CONTROL STRUCTURES FOR FLOW PROCESS

Mircea Dulău[1], Horaţiu Grif[1], Stelian Oltean[1], Attila Rezi[2]
[1]"Petru Maior" University of Tîrgu-Mureş
[2]S.A.C.P.I. Master
mdulau@engineering.upm.ro, hgrif@engineering.upm.ro

ABSTRACT
In the industrial domain, a large number of applications is covered by slow processes, including the flow, the pressure, the temperature and the level control. Each control system must be treated in steady and dynamic states and from the point of view of the possible technical solutions. Based on mathematical models of the processes and design calculations, PC programs allow simulation and the determination of the control system performances.
The paper presents a part of an industrial process with classical control loops of flow and temperature. The mathematical model of the flow control process was deducted, the control structure, based on experimental criterions, was designed and the version witch ensure the imposed performances was chosen. Using Matlab, the robustness performances were studied.

Keywords: flow control, tuning algorithm, robust control

1. General aspects of the plant

The plant is designed to cool the product (yeast) in a heat exchanger HE and transport at constant flow to a container of (pro)culture.

The plant consists of two hydraulic circuits, namely cooling agent circuit and product circuit, with the following equipments (Fig.1) [8]:

- P1 pump, for cooling agent recirculation, with constant rotation at 3000 *rot/min*; cooling agent temperature value in the input range $(0...-7)\ ^{0}C$;
- P2 pump, for product transport, with max. flow 80 m^3/h; product temperature value in the input range $(+3...+8)\ ^{0}C$;
- HE heat exchanger, with steel plates and V1, V2 volumes;
- proportional valve with three ways;
- pipelines for cooling and product circuits;
- flow transducer and indicator FI, placed on product circuit, at L distance of pump;
- PT 100 temperature transducer, placed on product circuit, at the exchanger output; measurement range is (-20...80) ^{0}C , (4...20) *mA* output;
- VS variable rotation, up to max. 1500 *rot/min*, the current (4...20) *mA*;
- FC flow controller (PLC Siemens), with analogical and digital inputs/outputs; the reference flow is $F_0 = 40\ m^3/h$;
- TIC temperature indicator and controller, with analogical and digital inputs/outputs;
- On/Off valve for opening/closing the cooling circuit.

Initially, the P2 pump for product transport turn on and signals start are transmitted to the controllers, P1 pump and On/Off valve.

The three ways valve keeps the set point temperature ($T_0 = -2.6\ ^{0}C$). If the temperature falls below $1.9\ ^{0}C$, the On/Off valve closes and the P1 pump ensures the cooling agent recirculation.

The P2 pump with variable rotation is the actuator for keeping the flow to the reference value. If the flow falls below minimum value, the plant enters in emergency mode, potentially freezing the heat exchanger.

If the flow reaches maximum value and the pump speed is low, the plant automatically stops because (perhaps) inappropriate viscosity of the product.

2.Mathematical modelling of the process

It is considered the hydraulic circuit for product (yeast), located between P2 pump and FI transducer. For this, the input/output mathematical model and the transfer function are determined, considering the case when the pipeline is equivalent with a hydraulic resistance (short pipeline).

The relationship between flow and differential pressure is [4,6]:

$$\Delta P = \frac{\rho \cdot F^2}{2\alpha^2 A^2}, \qquad (1)$$

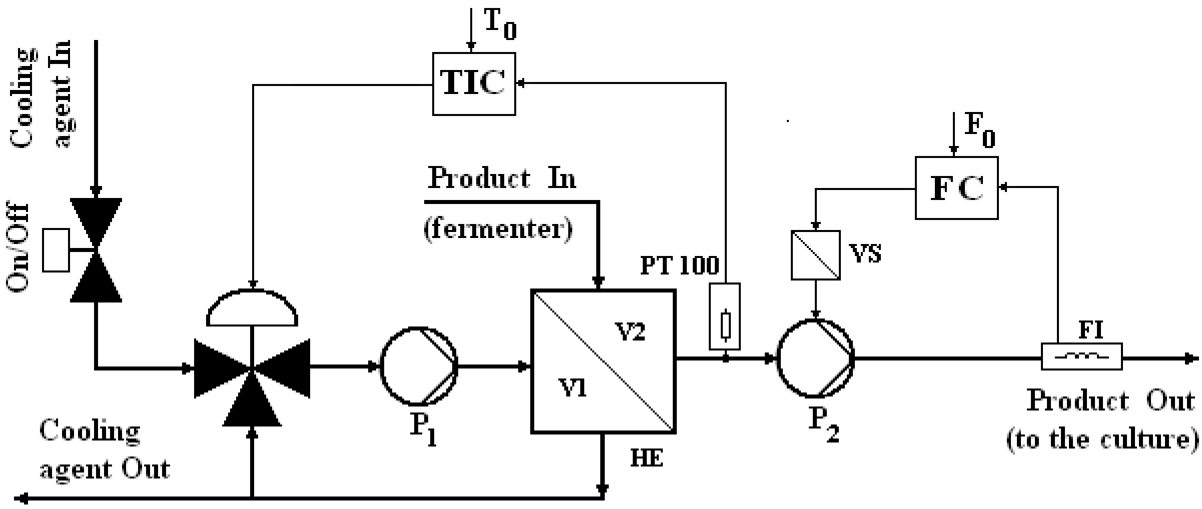

Fig. 1 – The process with flow and temperature loops

where: F – the flow by pipeline; ΔP – differential pressure; A – the pipeline section; α - the flow coefficient; ρ - the product density.

In steady state, the equilibrium relationship between product press force and reaction force is:

$$\Delta P_0 A - \frac{\rho \cdot F_0{}^2}{2\alpha^2 A^2} A = 0 \tag{2}$$

In dynamic state, the flow variations determine the speed variations, so the appearance of inertial effects:

$$\Delta P(t) A - \frac{\rho \cdot F^2(t)}{2\alpha^2 A} = \rho L \frac{d}{dt} F(t) \tag{3}$$

For quantities that are time function, arbitrary variations over the steady state are given:

$$\begin{aligned} &\Delta P(t) = \Delta P_0 + \Delta(\Delta P(t)) = \Delta P_0 + \Delta p(t) \\ &F(t) = F_0 + \Delta F(t) \end{aligned}, \tag{4}$$

then take account the steady state relationship and neglect the terms with $\Delta F^2(t)$. The result is:

$$\Delta p(t) A - \frac{\rho}{\alpha^2 A} F_0 \Delta F(t) = \rho \cdot L \frac{d}{dt} \Delta F(t). \tag{5}$$

After normalization to the steady state values, of the form: $y(t) = \Delta F / F_0$, $u(t) = \Delta p(t) / \Delta P_0$, results the mathematical model of the pipeline in dimensionless variables:

$$T_p \frac{dy(t)}{dt} + y(t) = k_p u(t) \tag{6}$$

Based on Laplace transform, the transfer function of the process is:

$$H_p(s) = \frac{k_p}{T_p \cdot s + 1} \tag{7}$$

where: $k_p = \alpha^2 \Delta P_0 A^2 / (\rho F_0^2)$ is the amplifier value and $T_p = \alpha^2 LA / F_0$ is the time constant.

No mathematical system can exactly model a physical process. The mathematical model take into account the dynamic model of the pipeline, between the measurement point and the controlled point, base on the impulse conservation low.

Typically, the pipeline length L, the flow F, the pressure P, the section A, the density ρ and the constant α would be measured experimentally and/or calculated, leading to the confidence intervals for these parameters and not just a single value [1,3]:

$$\begin{aligned} &F \in [F_n \pm \Delta F]; \\ &P \in [P_n \pm \Delta P]; \\ &\alpha \in [\alpha_n \pm \Delta\alpha]. \end{aligned} \tag{8}$$

The values F_n, P_n, α_n are called nominal values and the ΔF, ΔP, $\Delta\alpha$ are called the maximum deviations from the nominal values.

In practice, there are many admissible transfer functions for this process, one for each possible combination of F, P and α in the given intervals.

3. The control structure and robustness aspects

For the flow control loop, the transfer function of the whole process, results by serial connection of the transducer, the actuator and the pipeline, corrected with the delay time τ, due to the product transport phenomena.

The flow transducer and the actuator (VS+P2) are considered proportional type, with the transfer function k_T and k_E , resulting:

$$H_F(s) = k_T \cdot k_E \cdot \frac{k_p}{T_p s + 1} \cdot e^{-\tau \cdot s} = \frac{k_f}{T_f s + 1} \cdot e^{-\tau \cdot s} \tag{9}$$

A proportional-integrative (PI) algorithm is chosen, witch ensure by P component, speed in command development and by I component, high performances in steady state.

In this case, the open-loop transfer function of the system is:

$$H_d(s) = \frac{k_R}{T_i s}(1 + T_i s) \cdot \frac{k_f}{(T_f s + 1)} \cdot e^{-\tau \cdot s} \tag{10}$$

For tuning, the experimental criterions: Zeigler-Nichols, Oppelt, Chien-Hrones-Reswick and Kapelovici are used and is chosen the version witch ensure the imposed control performances.

For example, the Oppelt criterion recommend the tuning relationships for PI controller [4,6,7]:

$$k_R = 0.8 \cdot \frac{T_f}{k_f \cdot \tau}; \quad T_i = 3 \cdot \tau \qquad (11)$$

There are a variety of techniques that have been developed for robust control.

To be robust, the control system should meet the stability and performance requirements for all possible values of uncertain parameters.

The plant model uncertainty can be a fundamental limiting factor in determining what can be achieved with the feedback.

Considering some characteristic of the feedback system (ex. internally stable), a controller is robust with respect to this characteristic if this characteristic holds for every plant.

The two matrices S and T are known as the sensitivity function and the complementary sensitivity function, in the relationship [1,3,5]:

$$S + T = 1 \qquad (12)$$

The singular value Bode plots of each of these functions give information about the control system design.

4. Experimental results and conclusions

With Oppelt relationships (11), the closed-loop system ensures the imposed performances, namely: overshoot $\sigma = 4\%$, settling time $t_t < 40\,\text{sec.}$, steady state error $\varepsilon_{st} = 0$ (Fig.2).

The Matlab interface allows to simulate the behaviour of the flow process with different types of controllers, determined by experimental criterions.

The closed-loop system responses, considering step inputs can be viewed individually or in the same axes, allowing comparative studies about performances (Fig.3).

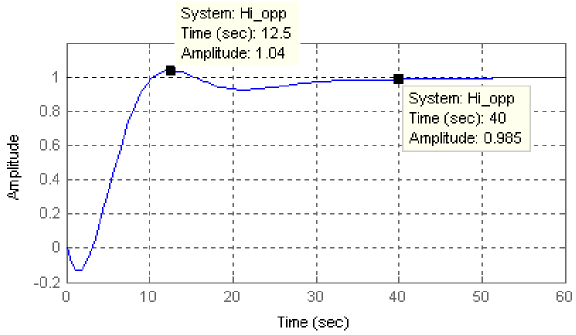

Fig. 2 – Step response with PI Oppelt controller

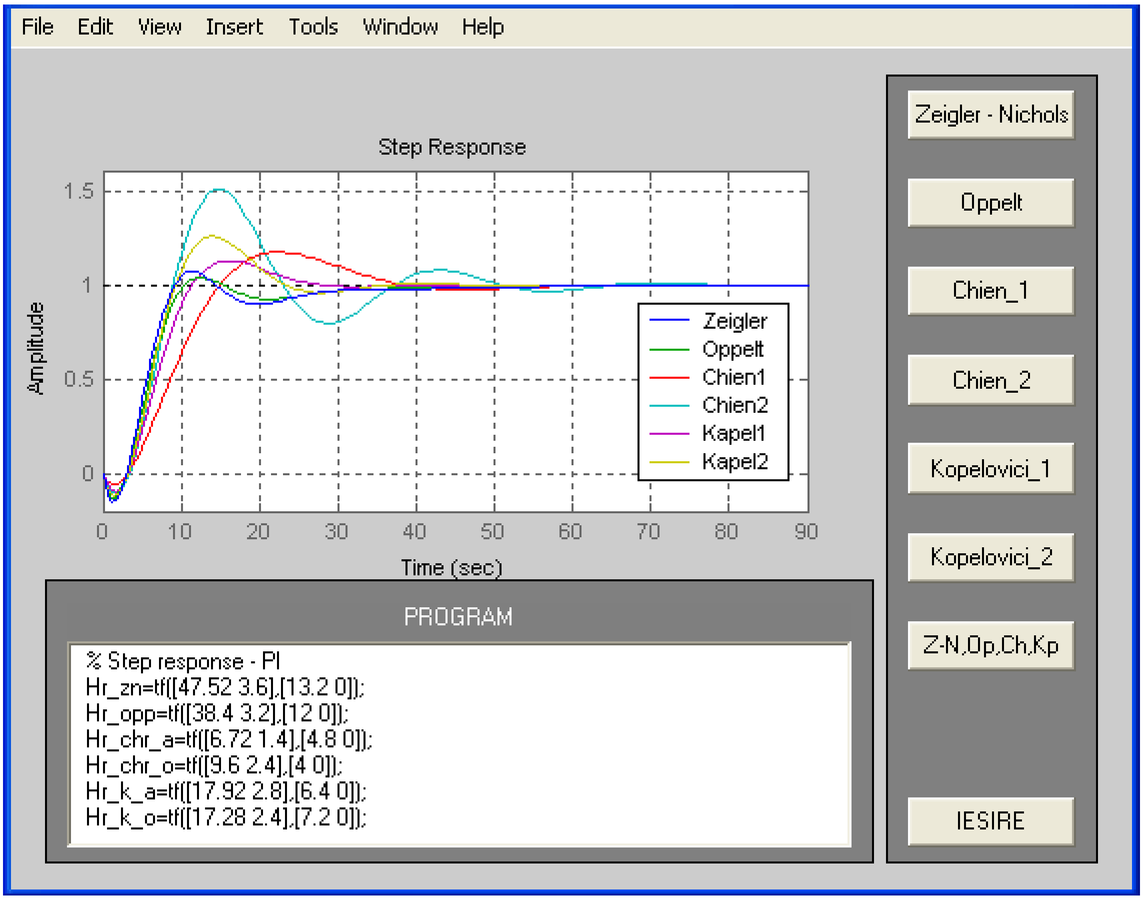

Fig. 3 – The Matlab interface

Some of parameters from the nominal relationship (7) have exact value (L, A) and some of these varies within a specific range of values, defining the uncertain model of the flow process, as follow [8]:

- the nominal value of $k_p = 0.5$ (depending of ΔP and F) and a range between 0.25 and 0.75;
- the nominal value of $T_p = 8$ sec. (depending of α and F) and a range with 10%;

To find how variations of the parameters from the nominal model affect the process and the closed-loop performances, with Matlab techniques are generated a number of random samples of the uncertain parameters and plot the corresponding step responses (Fig.4) [2].

The sensitivity function is a standard measure of closed-loop performances for the feedback system (Fig.5). In the time domain, the sensitivity function indicates how well a step disturbance can be rejected.

The closed-loop robustness analyze, refer to the stability and performance robustness of the closed-loop flow process and this analysis of the nominal closed-loop system indicates that the system is very robust, with 60 deg of phase margin (Fig.6).

In addition is possible to compute the worst-case value of the uncertain sensitivity function for the plant-controller feedback loop and the disturbance rejection characteristics.

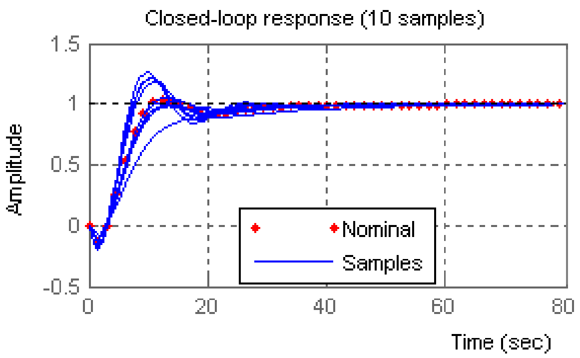

Fig. 4 – Closed-loop responses

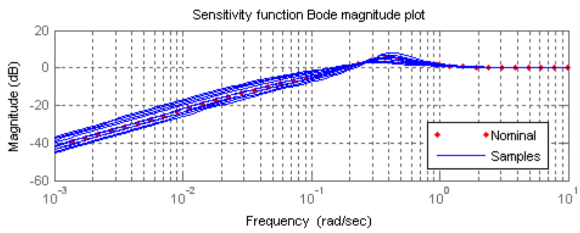

Fig. 5 – Sensitivity function

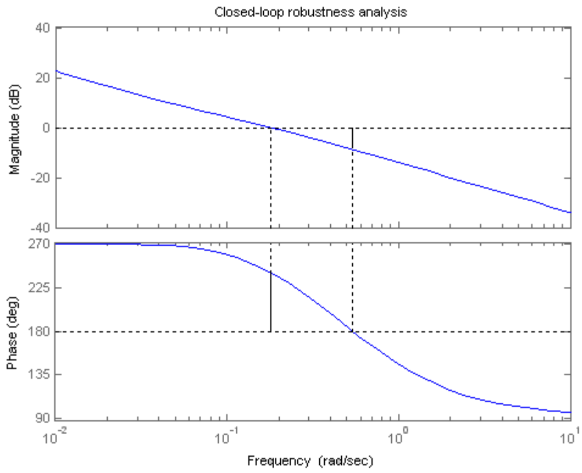

Fig. 6 – Closed-loop responses

Good models of systems are difficult to construct and require a variety of skills from physics, electrical, mechanical and computer engineering to design and implement. For this process the determined mathematical models allows to: describe the mechanism of the process; simulate the behaviour; establish the control structure and strategy.

The Matlab Toolbox offers a collection of functions that allows to analyze and to design the control system without/with uncertain elements [2].

References

[1] Astrom, K.J., *Model Uncertainty and Robust Control*, Department of Automatic Control, Lund University, Sweden, 2001.

[2] Balas, G. at al, *Robust Control Toolbox. For Use with Matlab*, Version 3, The MathWorks, 2006.

[3] Damen, A., Weiland, S., *Robust Control*, University of Technology Eindhoven, 2002.

[4] Dulău, M., *Automation of continuous processes. Thermal and chemical processes*, „Petru Maior" University of Tg.Mureş Publishing House, 2004.

[5] Dulău, M., *The Robust Control Analysis of a Chemical Process*, Acta Electrotehnica, Technical University of Cluj-Napoca, Vol. 50, No.1, Mediamira Science Publisher, pag. 67-72, 2009.

[6] Vânătoru, M., *Control of industrial processes*, Universitaria Publishing House, Craiova, 2001.

[7] Willis, M.J., *Proportional-Integral-Derivative Control*, Dept. of Chemical and Process Engineering, University of Newcastle, 1999.

[8] ***, *Technical Documentation of the beer factory*.