DIGITAL LINEAR QUADRATIC SMITH PREDICTOR

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ABSTRACT

Time-delays (dead times) are found in many processes in industry. Time-delays are mainly caused by the time required to transport mass, energy or information, but they can also be caused by processing time or accumulation. The contribution is focused on a design of universal digital algorithm for control of great deal of processes with time-delay. This requirement is successfully satisfied with digital Smith Predictor based on Linear Quadratic (LQ) method. A minimization of the quadratic criterion is realized using spectral factorization. The designed algorithm is suitable for control of stable, unstable and non-minimum phase processes. The algorithms for control of individual processes influenced by external disturbance were verified. The program system MATLAB/SIMULINK was used for simulation of designed algorithms.

INTRODUCTION

Time-delays appear not only in industrial processes, such as thermal, chemical, metallurgical or processes of plastic and rubber materials etc., but also in other fields, including economical and biological systems. They are caused by some of the following phenomena (Normy-Rico and Camacho 2007):

- the time needed to transport mass, energy or information,
- the accumulation of time lags in a great numbers of low order systems connected in series,
- the required processing time for sensors, such as analyzers; controllers that need some time to implement a complicated control algorithms or process.

The problem of controlling time-delay processes can be solved by several control methods (e. g. using PID controllers, time-delay compensators, model predictive control techniques).

Time-delay in a process increases the difficulty of controlling it. However, the approximation of higher-order process by lower-order model with time-delay provides simplification of the control algorithms. When high performance of the control process is desired or the relative time-delay is very large, the predictive control strategy can be successfully applied. The predictive control method 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 (SP) 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).

Although time-delay compensators appeared in the mid 1950s, their implementation with analog technique was very difficult and these were not used in industry. Because most of modern controllers are implemented on digital platforms, the discrete versions of the time-delay controllers are more suitable for time-delay compensation in industrial practice

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).

It is well known that classical analog Smith Predictor is not suitable for control of unstable processes. The designed digital LQ Smith Predictor eliminates this drawback.

The paper is organized in the following way. The problem of a control of the time-delay systems is described in Section 1. The general principle of the Smith Predictor is described in Section 2. The discretization of analogue version, principle of digital Smith Predictor and polynomial two degrees of freedom (2DOF) controller is introduced in Section 3. Primary Linear Quadratic controller of the digital Smith Predictor is proposed in Section 4. Results of simulation experiments are summed in Section 5. Section 6 concludes the paper.

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DIGITAL SMITH PREDICTOR

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

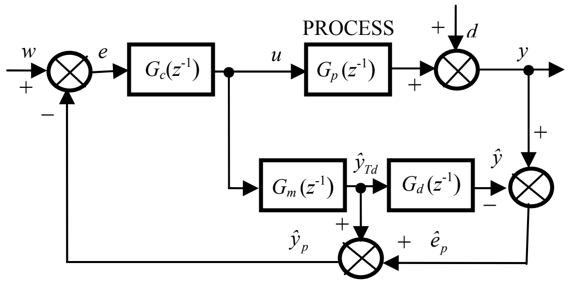

Figure 1: Block diagram of a digital Smith Predictor

The block diagram of a digital SP (see Hang, Lim, and Chong 1989; Hang, Tong, and Weng 1993) is shown in Fig. 1. The function of the digital version is similar to the classical analog version. 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 v 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 or methods based on algebraic approach). The outward feedback-loop through the block $G_d\left(z^{-1}\right)$ in Fig. 1 is used to compensate for load disturbances and modelling errors.
Number of higher order industrial processes can be approximated by a reduced order model with a pure time-delay. In this paper the following second-order linear model with a time-delay is considered

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

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.

Design of Polynomial 2DOF Controller

Previous simulation experiments demonstrated that polynomial theory is suitable method for design of the digital Smith Predictor. Polynomial control theory is based on the apparatus and methods of linear algebra (see e.g. Kučera 1993). The polynomial Smith Predictor based on the digital pole assignment was designed in (Bobál et al. 2011). The design of the controller algorithm is based on the general block scheme of a closed-loop with two degrees of freedom (2DOF) according to Fig. 2.

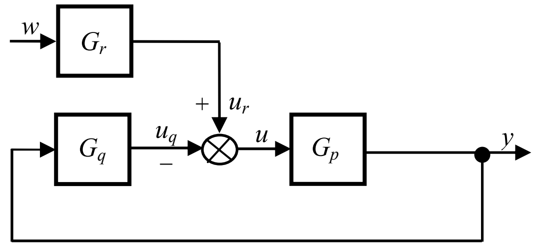

Figure 2: Block diagram of a closed loop 2DOF control system

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 order 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

$$G_r\left(z^{-1}\right)=\frac{R\left(z^{-1}\right)}{P\left(z^{-1}\right)}=\frac{r_0}{\left(1+p_1z^{-1}\right)\left(1-z^{-1}\right)} \qquad (3)$$

$$G_q\left(z^{-1}\right)=\frac{Q\left(z^{-1}\right)}{P\left(z^{-1}\right)}=\frac{q_0+q_1z^{-1}+q_2z^{-2}}{\left(1+p_1z^{-1}\right)\left(1-z^{-1}\right)} \qquad (4)$$

According to the scheme presented in Fig. 2 and equations (1) – (4) it is possible to derive the characteristic polynomial

$$A(z^{-1})P(z^{-1})+B(z^{-1})Q(z^{-1})=D_4(z^{-1}) \qquad (5)$$

where

$$D_4\left(z^{-1}\right)=1+d_1z^{-1}+d_2z^{-2}+d_3z^{-3}+d_4z^{-4} \qquad (6)$$

is the fourth degree characteristic polynomial.
The procedure leading to determination of polynomials Q, R and P in (3) and (4) can be briefly described as follows (see Bobál et al. 2005). A feedback part of the controller is given by a solution of the polynomial Diophantine equation (5). An asymptotic tracking is provided by a feedforward part of the controller given by a solution of the polynomial Diophantine equation

$$S(z^{-1})D_w\left(z^{-1}\right)+B(z^{-1})R(z^{-1})=D_4(z^{-1}) \qquad (7)$$

For a step-changing reference signal value, polynomial $D_w(z^{-1}) = 1 - z^{-1}$ and S is an auxiliary polynomial which does not enter into controller design.

A feedback controller to control a second-order system without time-delay will be derived from equation (5). A system of linear equations can be obtained using the uncertain coefficients method

$$\begin{bmatrix} b_1 & 0 & 0 & 1 \\ b_2 & b_1 & 0 & a_1-1 \\ 0 & b_2 & b_1 & a_2-a_1 \\ 0 & 0 & b_2 & -a_2 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ p_1 \end{bmatrix} = \begin{bmatrix} d_1+1-a_1 \\ d_2+a_1-a_2 \\ d_3+a_2 \\ d_4 \end{bmatrix} \qquad (8)$$

For a step-changing reference signal value it is possible to derive the polynomial R from equation (7) by substituting $z = 1$

$$R = r_0 = \frac{D(1)}{B(1)} = \frac{1+d_1+d_2+d_3+d_4}{b_1+b_2} \qquad (9)$$

The 2DOF controller output is then given by

$$\begin{aligned} u(k) = r_0 w(k) - q_0 y(k) - q_1 y(k-1) - q_2 y(k-2) \\ +(1+p_1)u(k-1) + p_1 u(k-2) \end{aligned} \qquad (10)$$

Minimization of LQ Criterion

The linear quadratic methods try to minimize the quadratic criterion with penalization of the controller output

$$J = \sum_{k=0}^{\infty} \left\{ \left[w(k)-y(k)\right]^2 + q_u \left[u(k)\right]^2 \right\} \qquad (11)$$

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). The standard procedure of the minimization of the criterion (11) is based on the state description of the system and leads to the solution of the Riccati Equation. In this paper, criterion minimization is realized through spectral factorization for the input-output description of the system (Bobál et al. 2005).

If the sequences of the values of both tracking error and input signal are considered as polynomials, it is possible to rewrite the criterion (11) using notation $\langle x(z) \rangle = x(0)$

$$J = \left\langle E(z)E(z^{-1}) + q_u U(z)U(z^{-1}) \right\rangle \qquad (12)$$

where $E(z)$ and $U(z)$ are the conjugated polynomials to the polynomials $E(z^{-1})$ and $U(z^{-1})$, which means their negative powers are replaced by positive ones.

The tracking error polynomial

$$\begin{aligned} E(z^{-1}) &= W(z^{-1}) - Y(z^{-1}) \\ &= \left[1 - \frac{B(z^{-1})R(z^{-1})}{A(z^{-1})P(z^{-1}) + B(z^{-1})Q(z^{-1})}\right] W(z^{-1}) \end{aligned} \qquad (13)$$

and the input signal polynomial

$$U(z^{-1}) = \frac{A(z^{-1})R(z^{-1})}{A(z^{-1})P(z^{-1}) + B(z^{-1})Q(z^{-1})} W(z^{-1}) \qquad (14)$$

are substituted into criterion (11). It can be verified (Šebek and Kučera 1982) that the criterion is minimal if equation (5) is valid. The polynomial $D(z^{-1})$ is the result of spectral factorization according to the equation

$$A(z^{-1}) q_u A(z) + B(z^{-1})B(z) = D(z^{-1})\delta D(z) \qquad (15)$$

where δ is a constant chosen so that $d_0 = 1$. The spectral factorization of a polynomial leaves its stable part unchanged, while the unstable parts change to reciprocal ones (stable). Spectral factorization of polynomial of the first and the second degree could be computed simply; the procedure for the higher degrees must be performed iteratively.

While performing the spectral factorization of a polynomial of the second degree

$$M_2\left(z^{-1}\right) = m_0 + m_1 z^{-1} + m_2 z^{-2}$$

the following equation is solved

$$M_2\left(z^{-1}\right) M_2(z) = D_2\left(z^{-1}\right) \delta D_2(z) \qquad (16)$$

where

$$D_2\left(z^{-1}\right) = 1 + d_1 z^{-1} + d_2 z^{-2} \qquad (17)$$

The products of the polynomials could be extended as

$$\begin{aligned} m_0 + m_1(z+z^{-1}) + m_2(z^2+z^{-2}) = \delta(1+d_1{}^2+d_2{}^2) \\ + \delta d_1(1+d_2)(z+z^{-1}) + \delta d_2(z^2+z^{-2}) \end{aligned} \qquad (18)$$

where the constants of the factorized polynomial on the left side of the equation (13) are combined into the coefficients m_0, m_1 and m_2. Comparing the left and the right side of equation (13), one obtains

$$m_0 = \delta(1+d_1{}^2+d_2{}^2); \quad m_1 = \delta d_1(1+d_2); \quad m_2 = \delta d_2 \qquad (19)$$

Solving equations (19), the following expressions are derived

$$\delta = \frac{\lambda + \sqrt{\lambda^2 - 4m_2{}^2}}{2}; \quad \lambda = \frac{m_0}{2} - m_2 + \sqrt{\left(\frac{m_0}{2} + m_2\right)^2 - m_1{}^2};$$
$$d_1 = \frac{m_1}{\delta + m_2}; \quad d_2 = \frac{m_2}{\delta}$$
$$(20)$$

Solving the spectral factorization of equation (15), an identical expression can be used, but is necessary to convert the left side of this equation to the form used in equation (16), thus

$$\begin{aligned} m_0 &= q_u\,(1+a_1^2+a_2^2)+b_1^2+b_2^2 \\ m_1 &= q_u(a_1+a_1a_2)+b_1b_2; \quad m_2 = q_u a_2 \end{aligned} \qquad (21)$$

PRIMARY LQ CONTROLLER OF DIGITAL SMITH PREDICTOR

From the previous paragraph, it is obvious that using analytical spectral factorization, only two parameters of the second degree polynomial $D_2(z^{-1})$ (17) 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 using the fourth degree polynomial $D_4(z^{-1})$ (6) in equations (5) and (7).
From expression (17) it is obvious that polynomial

$$D_2(z) = z^2 + d_1 z + d_2 \tag{22}$$

have 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

$$D_4(z) = z^4 + d_1 z^3 + d_2 z^2 + d_3 z + d_4 \tag{23}$$

For both two types of the processes the suitable pole assignment was designed:

1st possibility:
Polynomial (18) has two different real poles α, β (computed from (17)) and user-defined real poles γ, δ. Then it is possible to write polynomial (18) as a product root of factor

$$D_4(z) = (z-\alpha)(z-\beta)(z-\gamma)(z-\delta) \tag{24}$$

and it is possible to express its individual parameters as

$$\begin{aligned} d_1 &= -(\alpha+\beta+\gamma+\delta) \\ d_2 &= \alpha\beta + \gamma\delta + (\alpha+\beta)(\gamma+\delta) \\ d_3 &= -\left[(\alpha+\beta)\gamma\delta + (\gamma+\delta)\alpha\beta\right] \\ d_4 &= \alpha\beta\gamma\delta \end{aligned} \tag{25}$$

2nd possibility:
Polynomial (18) has the complex conjugate pole $z_{1,2} = \alpha \pm j\beta$ (computed from (17)) and user-defined real poles γ, δ. Then polynomial (18) has the form

$$D_4(z) = (z-\alpha-j\beta)(z-\alpha+j\beta)(z-\gamma)(z-\delta) \tag{26}$$

and its individual parameters can be expressed as

$$\begin{aligned} d_1 &= -(2\alpha+\gamma+\delta) \\ d_2 &= 2\alpha(\gamma+\delta) + \alpha^2 + \beta^2 + \gamma\delta \\ d_3 &= -\left[2\alpha\gamma\delta + (\alpha^2+\beta^2)(\gamma+\delta)\right] \\ d_4 &= (\alpha^2+\beta^2)\gamma\delta \end{aligned} \tag{27}$$

The control algorithm based on the LQ control method contains the following steps:

1. The parameters of the polynomial $M_2(z^{-1})$ are computed according to equations (21).
2. The parameters of the polynomial $D_2(z^{-1})$ are computed according to equations (20).
3. If the polynomial (22) has the real poles α, β, its parameters are computed according to equations (25), otherwise, they are computed according to equations (27).
4. The controller parameters are computed using matrix equation (8) and equation (9).
5. The controller output is given by equation (10).

Penalization of the controller output is performed by setting $q_u \geq 0$. With increased penalization constant, the amplitude of the controller output decreases and thereby, the flow of the process output is smoothened and any possible oscillations or instability are damped.

SIMULATION VERIFICATION AND RESULTS

A simulation verification of the designed predictive algorithm was performed in MATLAB/SIMULINK environment. A typical control scheme, which was used, is depicted in Fig. 3. This scheme is used for systems with time-delay of two sample steps. Individual blocks of the Simulink scheme correspond to blocks of the general control scheme presented in Fig. 2. It is possible to influence the output of the process with the non-measurable disturbance *d*.
The above mentioned Smith Predictor has universal usage for control of great deal of processes with time-delay. Therefore, four types of processes were chosen for simulation verification of controller algorithm. Consider the following continuous-time transfer functions:

1) Stable non-oscillatory $G_1(s) = \dfrac{2}{(s+1)(4s+1)} e^{-4s}$

2) Stable oscillatory $G_2(s) = \dfrac{2}{4s^2+2s+1} e^{-4s}$

3) Non-minimum phase $G_3(s) = \dfrac{2(1-5s)}{(s+1)(4s+1)} e^{-4s}$

4) Unstable $G_4(s) = \dfrac{2(s+1)}{(2s-1)(4s+1)} e^{-4s}$

Let us now discretize them with a sampling period $T_0 = 2$ s, then the discrete forms are

$$G_1(z^{-1}) = \frac{0.4728z^{-1} + 0.2076z^{-2}}{1 - 0.7419z^{-1} + 0.0821z^{-2}} z^{-2}$$

$$G_2(z^{-1}) = \frac{0.6806z^{-1} + 0.4834z^{-2}}{1 - 0.7859z^{-1} + 0.3679z^{-2}} z^{-2}$$

$$G_3(z^{-1}) = \frac{-1.0978z^{-1} + 1.7783z^{-2}}{1 - 0.7419z^{-1} + 0.0821z^{-2}} z^{-2}$$

$$G_4(z^{-1}) = \frac{1.3248z^{-1} + 0.0274z^{-2}}{1 - 3.3248z^{-1} + 1.6487z^{-2}} z^{-2}$$

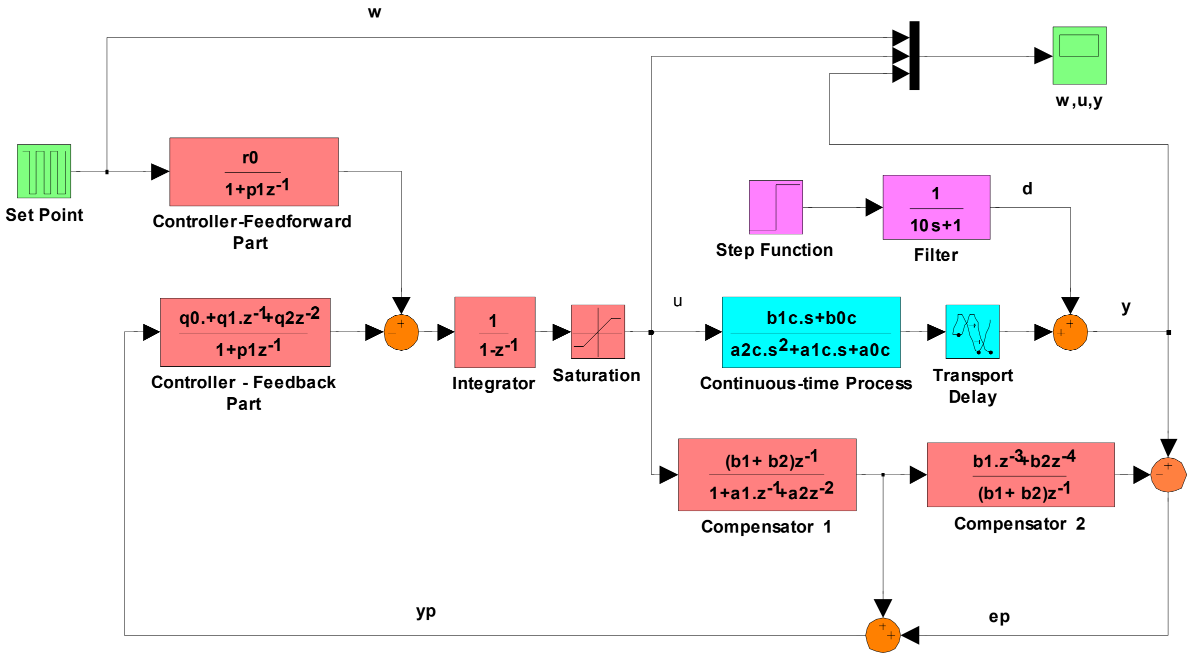

Figure 3: Simulink control scheme

The step responses of individual models are shown in Figs. 4 – 7.

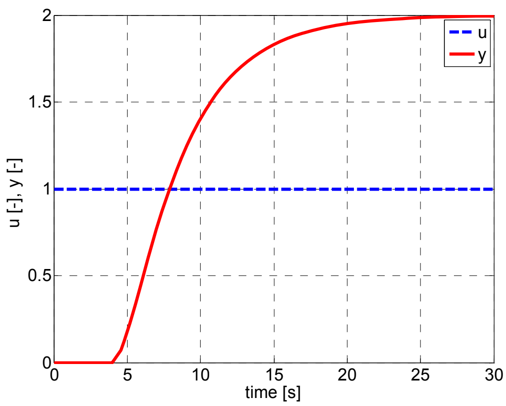

Figure 4: Step response of the model $G_1(s)$

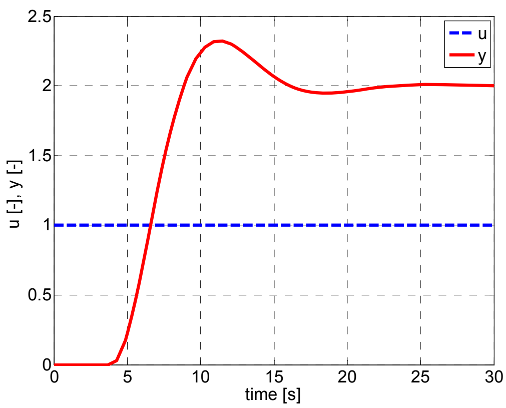

Figure 5: Step response of the model $G_2(s)$

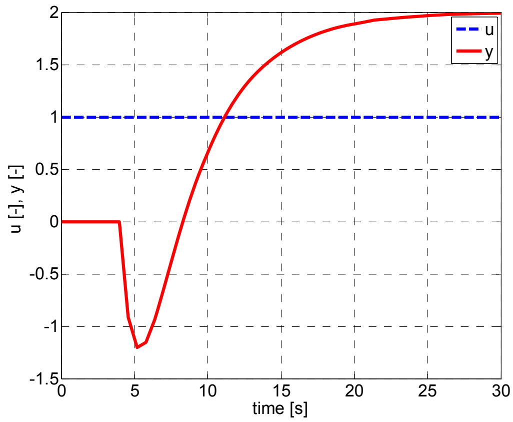

Figure 6: Step response of the model $G_3(s)$

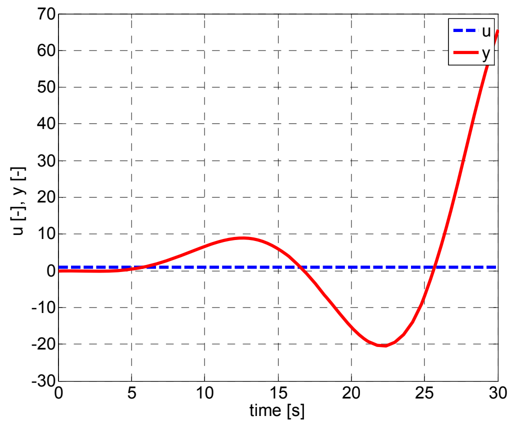

Figure 7: Step response of the model $G_4(s)$

The processes which are described by the above mentioned transfer functions were used in the Simulink control scheme for the verification of the dynamical behaviour of individual closed control loops. In time 500 – 800 s an exponential external disturbance

$$d(t) = 0.25\left(1 - e^{-0.1t}\right)$$

acted on the system output. The computed poles α, β and user-defined real poles γ, δ are introduced for individual simulation experiments including characteristic polynomial (25). For all experiments, the penalization factor was chosen $q_u = 1$.

Simulation control of model $G_1\left(z^{-1}\right)$

The poles: $\alpha,\beta = 0.2130 \pm 0.2762i;\quad \gamma = 0.1;\quad \delta = 0.5$

The characteristic polynomial:

$D_4(z) = z^4 - 1.0380z^3 + 0.3666z^2 - 0.0542z + 0.0027$

The courses of the control variables are shown in Fig. 8, the quality of control is very good.

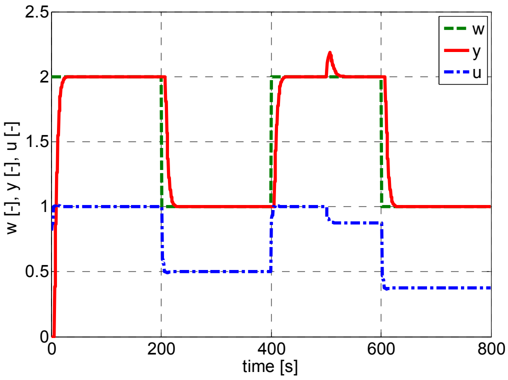

Figure 8: Control of the model $G_1\left(z^{-1}\right)$

Simulation control of model $G_2\left(z^{-1}\right)$

The poles: $\alpha,\beta = 0.1451 \pm 0.3820i;\quad \gamma = 0.1;\quad \delta = 0.5$

The characteristic polynomial:

$D_4(z) = z^4 - 0.8902z^3 + 0.3911z^2 - 0.1147z + 0.0027$

The courses of the control variables are shown in Fig. 9, the quality of control is very good.

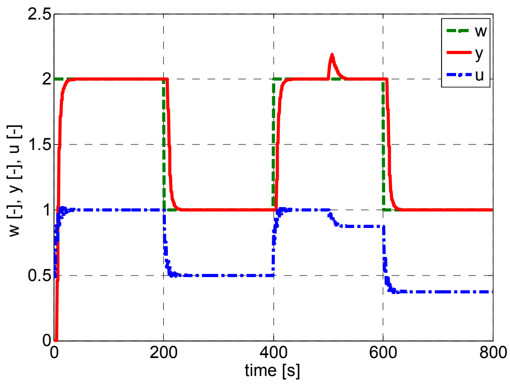

Figure 9: Control of the model $G_2\left(z^{-1}\right)$

Simulation control of model $G_3\left(z^{-1}\right)$

The poles: $\alpha = 0.6153;\quad \beta = 0.0325;\quad \gamma = 0.1;\quad \delta = 0.75$

The characteristic polynomial:

$D_4(z) = z^4 - 1.4973z^3 + 0.6449z^2 - 0.0653z + 0.0015$

The courses of the control variables are shown in Fig. 9. The process output y has typical character for the control of the non-minimum phase system (undershoot of y in the initial time-interval). The stability of a control-loop is very dependent on pole δ. For small δ the control loop is unstable, for suitable chosen δ, the quality of control is very good.

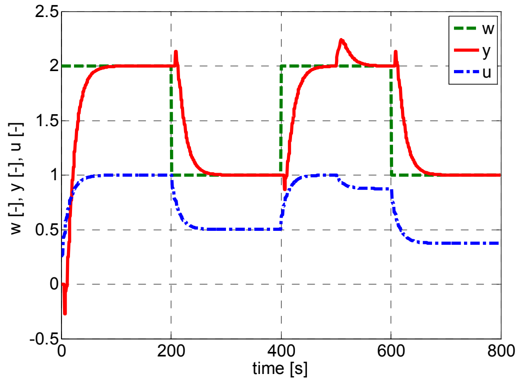

Figure 10: Control of model $G_3\left(z^{-1}\right)$

Simulation control of model $G_4\left(z^{-1}\right)$

The poles: $\alpha,\beta = 0.3470 \pm 0.1720i;\quad \gamma = 0.1;\quad \delta = 0.5$

The characteristic polynomial:

$D_4(z) = z^4 - 1.2940z^3 + 0.6164z^2 - 0.1247z + 0.0075$

The courses of the control variables are shown in Fig. 10, the quality of control is very good.

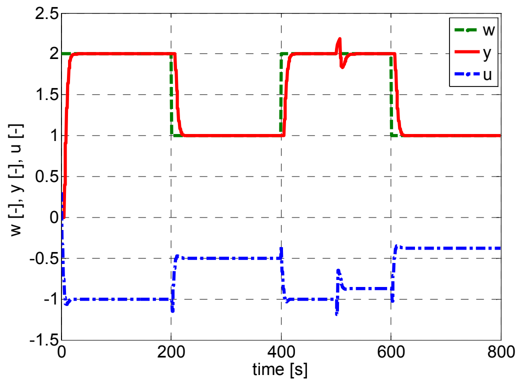

Figure 10: Control of the model $G_4\left(z^{-1}\right)$

CONCLUSION

The contribution presents new generalized strategy for design of the polynomial digital Smith Predictor for control systems with time-delay. The primary controller is based on minimization of the linear quadratic criterion. Minimization of criterion is realized through spectral factorization. This controller was derived purposely by analytical way (without utilization of numerical methods) to obtain algorithms with easy implementability in industrial practice. Four models of control processes were used for simulation verification. Main contribution of the proposed method is the universal applicability of digital Smith Predictor for unstable processes. The designed predictive controller was successfully verified not only by simulation but also in real-time laboratory conditions for control of a heat exchanger.

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