The algorithms for control of heating massive material

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Algoritmus controly ohrievaného masívneho materiálu

In numerous technological processes a change on the output follows change on the input pending specific time. This time is called dead time and if this time is too large, it causes problems in the control. This contribution is aimed at analyzing the algorithms of discreet regulation of the systems with dead time. Verified were classical PID regulator and a regulator using Dead Beat method. The control was also tried with Dead interval method. The regulators were tested by simulation and in the electrical laboratory furnace. The task was to control the temperature inside the material heated by furnace power.

Key words*: regulator, control, dead time, heating.*

Introduction

Temperature control inside heated massive material is still a great problem. Basically it is concerned with the control of the system with great persistence on the output. This is the system wherein the change on the input represents measured temperature after actuating intervention (heating on) will be showed after finite time. This time is called transport delay and when it is somewhat greater it causes no problems with the control. Short dead time can substitute several small time constants or describe real time delay of the process. Large delay times are exclusively native transport delays. Therefore it is necessary to resolve the processes with native delay time and processes that also have additional dynamics. In this work four ways of heating control were tested, inner temperature was stabilized at required value with the best quality of the control. The heated material was a model of steel roll that was placed in the laboratory electrical furnace. In the roll was one thermocouple that measured internal temperature. The control algorithm was executed by industry automaton (PLC) and recording of the temperature and actuating value ran on the computer (Fig. 1). Within the framework of the experiments with temperature control, was also tried a system for indirect temperature measurement inside the roll. For this experiment was needed to place several thermocouples on the roll surface and five controlling thermocouples into the roll. The design of the temperature control system based on indirect measurement of the temperature inside the roll is presented in the last chapter.

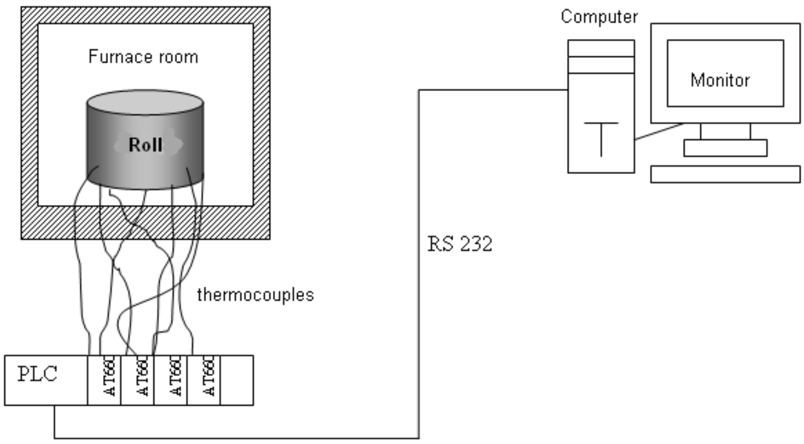

Fig. 1. Connection scheme of measuring system.

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Design of discrete regulator

Because electrical furnaces allow control of heating only modo et forma heating on/off, it was needed to adapt control for a discrete regulator. The assumption was that output from the mathematical regulator is a real number from interval 0 – 1, that represents required furnace power at given time step *k*. When sampling period was T_0 and output from regulator was calculated as 0.5 then 50 % from the time T_0 was heating on and remaining time till the end of period T_0 was heating off. The furnace was heated with given time step with the power 50 %.

Mathematical model of regulated system

In the creation of mathematical model of the regulated system, furnace control by percentage change of the input power was considered. On this principle was done the discrete identification of regulated system. The system was excited by step change of the power from 0 to 25 % untill the internal temperature was stabilized at certain value. For discrete parametric identification was recorded the data about power – actuating value *u* and measured internal temperature – regulated value *y*. The files with measured datas were directly used in the Matlab environment. The ARMAX model of the second order with result form (1) (Hanuš, 2000) was used for identification. Applied was function such as *load*, *armax*, *sett, present*, *dstep*, a *tf*. These functions can estimate unknown parameters a_1, a_2, b_1, b_2 of the model.

$$\begin{aligned} y(k) &= -(a_1 y(k-1) + a_2 y(k-2)) + ((b_1 u(k-1) + b_2 u(k-2)) = \\ &-(-1{,}051 y(k-1) + 0{,}2352 y(k-2)) + (295{,}3 u(k-1) + 272{,}2 u(k-2)) \end{aligned} , \qquad (1)$$

Choice of sampling period

Seeing that regulated system is with time delay τ_d it was needed to correct to choice of the sampling period. This period was calculated using three methods. The first one (2) directly considered τ_d = 600 s, in the second (3) the time-out was T_u = 1140 s, and for the third method (4) we needed to know the time after 95 % consolidation of regulated value *y* (T_{95} =16986 s). In Fig. 2 is depicted the behaviour of control with classical Dead Beat regulator and sampling period T_0 = 150 s. Short sampling period is the reason for insufficient heating and the regulator was inefficient. For calculation parameters of the model as well as regulator parameters we finally used T_0 = 2400 s because it results from the formula (4) (Bobál, 1999).

$$T_0 = \left(\frac{1}{4} \div \frac{1}{8}\right)\tau_d = 150 \text{ až } 75 \; , \qquad [s] \qquad (2)$$

$$T_0 = (0.35 \div 1.2) T_u = 399 \text{ až } 1368 \; , \qquad [s] \qquad (3)$$

$$T_0 = \left(\frac{1}{6} \div \frac{1}{15}\right) T_{95} = 2831 \text{ až } 1132 \; , \qquad [s] \qquad (4)$$

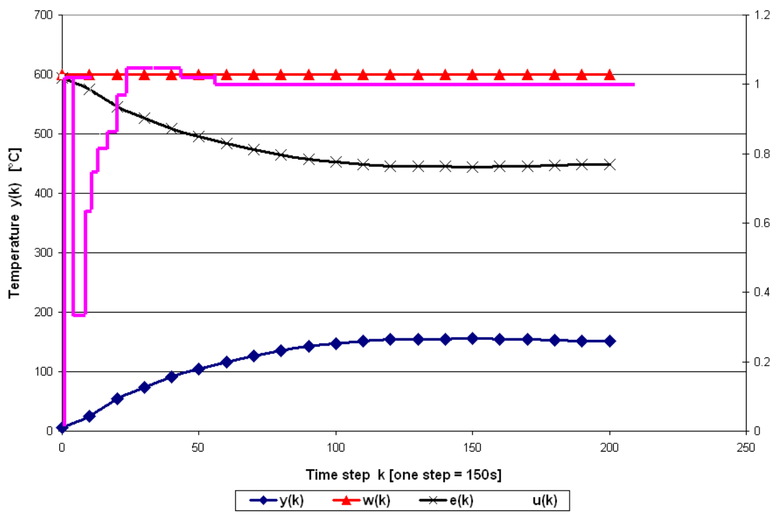

Fig. 2. Control of heating with classical DB regulator and T0=150 s.

Mathematical model of discrete regulator

For chosen model of the regulated system (1) and sampling period T_0 model of the regulator was built up according to (Bobál, 1999). The regulator was created for classical DB (Dead Beat) algorithm (5), model for extended eDB (extended Dead Beat) algorithm (6) and classical PI regulator (7). The following equations represent regulators in the form of differential equations where *e(k)* is the regulation error in step *k*, *u* is the actuating value, q_i , p_i , q_{di} (i=1, 2) are estimated paremeters of regulators, and u^0 is A/D converter constraint (Alexík, 2005).

$$u(k) = ((q_0 . e(k))+(q_1 . e(k-1))+(q_2 . e(k-2)))+((p_1 . u(k-1))+(p_2 . u(k-2))=((0{,}0018 . e(k)) +(-0{,}0019 . e(k-1))+(0{,}0004 . e(k-2)))+((0{,}5203 . u(k-1))+(0{,}4796 . u(k-2)) \quad , \tag{5}$$

$$u(k) = ((q_0 . e(k))+(q_1 . e(k-1))+(q_2 . e(k-2)))+((p_1 . u(k-1))+(p_2 . u(k-2))- ((q_{d1} . (u(k-1)-u^0(k-1)))+(q_{d2} . (u(k-2)-u^0(k-2)))) = ((0{,}0018 . e(k))+(-0{,}0019 . e(k-1))+ (0{,}0004 . e(k-2)))+((0{,}5203 . u(k-1))+(0{,}4796 . u(k-2)) -((-0{,}5306 . (u(k-1)-u^0(k-1))) +(0{,}7148 . (u(k-2)-u^0(k-2)))), \tag{6}$$

$$u(k) = ((q_0 . e(k))+(q_1 . e(k-1))) = ((0{,}0000576 . e(k))+(-2{,}29534E-05 . e(k-1))), \tag{7}$$

The modified algorithm (8) derived by (Alexík, 2005), was not used because the applied sampling period was greater than the dead time. Presented extended form (8) was derived for the system of third order and this derivation is only valid for the systems with dead time greater than T_0. The calculation of dead time "z^{-d}" (for $d > 0$, where d is the number of dead time steps according to sampling period T_0) represents the shift of the output from the regulator „*u(k-i)*" and modification of the anti-windup part (the third row) in equation (6). Modified DB algorithm for the systems with dead time has the following form:

$$\begin{aligned} u(k) &= q_0 e(k) + q_1 e(k-1) + q_2 e(k-2) + q_3 e(k-3) + \\ &\left[p_1 u(k-d-1) + p_2 u(k-d-2) + p_3 u(k-d-3)\right] - \\ &- \begin{bmatrix} q_{d1} u_d^0(k-1) + q_{d2} u_d^0(k-2) + q_{d3} u_d^0(k-3) + \\ + q_{d4} u_d^0(r-2) + q_{d5} u_d^0(r-1) + q_{d6} u_d^0(r) \end{bmatrix} \end{aligned} \tag{8}$$

where $r = \left[k-(n+d)\right]$ *for* $(n+d) > 6$ else $r = 6$

if $(n+d) < 6$ then $q = d$ else $q = 6$; for $i = (n+q)$ to $q \to p_i = p_{i-q}$;

for $i = 1$ to $q \to p_i = 0$; $q_{di} = p_i + \dfrac{q_i}{q_0}$ for $i = 1,2,3$ and $q_{di} = p_i$ for $i = 4,5,6;$

$u_d^0(k-1) = \left[u(k-1) - u^0(k-1)\right]$ where $u^0(k)$ is the D/A converter constraint,

The algorithm (8) can be applied on time delayed processes and the equation of the regulator can be applied also to higher order of the system and also with continuous identification to ensure adaptive control.

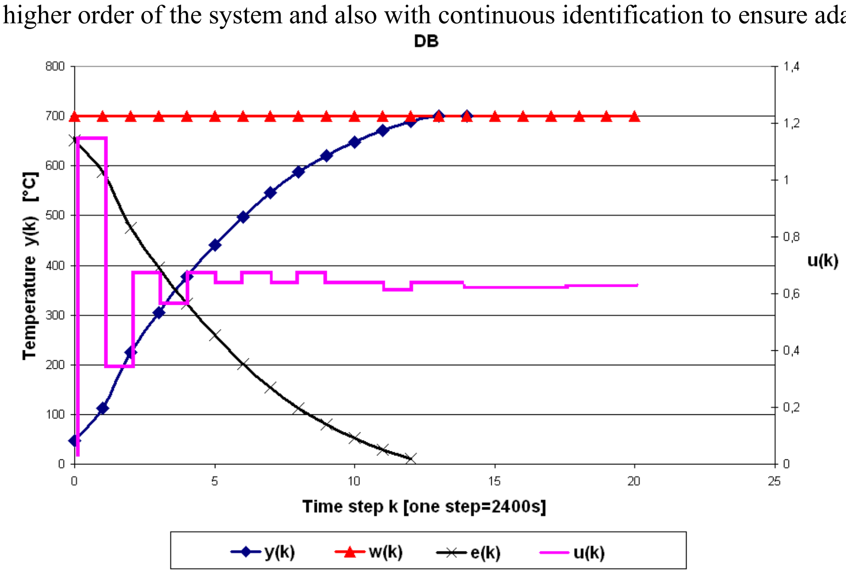

Fig. 3. Control of heating with classical DB regulator.

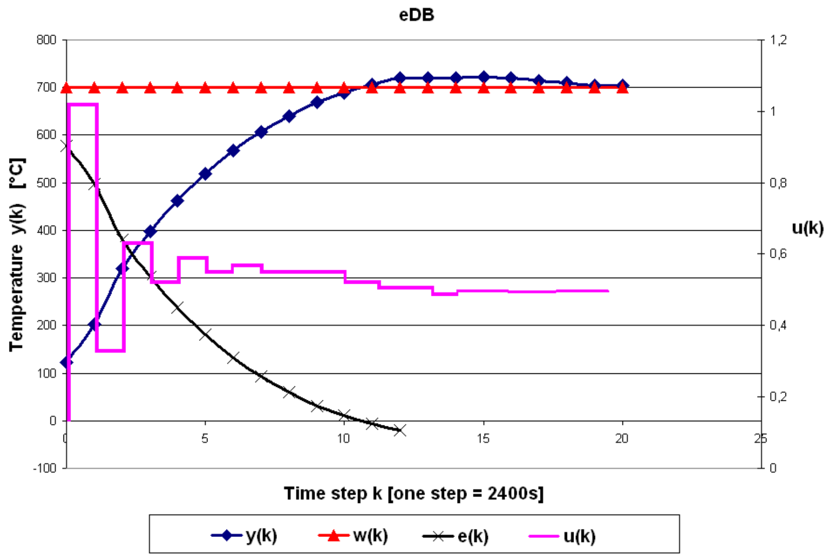

Fig. 4. Control of heating with extended eDB regulator.

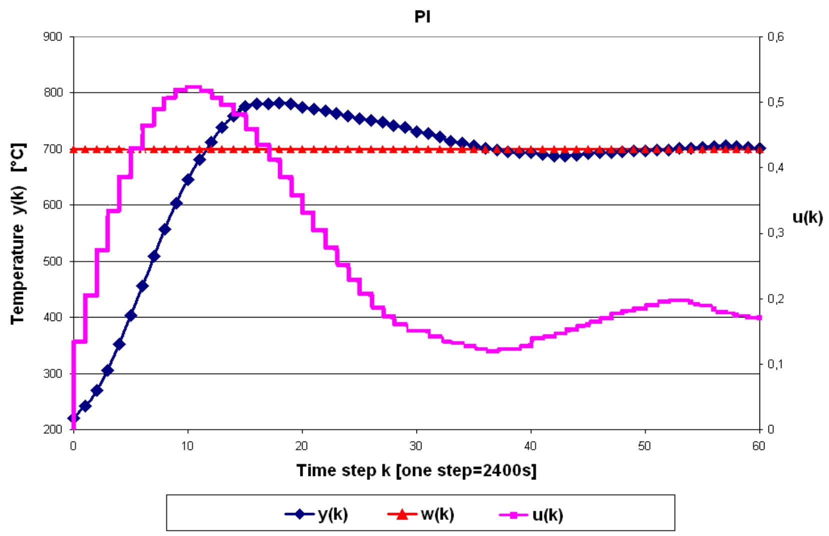

Fig. 5. Control of heating with discrete PI regulator.

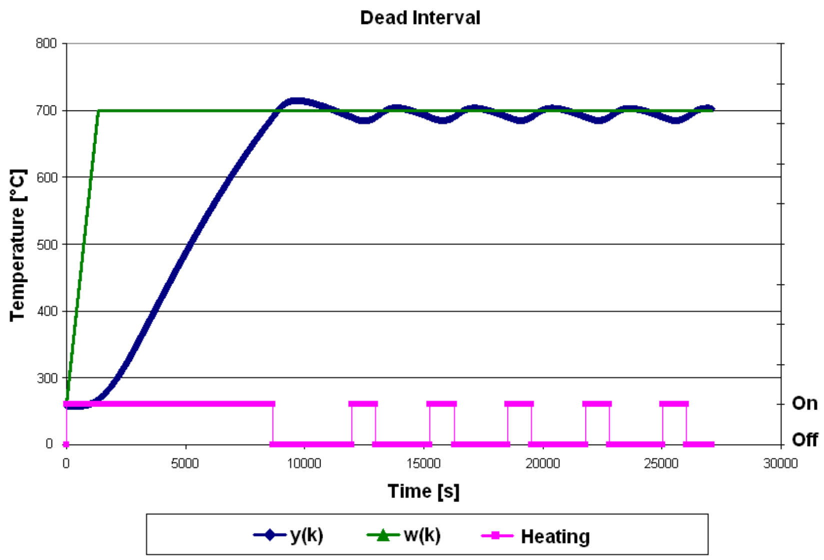

Fig. 6. Control of heating with Dead Interval method.

Evaluation of the results

Table 1 compares obtained results near various regulators. The behavior of control with these regulators is depicted in Figs. 3-5. The last row in the table represents control with the Dead interval method (Trefa, 2005) where the heating was on during control when measured temperature was decreased below the required temperature (leading line, holding line). The Dead interval represents temperature tolerance, at which the regulator is non-sensitive (Fig. 6). The table compares individual ways of control in the term of quality of regulation. It follows from the table that the best control was reached when classical DB regulator and Dead interval method were used. In the table, δ_{max} represents overshooting, T_{max} time of the first amplitude, T_{reg} time of regulation, T_u, T_n, T_p represents time-out, slope time, and transition time respectively. *P* is an area under regulation errors. For the systems with dead time it is possible to also apply a prediction regulator. Its characteristic property is great sensitivity to change of process delay (*d*).

Tab. 1. Comparison of quality of regulation near discrete regulators.

Alg./Criterion	δ_{max} [%]	T_{max} [s]	T_{reg} [s]	T_u [s]	T_n [s]	T_p [s]	P
DB	0,1428	31200	33600	1200	13200	14400	1412542
eDB	3,3333	33600	36000	1200	18000	19200	940897
PI	16	38400	100800	2400	-	-	1192165
Dead Interval	2,3333	9929	13844	-	-	-	1538452

Proposal of control system basically on indirect measurement

For heating control of the roll it was needed to measure its inner temperature in every time step. For the measurement of temperature in the roll, thermocouples were placed, where one was used to measure the temperature like controlled value *y*. In laboratory conditions positioning of the thermocouples is not a problem but the real conditions have limits or disallow it. The problem is the size of the real object (e.g. large steel roll in the real annealing furnace), or destructive environment (high temperature, that can destroy the thermocouples inside the roll). In previous chapter were compared various methods for control of temperature, basically direct measurement of temperature from thermocouples placed inside the roll. The control can be ensured also basically on indirectly measured temperature. The basis for the calculation of all inner temperatures (within selected field of inner points) is partial Furrier – Kirhhoff diferential equation of heat conduction (9) (Kostúr, 2005).

$$\frac{\partial t}{\partial \tau} = a\left(\nabla^2 t + \frac{i_{Q_v}}{\lambda}\right), \tag{9}$$

where $a = \frac{\lambda}{c \cdot \rho}$, $\left[\frac{m^2}{s} = \frac{Wm^{-1}K^{-1}}{Jkg^{-1}K^{-1}kg \cdot m^{-3}}\right]$ is heat conductivity, that characterizes speed of temperature changes in material,

λ is heat conduction factor $\left[Wm^{-1}K^{-1}\right]$, depends on the kind of material,

c is specific heat capacity,

ρ is specific material weight (density).

If there is creation or consumption of heat in the object, then the power of the inner heat sources i_{Q_v} is defined for unit of volume [W.m^{-3}]. According to this equation it is possible to estimate the inner temperature from directly measured temperatures from the surface. Because laboratory conditions enable to place thermocouples inside the roll, these thermocouples were used as a check for the model verification. For the comparison of direct and indirect measurement, a measuring and control system was designed based on PVI Demo application. The application makes record of the measured temperatures to the database, visualization of time behavior of the temperatures and communication with control algorithm in the PLC. The control of the heat is ensured by an automaton (PLC), that can to execute the control algorithm of discrete regulator. In Fig. 7 is depicted a PVI demo application (Kostúr, 2006). It runs in on-line mode (during control of the head), so that we can watch direct and indirect temperatures in the window. Indirect measurement of temperature is the first step toward obtaining information on controlled temperature which we are unable to measure directly. If we obtain it in this way then there is no problem in calculating the regulation error and subsequently the control quantity or the actuating quantity (increment/decrement) of the furnace heating power. In the foreground of the window is a comparison of direct (blue line) and indirect measured temperature (red line). Also it is possible to watch the behavior of measured surface temperatures (the window in the background) (Kačur, 2006).

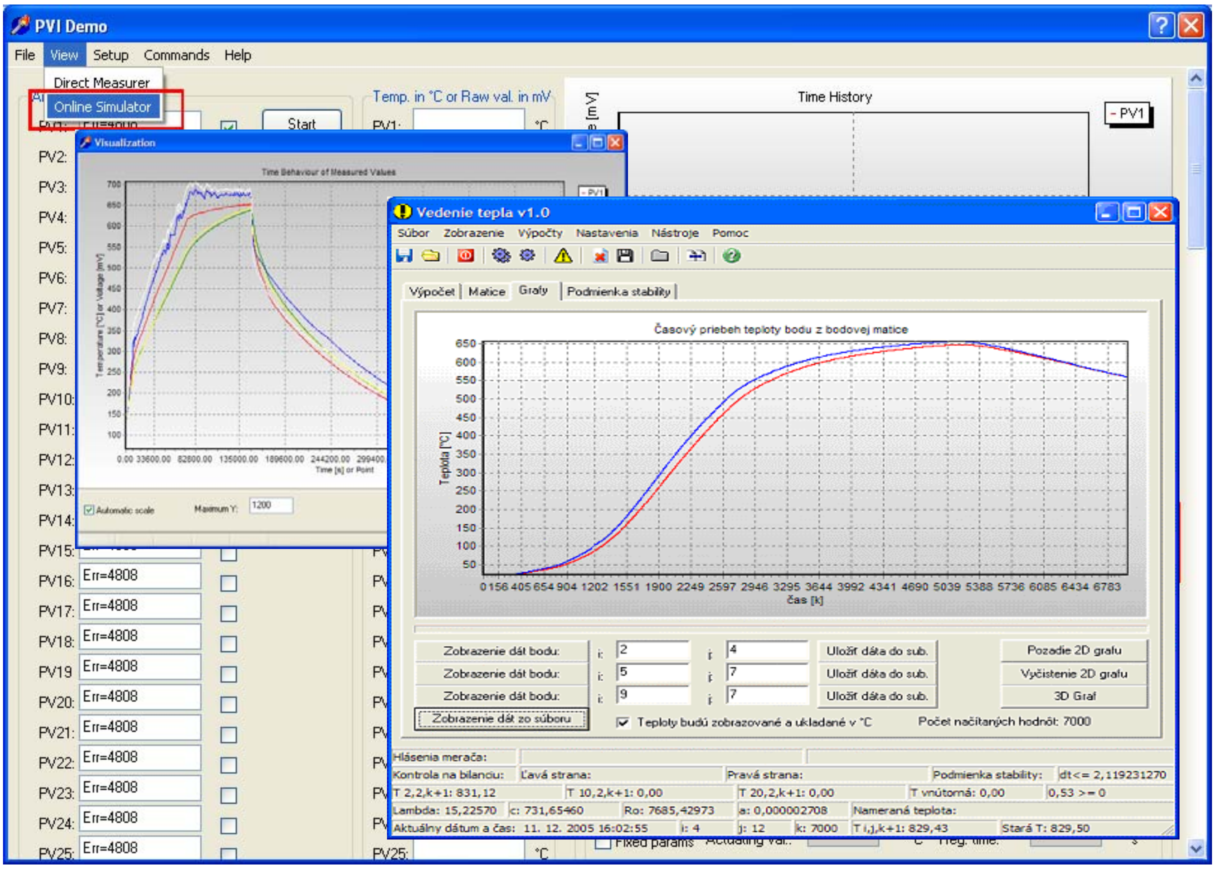

Fig. 7. Visualization a control system for indirect measurement.

Conclusion

The results obtained show that in the case of control of heating inside heated massive material it is best to use control with dead interval or the classical DB regulator. The second way is preferable to use when the heating can be controlled directly by the heat input power of the furnace. However, a disadvantage is long time of regulation. The first way ensures quicker heating and can also be used in the case of two-state control (heating on/off). The control of the heat can be ensured also basically on indirectly measured temperature inside the roll. The proposed control system needs to measure surface temperatures of the objects and has advanced hardware demands. On the other hand, the control system, after verification of the mathematical model, is preferable in terms of cost of thermocouples, which might be destroyed.

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