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CONTROL OF A LABORATORY CHEMICAL REACTOR USING ROBUST PI CONTROLLER

J. Závacká, M. Bakošová, K. Vaneková

Slovak University of Technology in Bratislava, Faculty of Chemical and Food Technology, Institute of Information Engineering, Automation and Mathematics, Radlinského 9, 812 37 Bratislava, Slovakia
fax : +421 2 52496469, e-mail: jana.zavacka@stuba.sk

Abstract: The paper presents a method for design of robust PI controllers for systems with interval uncertainty. The method is based on plotting the stability boundary locus in the (k_p, k_i)-plane. Then parameters of stabilizing PI controllers are determined. The designed robust PI controller is used for control of a laboratory chemical continuous stirred tank reactor Armfield PCT40. The reactor is used for preparing of NaCl solution with desired concentration. The conductivity of the solution is the controlled variable and the volumetric flow rate of water is the control variable.

Keywords: interval uncertainty, PI controller, robust control, chemical reactor

1. INTRODUCTION

Chemical reactors are ones of the most important plants in chemical industry, see e.g. Mikleš and Fikar (2007). Their operation, however, is corrupted with various uncertainties. Some of them arise from varying or not exactly known parameters, as e.g. reaction rate constants, reaction enthalpies or heat transfer coefficients. In other cases, operating points of reactors vary or reactor dynamics is affected by various changes of parameters of inlet streams. All these uncertainties can cause poor performance or even instability of closed-loop control systems. Application of robust control approach can be one of ways for overcoming all these problems, which may seriously influence control design for chemical reactors and other chemical processes, see e.g. Alvarez-Ramirez and Femat (1999), Gerhard et al. (2004).

In this paper, a simple method for design of robust PI controllers is presented (Tan and Kaya (2003)). The method is based on plotting the stability boundary locus in the (k_p, k_i)-plane and then parameters of a stabilizing PI controller are determined from the stability region. The PI controller stabilizes a controlled system with interval parametric uncertainties, when the stability region is found for sufficient number of Kharitonov plants.

The approach is used for design of a robust PI controller for a laboratory continuous stirred tank reactor, which can be modelled in the form of a transfer function with parametric interval uncertainty. The reactor serves for preparing of the NaCl solution with required concentration. Composition of the solution is determined by measurement of the solution conductivity and the conductivity is the controlled variable. The volumetric flow rate of water which is used for adulterating of NaCl solution, is the control variable.

2. DESCRIPTION OF THE LABORATORY CONTINUOUS STIRRED TANK REACTOR

Multifunctional process control teaching system - The Armfield PCT40 (Armfield (2005), Vojtešek et al. (2007)) is the system which enables to test a wide class of technological processes, as a tank, a heat exchanger, a continuous stirred tank reactor and their combinations (Armfield (2006a), Armfield (2006b)).

PCT40 unit consists of two process vessels, several pumps, sensors and connection to the computer. Additional equipments PCT41 and PCT42 (Figure 1) represent a chemical reactor with a stirrer and a cooling/heating coil.

Fig. 1. Laboratory continuous stirred tank reactor

Inlet streams of reactants can be injected into the reactor via a normally closed solenoid valve or by a proportional solenoid valve (PSV). The third possibility for feeding water into the reactor is using one of two peristaltic pumps. The technological parameters of the reactor are shown in Table 1.

Table 1. Technological parameters of the reactor

Parameter	Value
Vessel diameter	0.153 m
Maximum vessel depth	0.108 m
Maximum operation volume	2 l
Minimum vessel depth	0.054 m
Minimum operation volume	1 l

The connection to the computer is realized via an I/O connector, which is connected to the PCL card. The card used is the MF624 multifunction I/O card from Humusoft. This card has 8 inputs and 8 outputs. The whole system provides 9 inputs and 17 outputs, hence two MF624 cards were used. This connection enables use of Matlab Real-time Toolbox and Simulink or data entry from the Matlab command window.

NaCl solution with the concentration 0.8555 mol/dm^3 is fed into the reactor by a peristatic pump. The performance of the pump may be theoretically set in the range $0 - 100\%$. But for the pump performance less than 20%, revolutions of the rotor are very small and the produced force is not high enough to transport the fluid from the barrel. The volumetric flow rate of the NaCl solution for all measurements was 0.2222 dm^3/min, which represents the pumpe performance 30%.

The water was dosed into the reactor by the PSV. Application of the PSV allowed flow measurements by the adjoint flowmeter. The PSV opening could be again done in the range $0-100\%$, but the volumetric flow rate of water for the PSV opening in the range $0 - 15\%$ was negligible.

For control purposes, the laboratory continuous stirred tank reactor is a SISO system. The control variable is the volumetric flow rate of water (F) and the controlled variable is the conductivity of the NaCl solution (G) inside the reactor. Used water was cold water from the standard water distribution. The volume of the solution in the reactor was kept constant with the value 1 dm^3 during all experiments.

3. PROCESS IDENTIFICATION

Identification of the controlled laboratory reactor was done from measured step responses. The constant flow rate 0.2222 dm^3/min of NaCl solution dosed into the reactor was assured by the peristaltic pump with performance 30% in all experiments. Three various step changes of water flow rate were realized: $0 - 0.1804$ dm^3/min, $0 - 1.3$ dm^3/min and $0-1.78$ dm^3/min which represented the PSV opening $0-20\%$, $0-50\%$ and $0-100\%$. The step responses were measured repeatedly. The resultant transfer function of the laboratory reactor was identified (Ľ. Čirka and Fikar (2007)) in the form of a transfer function (1) with the parametric interval uncertainty. The values of the uncertain parameters are shown in Table 2. Nominal values of the uncertain parameters are the mean values of intervals.

$$G(s) = \frac{b_0}{a_2 s^2 + a_1 s + a_0} \tag{1}$$

Table 2. Uncertain parameters

Parameter	Minimal value	Maximal value	Nominal value
b_0	0.00405	0.178	0.091
a_2	130	500	315
a_1	36.5	148	92.25
a_0	1	1	1

The measured step response of the laboratory reactor and the simulated step response of the reactor with the identified transfer function (1) are compared in Figure 2 for the maximal step change of input variable.

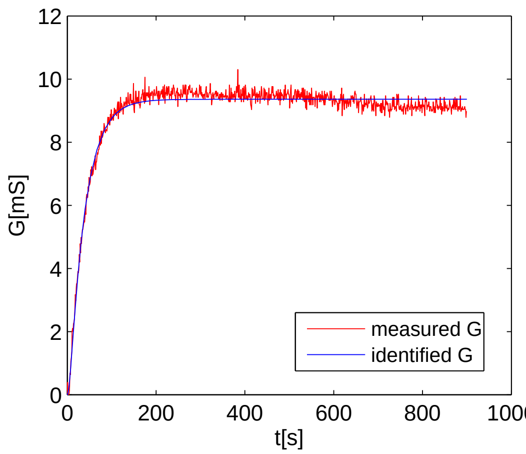

Fig. 2. Comparision of the measured and the simulated step responses of the reactor

4. DESIGN OF A ROBUST PI CONTROLLER

A simple method based on plotting the stability boundary locus in the (k_p, k_i)-plane is used for robust PI controller design, Tan and Kaya (2003), Závacká et al. (2008). Parameters of a stabilizing PI controller are detemined from the stability region of the (k_p, k_i)-plane. The PI controller stabilizes a controlled system with interval parametric uncertainties, when the stability region is found for suffucient number of Kharitonov plants.

For the controlled system in the form of the transfer function (1) with interval uncertainty (Table 2), the Kharitonov polynomials $N_i(s)$, $i = 1, 2$ for the numerator and $D_j(s)$, $j = 1, 2, 3, 4$ for the denominator can be created, as it is seen in (2), (3).

$$\begin{aligned} N_1(s) &= b_0^- \\ N_2(s) &= b_0^+ \end{aligned} \tag{2}$$

$$\begin{aligned} D_1(s) &= a_2^- + a_1^- + a_0 \\ D_2(s) &= a_2^+ + a_1^+ + a_0 \\ D_3(s) &= a_2^+ + a_1^- + a_0 \\ D_4(s) &= a_2^- + a_1^+ + a_0 \end{aligned} \tag{3}$$

where b_0^- and b_0^+ are lower and upper bounds of the b_0 interval and a_k^- and a_k^+, $k = 1, 2$, are lower and upper bounds of intervals of denominator parameters. 8 Kharitonov systems (4) can be obtained using polynomials (2), (3)

$$G_{ij}(s) = \frac{N_i(s)}{D_j(s)} \tag{4}$$

Substituting $s = j\omega$ into (4) and decomposing the numerator and the denominator polynomials of (4) into their even and odd parts one obtains

$$G_{ij}(j\omega) = \frac{N_{ie}(-\omega^2) + j\omega N_{io}(-\omega^2)}{D_{je}(-\omega^2) + j\omega D_{jo}(-\omega^2)} \tag{5}$$

The closed loop characteristic polynomial is as follows

$$\begin{aligned} \Delta(j\omega) = {} & [k_i N_{ie}(-\omega^2) - k_p\omega^2 N_{io}(-\omega^2) - \\ & -\omega^2 D_{jo}(-\omega^2)] + j[k_p\omega N_{ie}(-\omega^2) + \\ & +k_i\omega N_{io}(-\omega^2) + \omega D_{je}(-\omega^2)] \end{aligned} \tag{6}$$

Then, equating the real and imaginary parts of $\Delta(j\omega)$ to zero, one obtains

$$\begin{aligned} & k_p(-\omega^2 N_{io}(-\omega^2)) + k_i(N_{ie}(-\omega^2)) \\ & = \omega^2 D_{jo}(-\omega^2) \end{aligned} \tag{7}$$

and

$$\begin{aligned} & k_p(N_{ie}(-\omega^2)) + k_i(N_{io}(-\omega^2)) \\ & = -D_{je}(-\omega^2) \end{aligned} \tag{8}$$

After denoting

$$\begin{aligned} F_i(\omega) &= -\omega^2 N_{io}(-\omega^2) \\ G_i(\omega) &= N_{ie}(-\omega^2) \\ H_i(\omega) &= N_{ie}(-\omega^2) \\ I_i(\omega) &= N_{io}(-\omega^2) \\ J_j(\omega) &= \omega^2 D_{jo}(-\omega^2) \\ K_j(\omega) &= -D_{je}(-\omega^2) \end{aligned} \tag{9}$$

(7), (8) and (9) can be written as

$$\begin{aligned} k_p F_i(\omega) + k_i G_i(\omega) &= J_j(\omega) \\ k_p H_i(\omega) + k_i I_i(\omega) &= K_j(\omega) \end{aligned} \tag{10}$$

From these equations, parameters of the PI controller are expressed in the form

$$k_p = \frac{J_j(\omega) I_i(\omega) - K_j(\omega) G_i(\omega)}{F_i(\omega) I_i(\omega) - G_i(\omega) H_i(\omega)} \tag{11}$$

and

$$k_i = \frac{K_j(\omega) F_i(\omega) - J_j(\omega) H_i(\omega)}{F_i(\omega) I_i(\omega) - G_i(\omega) H_i(\omega)} \tag{12}$$

Consider one of the systems (4), where $i = 2$ and $j = 2$

$$G_{22}(s) = \frac{0.178}{500s^2 + 148s + 1} \tag{13}$$

The closed loop characteristic polynomial has according to (6) the form

$$\begin{aligned} \Delta(j\omega) = {} & [-a_1^+\omega^2 + b_0^+ k_i] + \\ & +j[-a_2^+\omega^3 + b_0^+ k_p\omega + \omega] \end{aligned} \tag{14}$$

and then

$$\begin{aligned} k_p &= 2890\omega^2 - 5.6180 \\ k_i &= 831.4607\omega^2 \end{aligned} \tag{15}$$

The stability boundary of the closed loop characteristic polynomial in the (k_p, k_i)-plane for $\omega =$

$[0 : 0.001 : 0.5]$ is plot in the Figure 3. It is seen in the figure that the region is split in two parts, stable and unstable ones. Parameters k_p and k_i of the stabilizing controller are chosen from the stable region.

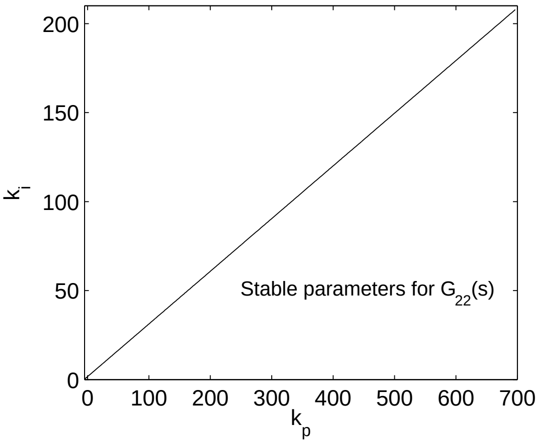

Fig. 3. Stability region of parameters k_p, k_i for the system $G_{22}(s)$

Stable regions for all 8 Kharitonov systems are obtained alike. In the Figure 4 are shown stable regions for 8 Kharitonov systems (4). The controller which stabilizes all 8 Kharitonov systems has to be found in the intersection of all stable regions, which is in detail displaied in the Figure 5.

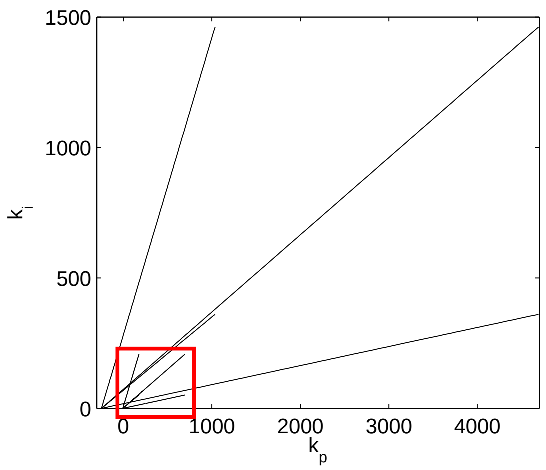

Fig. 4. Stability regions for 8 Kharitonov plants

The parameters of the robust PI controller for control of the laboratory reactor (16) were chosen from the stable region of parameters k_p, k_i according to simulation results obtained for various choices of PI controllers.

$$C(s) = \frac{k_p s + k_i}{s} = \frac{110s + 12}{s} \tag{16}$$

The designed PI controller was used for control of the laboratory reactor. The controlled variable $y(t)$ was the conductivity G $[mS]$ of the NaCl

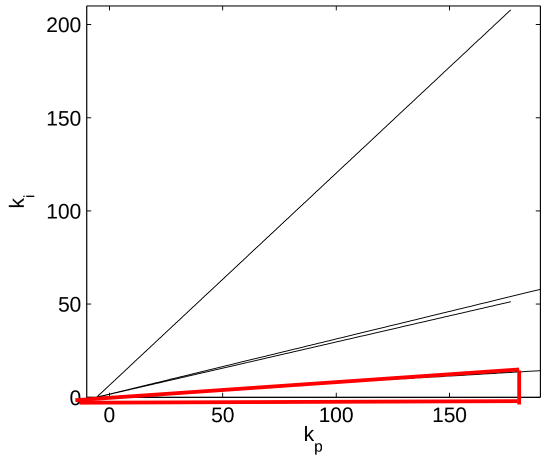

Fig. 5. Detail of the stability region for 8 Kharitonov plants

solution, control variable $u(t)$ was the water flow rate F $[dm^3.min^{-1}]$ and the reference $w(t)$ was the conductivity of the NaCl solution which corresponded to the required concentration of the NaCl solution.

Obtained experimental results are presented in the Figures 6 and 7. Robustness of the designed PI controller (16) was tested by setting the reference value in a wider area. In the Figure 6 are control responses of the reactor for $w \in [8; 16]$ mS and in the Figure 7 for $w \in [11; 21]$ mS.

5. CONCLUSION

The robust PI controller was designed for control of the laboratory continuous stirred tank reactor. A simple robust synthesis was used which was based on plotting the stability boundary locus in the (k_p, k_i)-plane. The stabilizing PI controller was chosen from the stable region of the (k_p, k_i)-plane. The designed controller was tested experimentally by control of a laboratory reactor. Obtained experimental results confirm that the designed robust PI controller succesfully controlled the laboratory reactor. The varying reference was always reached. The conrol responses were without overshoots and fast enough. The future work will be focused on improvement the choice of a stabilizing controller so that also the quality of control will be assured.

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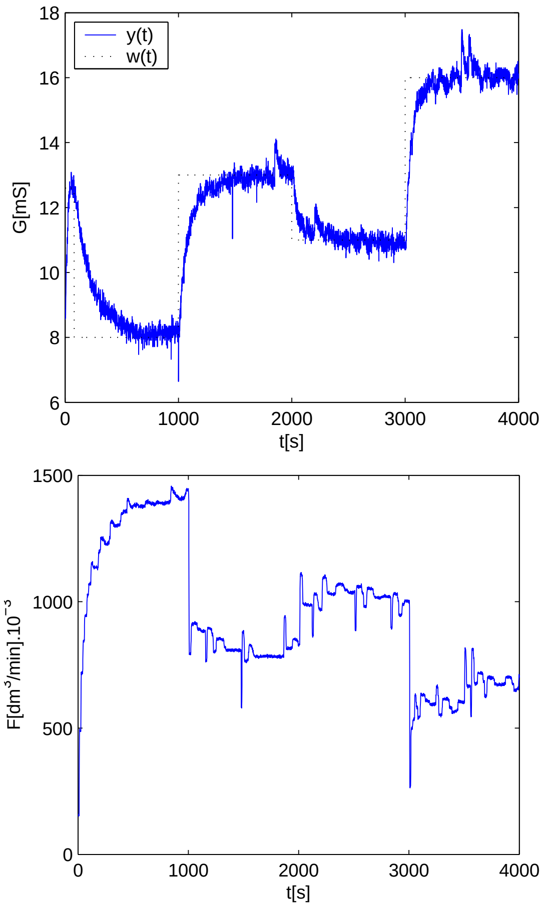

Fig. 6. Control of the reactor with robust PI controller

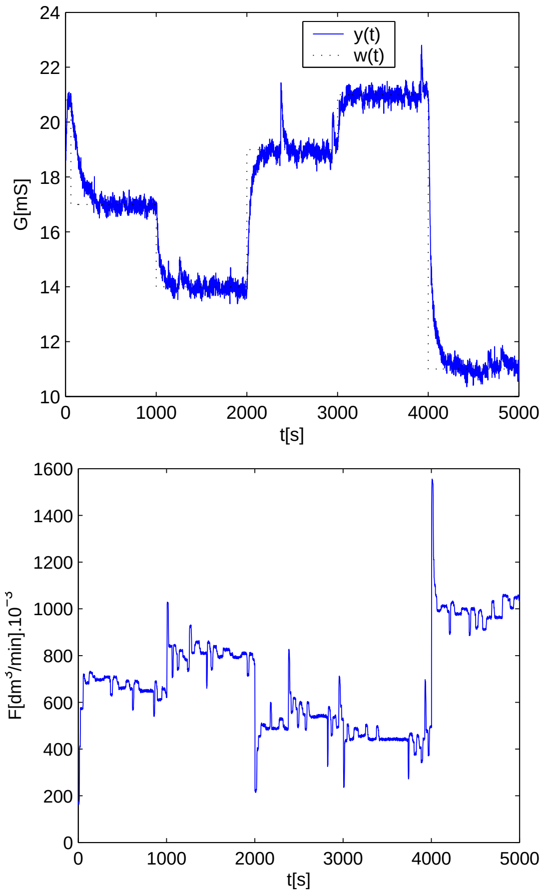

Fig. 7. Control of the reactor with robust PI controller

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