ultimate gain and ultimate period were found to be Kcu=42 y Pu=1.52.

Table 2. Calculated controller settings.

Controller	K_c	τ_I	τ_D
P-ZN	21	-	-
PI-ZN	18.9	1.266	-
PID-ZN	25.2	0.76	0.19

The performance index proposed by Ogunnaike and Ray [14] was used to evaluate the strategies performance. ITSE (integral time weighting of square error) defined by (7).

ITSE gives large penalization to large errors at large times. Therefore, it is a good measure of the controllers' performance.

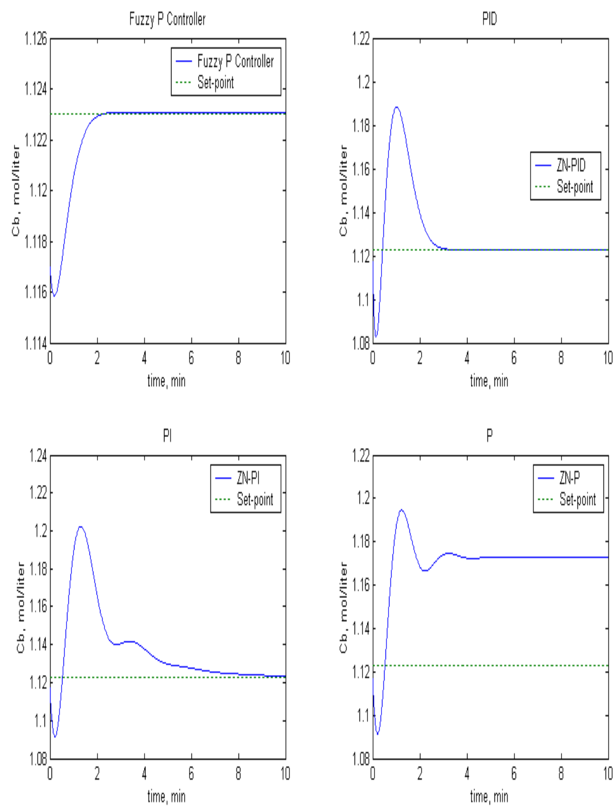
$$ITSE = \int_0^{\infty} t\varepsilon^2 dt \qquad (15)$$

The closed-loop set point responses for the four controllers are shown in Fig. 6. According to Table 3 and Fig. 6, different algorithms produce different control action. Note that the ZN-P method produces no satisfactory control. ZN-PI controller offers a slow response. However, the proposed fuzzy and ZN-PID controllers provide satisfactory set point response, but PID gives excessive oscillations and large overshoot. Moreover, the proposed controller has much smaller overshoot than PID and smaller ITSE.

Table 3. Performance indices of the evaluated controllers.

Controller	*ITSE*
P-ZN	2.7801
PI-ZN	0.6271
PID-ZN	0.3346
FLC	0.0006

Fig. 6 Set-point responses with different controllers



V. CONCLUSIONS

The presented control configuration for inverse response processes results in a simpler fuzzy P controller with one input and one output. For set-point tracking, the proposed controller makes its superiority clear compared with P, PI and PID controllers tuned with the Ziegler-Nichols method in a standard feedback configuration. The comparison shows that the action of a PID controller for inverse response processes can be successfully substituted by the proposed controller.

ACKNOWLEDGMENT

This research was supported by a doctoral fellowship from Consejo Nacional de Ciencia y Tecnología (CONACYT), México.

REFERENCES

[1] Shinskey F. G., “Process Control Systems”, 1979, Mc-Graw Hill, 2nd edition, USA.

[2] Arulselvi S., Uma G., Chidambaram M., “Design of PID Controller for Boost Converter with RHS Zero”, Conf. Proc. IPEMC Int. Power Electron and Motion Control Conf., 2004, 532-537.

[3] Ying C. P., Chun T. Y., Zhi Z. Q., Dong Z. W., “A New Design Method of PID Controller for Inverse Response Processes with Dead Time”, IEEE, 2005, 1036-1039.

[4] Zhang W., Xu X., and Sun Y., “Quantitative Performance Design for Inverse Response Processes”. Ind. Eng. Chem. Res., 2000, 39, 2056-2061.

[5] Scali C. and Rachid A., “Analytical Design of Proportional-Integral-Derivative Controllers for Inverse Response Processes”, Ind. Eng. Chem. Res.,1998, 37, 1372-1379.

[6] Stephanopoulus. G., “Chemical Process Control: An Introduction to Theory and Practice”, 1984, Prentice-Hall, USA.

[7] Iinoya K. and Altpeter R. J., “Inverse Response in Process Control”, Ind. Eng. Chem. Res., 1962, 54, 39-43.

[8] Morari M. and Zafirou E., “Robust Process Control”, 1989, Prentice-Hall International, USA.

[9] Luyben W. L., “Tuning Proportional-Integral Controllers for Processes with both Inverse Response and Dead Time”, Ind. Eng. Chem. Res., 2000, 39, 973-976.

[10] Chien I. L., Cheng Y. C., Chen B. S., Chuang C. Y., “Simple PID Controller Tuning Method for Processes with Inverse Response plus Dead Time or Large Overshoot Response plus Dead Time”, Ind. Eng. Chem. Res., 2003, 42, 4461-4477.

[11] Kantor J.C., “Sability of State Feedback Transformations for Nonlinear Systems-Some Practical Considerations”, Proceedings of American Control Conference, IEEE Press: Piscataway, NJ, 1986, 1014.

[12] Engell S. and Klatt K. U., “Nonlinear Control of a Non Minimum-PhaseCSTR”, Proceedings of the 1993 American Control Conference, IEEE Press:Piscataway, NJ, 1993, 2941.

[13] Van de Vusse, “Plug Flow Type Reactor versus Tank Reactor”, Chem. Eng. Sci., 1964, 19, 994.

[14] Ogunnaike B. A. and Ray W.H., “Process Dynamics, Modeling and Control”, Oxford University Press: New York, 1994, 229-231, USA.