LQ CONTROL OF HEAT EXCHANGER – DESIGN AND SIMULATION

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ABSTRACT

Heat exchangers are devices whose primary responsibility is the transfer (exchange) of heat, typically from one fluid to another. However, they are not only used in heating applications, such as space heaters, but are also used in cooling applications, such as refrigerators and air conditioners. Heat exchange processes often contain time-delay. This paper deals with design of universal and robust digital control algorithms for control of great deal of processes with time-delay. These algorithms are realized by the digital Smith Predictor (SP) based on polynomial approach – by minimization of the Linear Quadratic (LQ) criterion. For a minimization of the LQ criterion is used spectral factorization with application of the MATLAB polynomial Toolbox. The designed polynomial digital Smith Predictors were verified in simulation conditions. Simulation model for a verification of the designed control algorithms was realized using experimental measured data on the laboratory heat exchanger. The program system MATLAB/SIMULINK was used for simulation of the designed algorithms.

INTRODUCTION

Heat exchangers are used for the purpose or transferring heat from a hot fluid to a cold fluid. They are requisite in a range of industrial technologies, particularly in the energetic, metallurgical, chemical and processing of polymer and rubber materials. It is possible to divide heat exchangers into three basic groups: *direct contact exchangers, recuperators, regenerators*. Recuperating (through-flow) heater exchangers are definitely used in industrial practice. Their principle consists in following: the hot and cold fluids are separated by a wall and heat is transferred by conduction through the wall. This class includes double pipe (hairpin), shell and tube, and compact (plate and frame, etc.) exchangers. Heat exchangers are typical systems with time-delay (dead-time) and therefore their good function is dependent on the design and implementation of the optimal control system.

The existence of pure time lag, regardless if it is present in the control or/and the state, may cause undesirable system transient response, or even instability. Consequently, the problem of controllability, observability, robustness, optimization, adaptive control, pole assignment and particularly stability and robust stabilization for this class of systems, has been one of the main interests for many scientists and researchers during the last five decades.

When a high performance of the control process is desired or the relative time-delay is very large, a predictive control strategy is one possible approaches for a control of time-delay processes. The predictive control strategy includes a model of the process in the structure of the controller. The first time-delay compensation algorithm was proposed by (Smith 1957). This control algorithm known as the Smith Predictor contained a dynamic model of the time-delay process and it can be considered as the first model predictive algorithm. First versions of Smith Predictors were designed in the continuous-time modifications, see e.g. (Normey-Rico and Camacho 2007).

Since 1980s digital time-delay compensators can be implemented. The digital time-delay compensators are presented e.g. in (Vogel and Edgar 1980, Palmor and Halevi 1990, Normey-Rico and Camacho 1998). Some Self-tuning Controller (STC) modifications of the digital Smith Predictors (STCSP) are designed in (Hang et al. 1989; Hang et al. 1993; Bobál et al. 2011). Two versions of the STCSP were implemented into MATLAB/SIMULINK Toolbox (Bobál et al. 2012a; Bobál et al. 2012b).

One of possible approaches to control processes with time-delay is digital Smith Predictor based on polynomial theory. Polynomial methods are design techniques for complex systems (including multivariable), signals and processes encountered in Control, Communications and Computing that are based on manipulations and equations with polynomials, polynomial matrices and similar objects. Systems are described by input-output relations in fractional form and processed using algebraic methodology and tools. The design procedure is thus reduced to algebraic polynomial equations (Šebek and

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Hromčík 2007). Controller design consists in solving polynomial (Diophantine) equations. The Diophantine equations can be solved using the uncertain coefficient method – which is based on comparing coefficients of the same power. This is transformed into a system of linear algebraic equations (Kučera 1993). The polynomial digital LQ Smith Predictor for control of unstable and integrating time-delay processes has been designed in (Bobál et al. 2014).
A design of two versions of digital Smith Predictors were realized using minimization of LQ criterion which was solved by spectral factorization. A new universal Smith Predictor was successfully verified by control of a laboratory heat exchanger in simulation conditions.
The paper is organized in the following way. The general problem of control of time-delay systems is described in Section 1. The experimental laboratory heat equipment containing the heat exchanger is described in Section 2. The general principle of the digital Smith Predictor is described in Section 3. The experimental identification of the laboratory heat exchanger is introduced in Section 4. Two versions of primary LQ controllers of the Smith Predictor are proposed in Section 5. Results of simulation experiments are summed in Section 6. Section 7. concludes the paper.

LABORATORY HEAT EQUIPMENT

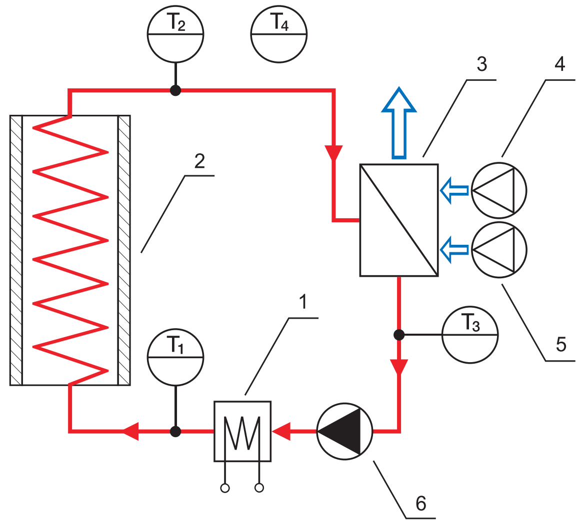

Figure 1: Scheme of Laboratory Heat Equipment

A scheme of the laboratory heat equipment (Pekař et al.) is depicted in Fig. 1. The heat transferring fluid (e. g. water) is transported using a continuously controllable DC pump (6) into a flow heater (1) with max. power of 750 W. The temperature of a fluid at the heater output T_1 is measured by a platinum thermometer. Warmed liquid then goes through a 15 meters long insulated coiled pipeline (2) which causes the significant delay (20 – 200 s) in the system. The air-water heat exchanger (3) with two cooling fans (4, 5) represents a heat-consuming appliance. The speed of the first fan can be continuously adjusted, whereas the second one is of on/off type. Input and output temperatures of the cooler are measured again by platinum thermometers as T_2, respective T_3. The platinum thermometer T_4 is dedicated for measurement of the outdoor-air temperature. The laboratory heat equipment is connected to a standard PC via a technological multifunction I/O card MF 624. This card is designed for the need of connecting PC compatible computers to real world signals. The card is designed for standard data acquisition, control applications and optimized for use with Real Time Toolbox for SIMULINK. The MATLAB/SIMULINK environment was used for all monitoring and control functions.
Some journal or conference papers deal with control of heat exchangers. The comparison of PID controller and Smith Predictor for control of a heat exchanger is described in (Poorani et al.). Much attention is currently paid to Model Predictive Control (MPC) of heat exchangers. The robust MPC of the heat exchanger network is designed and verified by simulation in (Bakošová and Oravec 2013). The subject of paper (Krishna et al.) is a design of the MPC for control of the shell and tube heat exchanger. The designed MPC algorithm and its comparison with PID were realized in simulation conditions. The cascade Generalized Predictive Control (GPC) for heat exchanger process is proposed in (Kokate et al.). The simulation comparison of the cascaded GPC and basic GPC control algorithm realized on a model of the heat exchanger is the main contribution of this paper. The adaptive GPC of a heat exchanger pilot plant is designed in (Bobál et al. 2013a; Bobál et al. 2013b; Zidane et al. 2012).
Disadvantages of MPC methods are quite complicated optimization calculations and in case of adaptive MPC recursive algorithms for the estimation of process model parameters. These computational disadvantages the newly designed digital Smith Predictors remove.

PRINCIPLE OF DIGITAL SMITH PREDICTOR

The discrete versions of the SP and their modifications are suitable for time-delay compensation in industrial practice.

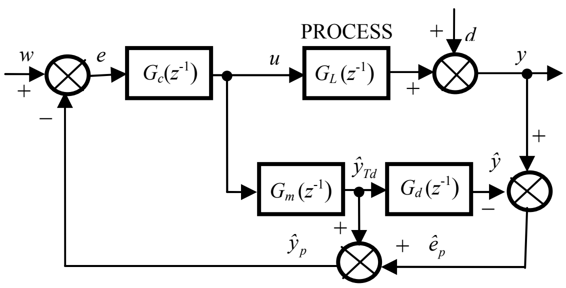

Figure 2: Block diagram of a digital Smith Predictor

The general block diagram of a digital Smith Predictor (see Hang et al. 1989; Hang et al. 1993) is shown in

Fig. 2. The function of the digital version is similar to the classical analog version. The block $G_L\left(z^{-1}\right)$ is the transfer function of the process with time delay. The block $G_m\left(z^{-1}\right)$ represents process dynamics without the time-delay and is used to compute an open-loop prediction. The difference between the output of the process y and the model including time delay $\hat{y}$ is the predicted error $\hat{e}_p$ as shown in Fig. 1, whereas e and d are the error and the measured disturbance, w is the reference signal. If there are no modelling errors or disturbances, the error between the current process output y and the model output $\hat{y}$ will be null. Then the predictor output signal $\hat{y}_p$ will be the time-delay-free output of the process. Under these conditions, the controller $G_c\left(z^{-1}\right)$ can be tuned, at least in the nominal case, as if the process had no time-delay. The primary (main) controller $G_c\left(z^{-1}\right)$ can be designed by different approaches (for example digital PID control, pole assignment method et al.). The outward feedback-loop through the block $G_d\left(z^{-1}\right)$ in Fig. 2 is used to compensate for load disturbances and modelling errors. By the reduced order model with a pure time-delay can be approximated a number of higher order models of industrial processes. In this paper the following second-order linear model with a time-delay is considered

$$G_L\left(z^{-1}\right)=\frac{B\left(z^{-1}\right)}{A\left(z^{-1}\right)}z^{-d}=\frac{b_1z^{-1}+b_2z^{-2}}{1+a_1z^{-1}+a_2z^{-2}}z^{-d} \qquad (1)$$

The term z^{-d} represents the pure discrete time-delay. The time-delay is equal to dT_0 where T_0 is the sampling period.

Individual transfer functions in the block diagram (see Fig. 2) for the second order model are introduced in (Bobál et al. 2011; Bobál et al. 2014).

DESIGN OF PRIMARY POLYNOMIAL 2DOF LQ CONTROLLER

Polynomial control theory uses the apparatus and methods of linear algebra. The design of the control algorithm is based on a general block scheme of a closed-loop with two degrees of freedom (2DOF) according to Fig. 3.

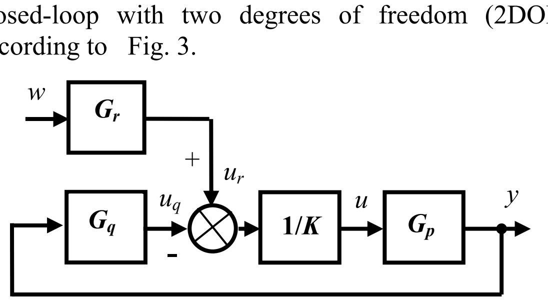

Figure 3: Block diagram of a closed loop 2DOF control system

The controlled process is given by the transfer function in the form

$$G_p(z^{-1})=\frac{Y(z)}{U(z)}=\frac{B(z^{-1})}{A(z^{-1})} \qquad (2)$$

where A and B are the second degree polynomials. The controller contains the feedback part G_q and the feedforward part G_r. Then the digital controllers can be expressed in the form of discrete transfer functions

$$G_r\left(z^{-1}\right)=\frac{R\left(z^{-1}\right)}{K\left(z^{-1}\right)P\left(z^{-1}\right)} \qquad (3)$$

$$G_q\left(z^{-1}\right)=\frac{Q\left(z^{-1}\right)}{K\left(z^{-1}\right)P\left(z^{-1}\right)} \qquad (4)$$

where $K\left(z^{-1}\right)=1-z^{-1}$.

According to the scheme presented in Fig. 3 and equations (1) – (4) it is possible to derive a polynomial Diophantine equation for computation of feedback controller parameters as coefficients of the polynomials Q and P

$$A(z^{-1})K(z^{-1})P(z^{-1})+B(z^{-1})Q(z^{-1})=D(z^{-1}) \qquad (5)$$

where $D\left(z^{-1}\right)$ is the characteristic polynomial.

Asymptotic tracking of the reference signal w is provided by the feedforward part of the controller which is given by solution of the following polynomial Diophantine equation

$$S(z^{-1})D_w\left(z^{-1}\right)+B(z^{-1})R(z^{-1})=D(z^{-1}) \qquad (6)$$

For a step-changing reference signal value, polynomial $D_w\left(z^{-1}\right) = 1 - z^{-1}$ and S is an auxiliary polynomial which does not enter into the controller design. Then it is possible to derive the polynomial R from equation (6) by substituting $z = 1$

$$R=r_0=\frac{D(1)}{B(1)} \qquad (7)$$

The 2DOF controller output is given by

$$u(k)=\frac{r_0}{K\left(z^{-1}\right)P\left(z^{-1}\right)}w(k)-\frac{Q\left(z^{-1}\right)}{K\left(z^{-1}\right)P\left(z^{-1}\right)}y(k) \qquad (8)$$

Two primary polynomial LQ controllers are derived in this paper using minimization of LQ criterion (Šebek and Kučera 1982). For a minimization procedure is used spectral factorization by means of the MATLAB Polynomial Toolbox 3.0 (Šebek 2014).

Minimization of LQ Criterion Using $u(k)$

In the first case the linear quadratic control methods try to minimize the quadratic criterion by penalization the value of the controller output

$$J=\sum_{k=0}^{\infty}\left\{\left[w(k)-y(k)\right]^2+q_u\left[u(k)\right]^2\right\} \quad (9)$$

where q_u is the so-called penalization constant, which gives the rate of the controller output on the value of the criterion (where the constant at the first element of the criterion is considered equal to one). In this paper, criterion minimization (9) will be realized through the spectral factorization for an input-output description of the system

$$A(z)q_uA\left(z^{-1}\right)+B(z)B\left(z^{-1}\right)=D(z)\delta D\left(z^{-1}\right) \quad (10)$$

where δ is a constant chosen so that $d_0 = 1$.

Spectral factorization of polynomials of the first and the second degree can be computed simply by analytical way (Bobál et al. 2005; Bobál et al. 2014); the procedure for higher degrees must be performed iteratively. The MATLAB Polynomial Toolbox is used for a computation of spectral factorization (10).

Because $A\left(z^{-1}\right)$ and $B\left(z^{-1}\right)$ are the second degree polynomials, factorized polynomial $D\left(z^{-1}\right)$ must be also the second degree

$$D_2\left(z^{-1}\right)=1+d_{21}z^{-1}+d_{22}z^{-2} \quad (11)$$

For computation of the spectral factorization (10) was used in this paper file *spf.m* by command

d = spf(a*qu*a' + b*b') (12)

It is obvious that by using of the spectral factorization, only two parameters d_{21} and d_{22} of the second degree polynomial $D_2(z^{-1})$ (11) can be computed. This approach is applicable only for control of processes without time-delay (out of Smith Predictor). The primary controller in the digital Smith Predictor structure requires usage of the fourth degree polynomial

$$D_4\left(z^{-1}\right)=1+d_1z^{-1}+d_2z^{-2}+d_3z^{-3}+d_4z^{-4} \quad (13)$$

in equations (5) and (6). The polynomial $D_2(z^{-1})$ (11) has two different real poles α, β or one complex conjugated pole $z_{1,2}=\alpha\pm j\beta$ (in the case of oscillatory systems). These poles must be included into polynomial $D_4(z^{-1})$ (13) and other two poles γ, δ are user-defined real poles. A suitable pole assignment was designed for both types of the processes in (Bobál et al. 2014).

Then the digital 2DOF controller (8) can be expressed in the form

$$\begin{aligned}&\left[1+\left(p_1-1\right)z^{-1}-p_1z^{-2}\right]u(k)\\&=r_0w(k)-\left(q_0+q_1z^{-1}+q_2z^{-2}\right)y(k)\end{aligned} \quad (14)$$

where

$$r_0=\frac{1+d_1+d_2+d_3+d_4}{b_1+b_2} \quad (15)$$

and parameters q_0, q_1, q_2 are computed from (5). The primary 2DOF controller output is given by

$$\begin{aligned}u(k)&=r_0w(k)-q_0y(k)-q_1y(k-1)-q_2y(k-2)\\&+\left(1-p_1\right)u(k-1)+p_1u(k-2)\end{aligned} \quad (16)$$

Minimization of LQ Criterion Using *Δu*(*k*)

In the second case the linear quadratic control methods try to minimize the quadratic criterion by penalization of the incremental value of controller output

$$J=\sum_{k=0}^{\infty}\left\{\left[w(k)-y(k)\right]^2+q_u\left[\Delta u(k)\right]^2\right\} \quad (17)$$

Equation (10) for computation of the spectral factorization changes into

$$\begin{aligned}&(1-z)A(z)q_u\left(1-z^{-1}\right)A\left(z^{-1}\right)\\&+B(z)q_uB\left(z^{-1}\right)=D(z)\delta D\left(z^{-1}\right)\end{aligned} \quad (18)$$

It is obvious that after arrangement and substitution the first term of the left side (18) has this form

$$\left(1+a_{s1}z+a_{s2}z^2+a_{s3}z^3\right)q_u\left(1+a_{s1}z^{-1}+a_{s2}z^{-2}+a_{s3}z^{-3}\right) \quad (19)$$

where

$$A_s\left(z^{-1}\right)=1+a_{s1}z^{-1}+a_{s2}z^{-2}+a_{s3}z^{-3} \quad (20)$$

and

$$a_{s1}=a_1-1;\quad a_{s2}=a_2-a_1;\quad a_{s3}=-a_3. \quad (21)$$

Because (20) is the third degree polynomial whose parameters and poles α, β and γ it is impossible to compute by an analytical way, MATLAB Polynomial Toolbox 3 was used for their computation using command (12).

The characteristic polynomial is the sixth degree polynomial in this case

$$\begin{aligned}D_6\left(z^{-1}\right)&=1+d_1z^{-1}+d_2z^{-2}+d_3z^{-3}\\&+d_4z^{-4}+d_5z^{-5}+d_6z^{-6}\end{aligned} \quad (22)$$

Spectral factorization (18) gives three optimal parameters of polynomial (20) and then it is possible to write characteristic polynomial (26) as a combination of polynomial (23) and product root of factors in positive power of variable z

$$\begin{aligned}D_6(z)&=\left(z^3+a_{s1}z^2+a_{s2}z+a_{s3}\right)\\&\left(z-\lambda\right)\left(z-\mu\right)\left(z-\nu\right)\end{aligned} \quad (23)$$

where λ, μ, ν are user-defined real poles. After modification (23) the characteristic polynomial is in the following form

$$D_6(z) = z^6 + d_1 z^5 + d_2 z^4 + d_3 z^3 + d_4 z^2 + d_5 z + d_6 \quad (24)$$

After comparison of (23) and (24) it is possible to obtain expressions for computation of individual parameters of polynomial (24)

$$\begin{aligned} d_1 &= a_{s1} - \lambda - \mu - \nu \\ d_2 &= a_{s2} + \nu(\lambda + \mu) - a_{s1}(\lambda + \mu + \nu) + \lambda\mu \\ d_3 &= a_{s1}\nu(\lambda + \mu) - a_{s2}(\lambda + \mu + \nu) - \lambda\mu\nu + a_{s3} \\ d_4 &= a_{s2}\mu(\lambda + \mu) - a_{s1}\lambda\mu\nu + a_{s2}\lambda\mu - a_{s3}(\lambda + \mu + \nu) \\ d_5 &= a_{s3}\lambda\mu - a_{s2}\lambda\mu\nu + a_{s3}\nu(\lambda + \mu) \\ d_6 &= -a_{s3}\lambda\mu\nu \end{aligned} \quad (25)$$

Then the 2DOF controller design consists of determination of parameters (26) of polynomial (25) using command (12) from the Polynomial Toolbox and solution of the Diophantine Equation for computation of feedback controller parameters

$$A_s(z^{-1})K(z^{-1})P(z^{-1}) + B(z^{-1})Q(z^{-1}) = D_6(z^{-1}) \quad (26)$$

where

$$K(z^{-1}) = 1 - z^{-1}; \quad P(z^{-1}) = 1 + p_1 z^{-1} + p_2 z^{-2}; \quad Q(z^{-1}) = q_0 + q_1 z^{-1} + q_2 z^{-2} + q_3 z^{-3} \quad (27)$$

and from expression (7)

$$r_0 = \frac{1 + d_1 + d_2 + d_3 + d_4 + d_5 + d_6}{b_1 + b_2} \quad (28)$$

The primary 2DOF controller output is given by

$$\begin{aligned} u(k) = {} & r_0 w(k) - q_0 y(k) - q_1 y(k-1) - q_2 y(k-2) \\ & + (p_1 - p_2)u(k-2) - p_2 u(k-3) \end{aligned} \quad (29)$$

SIMULATION VERIFICATION AND RESULTS

On the basis of identification experiments (Bobál et al. 2013), the discrete model in the following form

$$G(z^{-1}) = \frac{0.1494 z^{-1} + 0.028 z^{-2}}{1 - 0.6376 z^{-1} - 0.1407 z^{-2}} z^{-2} \quad (30)$$

with a sampling period T_0 = 50 s was used for a simulation verification of the designed control algorithms in MATLAB/SIMULINK environment. The simulation experiments have been realized using minimization of both criterions (9) and (17). For individual control experiments have been chosen following control conditions.

Influence of Penalization Factor q_u on Control Courses

The process which is described by transfer function (30) was used in the Simulink control scheme for the verification of the dynamical behaviour for different penalization factors.

Control using primary controller (16)

1. Experiment, q_u = 0.01
   The poles:
   $\alpha = 0.2089; \quad \beta = -0.1720; \quad \gamma = 0.01; \quad \delta = 0.1$
   The characteristic polynomial:
   $D_4(z) = z^4 - 0.1478z^3 - 0.0309z^2 + 0.0039z - 3.6100e-05$
2. Experiment, q_u = 1
   The poles:
   $\alpha = 0.7647; \quad \beta = -0.1725; \quad \gamma = 0.01; \quad \delta = 0.1$
   The characteristic polynomial:
   $D_4(z) = z^4 - 0.7012z^3 - 0.0667z^2 + 0.0140z - 1.3270e-04$
3. Experiment, q_u = 3
   The poles:
   $\alpha = 0.8597; \quad \beta = -0.7219; \quad \gamma = 0.01; \quad \delta = 0.1$
   The characteristic polynomial:
   $D_4(z) = z^4 - 0.2478z^3 - 0.6044z^2 + 0.0681z - 6.2060e-04$

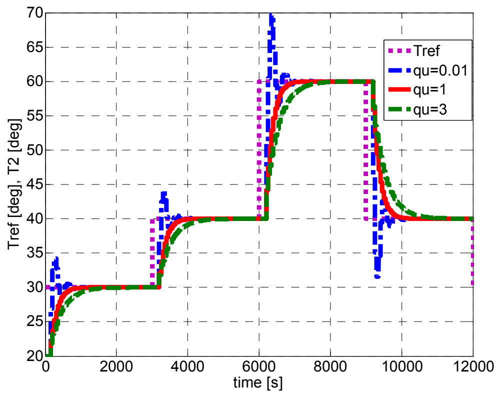

Figure 5: Courses of process outputs – controller (16)

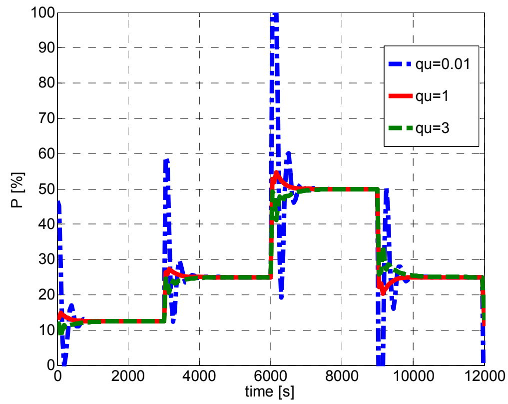

Figure 6: Courses of controller outputs – controller (16)

The courses of the process outputs and controller outputs for individual penalization factors q_u are shown in Figs. 5 and 6. From these Figs. follows that for low value of q_u the control courses oscillate. By increasing of q_u the courses of the control variables are without overshoots.

Control using primary controller (29)

1. Experiment, q_u = 0.01
   The poles:

$\alpha = -0.1739; \quad \beta, \gamma = 0.2531 \pm 0.2824i;$
$\lambda = 0.2; \quad \mu = 0.3; \quad \nu = 0.4$

The characteristic polynomial:

$$D_6(z) = z^6 - 1.2323z^5 + 0.6149z^4 - 0.1356z^3 - 1.6800e-05z^2 + 0.0052z - 6.0000e-04$$

2. Experiment, $q_u = 2$

   The poles:
   $\alpha = -0.1735; \quad \beta, \gamma = 0.7482 \pm 0.1661i;$
   $\lambda = 0.2; \quad \mu = 0.3; \quad \nu = 0.4$

   The characteristic polynomial:

$$D_6(z) = z^6 - 2.2228z^5 + 1.7782z^4 - 0.5610z^3 + 0.0252z^2 + 0.0186z - 0.0024$$

3. Experiment, $q_u = 5$

   The poles:
   $\alpha = -0.1735; \quad \beta, \gamma = 0.7915 \pm 0.1296i;$
   $\lambda = 0.2; \quad \mu = 0.3; \quad \nu = 0.4$

   The characteristic polynomial:

$$D_6(z) = z^6 - 2.3066z^5 + 1.8973z^4 - 0.6107z^3 + 0.0293z^2 + 0.0202z - 0.0027$$

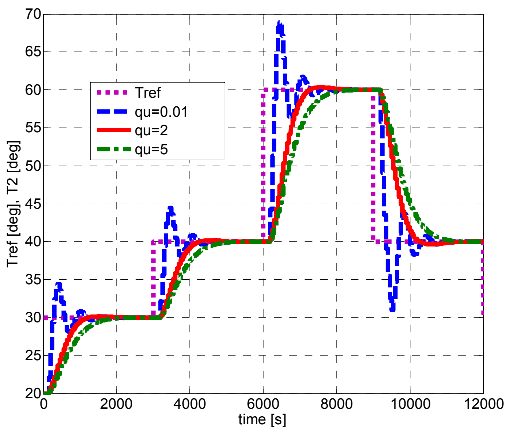

Figure 7: Courses of process outputs – controller (29)

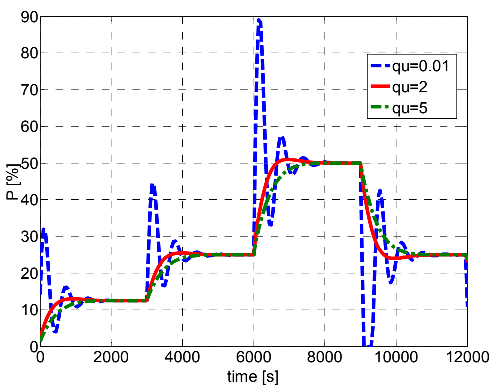

Figure 8: Courses of controller outputs – controller (29)

The courses of the process outputs and controller outputs for individual penalization factors q_u are shown in Figs. 7 and 8. From these Figs. it is evident that the dynamical behaviour of the control variables is similar as in case of controller (16). However, the transient responses are slower and controller (29) is more conservative and robust than controller (16).

CONCLUSION

The contribution presents the use of the MATLAB Polynomial Toolbox 3.0 for design of the polynomial digital Smith Predictor for control of the laboratory heat exchanger. The primary controllers of the digital Smith Predictor are based on minimization of the LQ criterion using spectral factorization. Two types of minimization of LQ criterions have been designed. In criterion (9) it is minimized a square of the controller output $u(k)$ – controller (16). In criterion (17) it is minimized a square of the increment value of the controller output $\Delta u(k)$ – controller (29). For the design of controller (16) two poles of the characteristic polynomial were determined using MATLAB Polynomial Toolbox and other two poles are user-defined. For the design of controller (29) three poles of the characteristic polynomial were determined using MATLAB Polynomial Toolbox and other three poles are user-defined. Simulation experiments demonstrated the influence of penalization factor q_u on the course of control variables. From comparison of both methods it is evident that minimization criterion (17) leads to more slow courses of control variables with their smaller oscillations for lower values q_u. The controller (29) is more conservative and robust than controller (16). From comparison of control using polynomial LQ Smith Predictor with MPC approach follows that algorithms of the first approach are relatively simple and are more suitable for application in industrial practice.

REFERENCES

Bobál, V., Böhm, J., Fessl, J. and J. Macháček. 2005. *Digital Self-tuning Controllers: Algorithms, Implementation and Applications.* Springer-Verlag, London.

Bobál, V., Chalupa, P., Dostál, P. and M. Kubalčík. 2011. "Design and simulation verification of self-tuning Smith predictors." *International Journal of Mathematics and Computers in Simulation*, 5, 342-351.

Bobál, V., Chalupa, P., Novák, J. and P. Dostál. 2012a. "MATLAB Toolbox for CAD of self-tuning of time-delay processes." In *Proc. of the International Workshop on Applied Modelling and Simulation*, Roma, 44 – 49.

Bobál, V., Chalupa, P. and J. Novák. 2012b. "Toolbox for CAD and Verfication of Digital Adaptive Control Time-Delay Systems." Available from http://nod32.fai.utb.cz/promotion/Software_OBD/Time_Delay_Tool.zip.

Bobál, V., Chalupa, P., Dostál, P. and M. Kubalčík. 2013a. "Identification and self-tuning predictive control of heat exchanger." In *Proceedings of the 2013 International Conference on Process Control*, Štrbské Pleso, Slovakia, 219-224.

Bobál, V., Kubalčík, M., Dostál, P. and J. Matějíček. 2013b. "Adaptive predictive control of time-delay systems." *Computers and Mathematics with Applications*, 66, 165-176.

Bobál, V., Chalupa, P., Dostál, P. and M. Kubalčík. 2014. “Digital control of unstable and integrating processes.” *International Journal of Circuits, Systems and Signal Processing*, 8, 424-432.
Camacho, E. F. and C. Bordons. 2004. *Model Predictive Control.* Springer-Verlag, London.
Hang, C. C., Lim, K. W. and B. W. Chong. 1989. “A dual-rate digital Smith predictor.” *Automatica*, 20, 1-16.
Hang, C. C., Tong, H. L. and K. H. Weng. 1993. *Adaptive Control*, North Carolina: Instrument Society of America.
Kokate, R. D. and L. M. Waghmare. 2010. “Cascade generalized predictive control for heat exchanger process.” *International Journal of Signal System Control and Engineering Application*, 3, 13-27.
Krishna, K., Ramkumar, K. and V. Alagesan. 2012. “Control of heat exchangers using model predictive control.” In *Proceedings of the IEEE International Conference on Advances in Engineering, Science and Management*, Nagapttmam, India, 242-246.
Kučera, V. 1993. “Diophantine equations in control – a survey.” *Automatica*, 29, 1361-1375.
Normey-Rico, J. E. and E. F. Camacho. 1998. “Dead-time compensators: A unified approach. In *Proceedings of IFAC Workshop on Linear Time Delay Systems (LDTS’98)*, Grenoble, France, 141-146.
Normey-Rico, J. E. and E. F. Camacho. 2007. *Control of Dead-time Processes*, Springer-Verlag, London.
Palmor, Z. J. and Y. Halevi. 1990. “Robustness properties of sampled-data systems with dead time compensators.” *Automatica*, 26, 637-640.
Pekař, L., Prokop, R. and P. Dostálek. 2009. “Circuit heating plant model with internal delays.”*WSEAS Transactions on Systems and Control*, 8, 1093-1104.
Poorani, V. J., and L. D. Vijay Anad. 2013. “Comparison of PID controller and Smith Predictor controller for heat exchanger.” In *Proceedings of the IEEE International Conference on Emerging Trends in Computing and Nanotechnology*, Tirunnelveli, India, 217-221.
Smith, O. J. 1957. “Closed control of loops.” *Chem. Eng. Progress*, 53, 217-219.
Šebek, M. 2014. *Polynomial Toolbox for MATLAB, Version 3.0.*, PolyX, Prague, Czech Republic.
Šebek, M. and M. Hromčík. 2007. “Polynomial design Methods.” *International of Robust Nonlinear Control*, 17, 679-681.
Šebek, M. and V. Kučera. 1982. “Polynomial approach to quadratic tracking in discrete linear systems.” *IEEE Trans. Automatic. Control* AC-27, 1248-1250.
Vogel, E. F. and T. F. Edgar 1980. “A new dead time compensator for digital control.” In *Proceedings ISA Annual Conference*, Houston, USA, 29-46.
Zidane, Z., Latkih, M. A and M. Ramzi. 2012. “Adaptive predictive control of heat exchanger.” *Journal of Mechanical Engineering and Automation*, 2, 100-107.

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