An Algebraic Approach to Continuous-Time Controller Design for Time-Delay Systems with Uncertain Parameters

Radek Matušů, and Roman Prokop

***Abstract*—**This paper deals with an algebraic approach to continuous-time controller design and particularly with its application to single-input single-output time-delay systems containing uncertain parameters. In the presented set of illustrative examples, a single positive scalar parameter is utilized for tuning the various continuous-time controllers for a first-order and second-order time-delay plant with uncertainty in all parameters at the same time (gain, time constants and time-delay term). Subsequently, the control design is followed by robust stability analysis of a family of closed-loop characteristic quasi-polynomials based on the graphical testing in order to verify the robust stability of final control loops. The obtained results are discussed and confirmed by control simulations performed in Matlab+Simulink environment.

***Keywords*—**Algebraic control design, time-delay systems, parametric uncertainty, robust stabilization, value set concept, zero exclusion condition.

I. Introduction

A simple and effective tuning methods for controllers with conventional PID structure are still highly valued, especially if they are able to cope with various disturbances, non-linearities, variations in parameters or presence of time-delays [1] – [8], because over 95% of contemporary industrial control applications employ PI(D) algorithms [9], [10] and so their appropriate tuning can bring a lot of benefits.

An elegant synthesis method for PI(D) as well as more complicated controllers is based on an algebraic approach [11], [12]. This control design technique, which was studied e.g. in [13] – [16], utilizes general solution of Diophantine equations in the ring of proper and (Hurwitz-)stable rational functions (R_{PS}), Youla-Kučera parameterization and conditions of divisibility in R_{PS}. One of the merits of the method is the existence of single scalar tuning parameter which can influence the properties of the final controller. The applicability of the designed regulator to a plant with uncertain parameters is also a frequently solved problem. Here, the most important task is represented by robust stability analysis. Number of suitable tools for systems with parametric uncertainty can be found e.g. in [17] or possibly in [18], [19].

This paper intends to present an algebraic approach to controller design with emphasis on its application to first-order and second-order time-delay systems with uncertain parameters. The realistic PID (for first-order plant) or more complex (for second-order plant) controller synthesis is followed by test of robust stability for a family of closed-loop characteristic quasi-polynomials. The applied analysis takes advantage of the value set concept in combination with the zero exclusion condition [17]. The brief theoretical foundations are supplemented by the set of illustrative examples.

Some topics related to this paper have been already published in previous works. For example, a comparison of parametric and unstructured approach to uncertainty modelling and robust stability analysis for time-delay systems has been shown in [20], [21]. This paper is focused only on case of parametric uncertainty, but deals with the problem in more detail. Moreover, it follows the works [22], [23], where the partial issues have been tentatively solved, and the paper [24] (with its intended journal extension) in which just one of the parameters was uncertain at the moment while the other two remained fixed. However this contribution deals with the case of all three (or even more) uncertain parameters together. The paper is the extended version of the conference contribution [25].

The work is organized as follows. In section II, the main problem is introduced and controlled plants are defined. The section III then describes the applied algebraic control design method and contains the calculations of the specific controllers. Next, the brief presentation of the value set concept and the zero exclusion condition as the utilized tools for robust stability analysis can be found in the section IV. The section V is focused on illustrative simulation examples for the first-order time-delay plant. The similar simulations but for second-order time-delay plant are provided in the following section VI. Finally, Section VII offers some conclusion remarks.

II. Problem Formulation

The key issue of this paper is to tune various fixed continuous-time controllers, designed by means of algebraic tools, and subsequently verify robust stability of the closed

Radek Matušů, and Roman Prokop are with the Centre for Security, Information and Advanced Technologies (CEBIA – Tech), Faculty of Applied Informatics, Tomas Bata University in Zlín, nám. T. G. Masaryka 5555, 760 01 Zlín, Czech Republic. The email contact is: rmatusu@fai.utb.cz.

The work was supported by the European Regional Development Fund under the project CEBIA-Tech No. CZ.1.05/2.1.00/03.0089. This assistance is very gratefully acknowledged.

loop under assumption of time-delay controlled system with uncertain parameters. More specifically, the first of the assumed plants is generally given as:

$$G(s,K,T,\Theta)=\frac{K}{Ts+1}e^{-\Theta s} \tag{1}$$

where parameters *K*, *T* and Θ represent gain, time constant and time-delay term, respectively. All of these parameters can vary within prescribed intervals, which is the main difference between this work and contribution [24] where just one of the parameters *K*, *T* and Θ was uncertain at the moment while the other two remained fixed. For the purpose of this paper, the parameters are supposed to be bounded by interval:

$$K,T,\Theta\in\langle 1;2\rangle \tag{2}$$

The time constant and time-delay term are assumed in seconds. The average value of the interval (2) is taken as the nominal one, i.e. the nominal system is described by:

$$G_N(s)=\frac{K_N}{T_Ns+1}e^{-\Theta_N s}=\frac{1.5}{1.5s+1}e^{-1.5s} \tag{3}$$

This nominal transfer function, or actually its approximation which is suitable for algebraic control synthesis, will be used during the controller design.

Furthermore, the second controlled plant is supposed to be given by the transfer function:

$$G(s,K,T_1,T_2,\Theta)=\frac{K}{(T_1s+1)(T_2s+1)}e^{-\Theta s} \tag{4}$$

where:

$$K,T_1,T_2,\Theta\in\langle 1;2\rangle \tag{5}$$

Analogically to the previous case, time values are assumed in seconds and the corresponding nominal system is:

$$G_N(s)=\frac{K_N}{(T_{1N}s+1)(T_{2N}s+1)}e^{-\Theta_N s}=\frac{1.5}{(1.5s+1)^2}e^{-1.5s} \tag{6}$$

III. CONTROL DESIGN METHOD

In this section, only the basic ideas and rules of the applied algebraic approach to control design will be described. The interested reader can find the future information in related literature, e.g. [13] – [16], [23].

The method is based on algebraic approach developed in [11], [12]. Roughly speaking, the technique supposes description of systems and signals not in the common ring of polynomials but in R_{PS}. The controller design itself draws upon general solutions of Diophantine equations in this ring. Once a stabilizing controller is obtained, the infinite amount of them can be expressed by means of known Youla-Kučera parameterization. Subsequent choice of the suitable regulator according to required properties such as reference tracking and disturbance rejection is based on conditions of divisibility in R_{PS}. Moreover, the obtained controller can be further tuned by a single scalar parameter $m>0$. More details of the approach, specific rules for calculation of controller parameters and tuning recommendations can be found in [13] – [16], [23], etc.

In the first case, the assumed nominal system is described by transfer function (3). Since this form with time-delay term is not appropriate for the algebraic synthesis, the function (3) has to be transferred into the rational form. The first order Padé approximation is a suitable tool for this purpose. Thus the transfer function used for the following controller design is:

$$\begin{aligned}G_A(s)&=\frac{b_1s+b_0}{s^2+a_1s+a_0}=\frac{-s+1.\overline{3}}{s^2+2s+0.\overline{8}}=\frac{-1.125s+1.5}{1.125s^2+2.25s+1}=\\&=\frac{1.5(1-0.75s)}{(1.5s+1)(1+0.75s)}\approx\frac{1.5}{1.5s+1}e^{-1.5s}=G_N(s)\end{aligned} \tag{7}$$

The stabilizing continuous-time realistic PID controller (for classical feedback control loop):

$$C(s)=\frac{\tilde{q}_2s^2+\tilde{q}_1s+\tilde{q}_0}{s(s+\tilde{p}_1)} \tag{8}$$

which assures reference tracking, have the parameters:

$$\begin{aligned}\tilde{p}_1&=p_0+m-p_0m\frac{b_1}{b_0}\\\tilde{q}_2&=q_1+\frac{p_0m}{b_0}\\\tilde{q}_1&=q_0+q_1m+a_1\frac{p_0m}{b_0}\\\tilde{q}_0&=q_0m+a_0\frac{p_0m}{b_0}\end{aligned} \tag{9}$$

where

$$\begin{aligned}p_0&=\frac{3m^2b_0b_1-a_0b_0b_1-3mb_0{}^2+a_1b_0{}^2-b_1{}^2m^3}{a_1b_0b_1-b_0{}^2-a_0b_1{}^2}\\p_1&=1\\q_0&=\frac{m^3-a_0p_0}{b_0}\\q_1&=\frac{3m-a_1-p_0}{b_1}\end{aligned} \tag{10}$$

The full derivation of these equations for controller parameters can be found e.g. in [23].

Application of the rules (9), (10) to approximated plant (7) and assumption of three various tuning parameters $m>0$ result in trio of controllers (8):

$$m = 0.3 \Rightarrow \quad \begin{aligned} \tilde{q}_2 &= 0.4675 \\ \tilde{q}_1 &= 0.3072 \\ \tilde{q}_0 &= 0.006075 \\ \tilde{p}_1 &= -0.3325 \end{aligned} \tag{11}$$

$$m = 0.8 \Rightarrow \quad \begin{aligned} \tilde{q}_2 &= 0.3794 \\ \tilde{q}_1 &= 0.7135 \\ \tilde{q}_0 &= 0.3072 \\ \tilde{p}_1 &= 1.5794 \end{aligned} \tag{12}$$

$$m = 1.5 \Rightarrow \quad \begin{aligned} \tilde{q}_2 &= 3.7293 \\ \tilde{q}_1 &= 7.8198 \\ \tilde{q}_0 &= 3.7969 \\ \tilde{p}_1 &= 7.7293 \end{aligned} \tag{13}$$

As can be seen, the parameters (11) represent an unstable controller which would not be suitable for practical application. Nevertheless, it will be used in simulation examples.

Now, assume the second case of nominal system given by (6). Its first order Padé approximation is:

$$\begin{aligned} G_A(s) &= \frac{b_1 s + b_0}{s^3 + a_2 s^2 + a_1 s + a_0} = \frac{-0.\overline{6}s + 0.\overline{8}}{s^3 + 2.\overline{6}s^2 + 2.\overline{2}s + 0.5926} = \\ &= \frac{-1.125s + 1.5}{1.6875s^3 + 4.5s^2 + 3.75s + 1} = \frac{1.5(1 - 0.75s)}{(1.5s+1)^2(1 + 0.75s)} \approx \\ &\approx \frac{1.5}{(1.5s+1)^2} e^{-1.5s} = G_N(s) \end{aligned} \tag{14}$$

Here, the application of the R_{PS} methodology leads to the stabilizing continuous-time controller with the general form:

$$C(s) = \frac{\tilde{q}_3 s^3 + \tilde{q}_2 s^2 + \tilde{q}_1 s + \tilde{q}_0}{s\left(s^2 + \tilde{p}_2 s + \tilde{p}_1\right)} \tag{15}$$

for which it was calculated (for two selected specific tuning parameters $m > 0$):

$$m = 0.45 \Rightarrow \quad \begin{aligned} \tilde{q}_3 &= \text{-}0.4304 \\ \tilde{q}_2 &= \text{-}0.5499 \\ \tilde{q}_1 &= \text{-}0.1614 \\ \tilde{q}_0 &= 0.009342 \\ \tilde{p}_2 &= 0.0\overline{3} \\ \tilde{p}_1 &= 0.4394 \end{aligned} \tag{16}$$

$$m = 0.65 \Rightarrow \quad \begin{aligned} \tilde{q}_3 &= 0.04654 \\ \tilde{q}_2 &= 0.253 \\ \tilde{q}_1 &= 0.2752 \\ \tilde{q}_0 &= 0.08485 \\ \tilde{p}_2 &= 1.2\overline{3} \\ \tilde{p}_1 &= 0.8574 \end{aligned} \tag{17}$$

IV. Investigation of Robust Stability

For the first case, all three tuned controllers (11), (12), (13) stabilize the approximation of nominal plant (7) as well as the nominal system (3) itself and, for the second event, both controllers (16), (17) stabilize the plants (14) and (6). However, the question is if they also robustly stabilize the family of systems (1), (2) and (4), (5), respectively. This problem can be solved by testing the robust stability of the corresponding families of closed-loop characteristic quasi-polynomials. For first case, the uncertain quasi-polynomial has the structure:

$$p_{CL}(s, K, T, \Theta) = (Ts+1)s\left(s + \tilde{p}_1\right) + Ke^{-\Theta s}\left(\tilde{q}_2 s^2 + \tilde{q}_1 s + \tilde{q}_0\right) \tag{18}$$

while for the second order controlled plant it is:

$$\begin{aligned} p_{CL}(s, K, T, \Theta) &= (T_1 s+1)(T_2 s+1)s\left(s^2 + \tilde{p}_2 s + \tilde{p}_1\right) + \\ &+ Ke^{-\Theta s}\left(\tilde{q}_3 s^3 + \tilde{q}_2 s^2 + \tilde{q}_1 s + \tilde{q}_0\right) \end{aligned} \tag{19}$$

In the quasi-polynomial (18), the uncertain plant parameters can vary according to (2) and the controller parameters are fixed to either (11), (12) or (13). Analogically, for (19), the plant parameters can lie within the interval (5) and controllers are determined to one of the cases (16) or (17).

Robust stability of the family (18) or (19) can be analyzed using very universal graphical method known as the value set concept in combination with the zero exclusion condition [17]. Again, the idea is going to be described very briefly. So, the value set at one frequency ω can be obtained by substitution of s for $j\omega$ in the family (18) or (19), fixing ω and letting the uncertain parameters range over the prescribed intervals. Further, the family is robustly stable if and only if it contains at least one stable member and the origin of the complex plane (the zero point) is excluded from the value sets at all non-negative frequencies.

For more details on the value set concept, the zero exclusion condition and related problems see e.g. [17] or [18], [19].

V. Illustrative Simulation Examples – First Order Plant

In this part, the robust stability of closed control loops with the family of plants (1), (2) and one of the PID controllers with parameters (11), (12) or (13) will be investigated. Subsequently, obtained results will be verified by means of control simulations.

The Matlab + Simulink environment was employed for plotting all of the value sets and control outputs. More specifically, the following settings were used: The value sets were depicted for selected range of frequencies starting from 0 while the value set for each fixed frequency consists of $21^3 = 9261$ points as the uncertain parameters are sampled $K, T, \Theta = 1:0.05:2$. Just for two zoomed cases (figs. 2 and 10), the lower amount of $11^3 = 1331$ points was used (thanks to different sampling $K, T, \Theta = 1:0.1:2$) for clearer view of the situation near the origin of the complex plane. Then, from the viewpoint of control simulations, a "representative" set of systems was chosen in a similar way. The thinner sampling of uncertain parameters was used here ($K, T, \Theta = 1:0.2:2$) which consequently resulted in $6^3 = 216$ "representative" systems for control simulations. Furthermore, the control output for the nominal plant (3) has been also added to the figures (red curve). In all simulations, the step load disturbance –0.3 was injected into the input of the controlled plant during the last third of simulation.

A. The First Controller

First, the regulator (8) tuned with $m = 0.3$, i.e. with parameters (11), is applied to control the family of systems (1), (2). The key object of interest from the robust stability point of view is the family of closed-loop characteristic quasi-polynomials with the structure (18) and respective parameters. The value sets of the family of quasi-polynomials for the range of frequencies ω from 0 to 1.2 with step 0.05 is shown in fig. 1. Then, the zoomed view to the neighbourhood of the zero point is given in fig. 2.

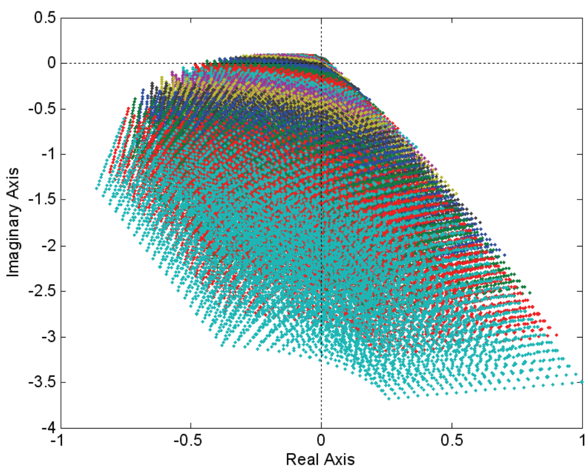

Fig. 1 the value sets – controller (11)

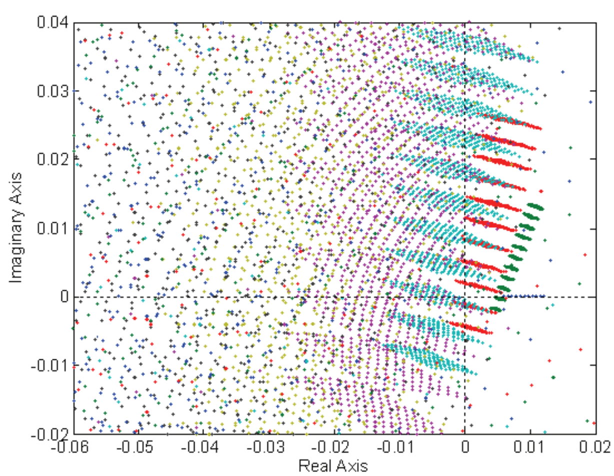

Fig. 2 the zoomed value sets – controller (11)

Since the origin of the complex plane is included in the value sets, the family of closed-loop characteristic quasi-polynomials and thus consequently also the whole control system is not robustly stable. This fact can be confirmed by simulation of control behaviour for "representative" set of systems plotted in fig. 3 where $w(t)$ represents reference signal and $y(t)$ stands for controlled outputs. The nominal system (3) is stabilized (even by the unstable controller (11)), but the whole controlled plant family (1), (2) is not. Moreover, fig. 4 shows the set of corresponding manipulated variables $u(t)$.

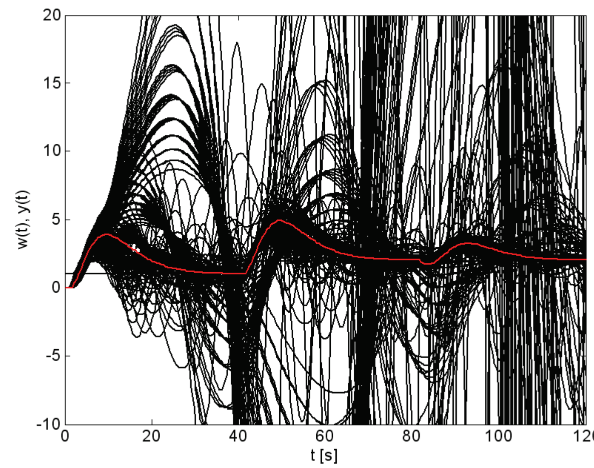

Fig. 3 set of output signals – controller (11)

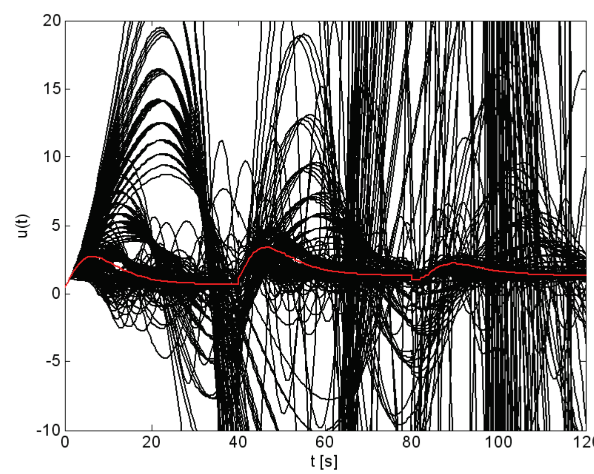

Fig. 4 set of manipulated variables – controller (11)

B. The Second Controller

Now, the tuning parameter $m = 0.8$ which leads to the controller (12) is supposed. Analogically to the previous case, the value sets of the corresponding family of quasi-polynomials for the range of frequencies $\omega = 0:0.05:2.2$ are visualized in fig. 5. The closer view of the complex plane origin is provided by fig. 6. The family of quasi-polynomials contains at least one stable member and the zero point is excluded from the value sets and thus the family is robustly stable. It can be verified by control simulations – see fig. 7 with "representative" set of output signals and fig. 8 with set of manipulated variables. As can be seen, the control loop really remains stable for all variations of parameters (2).

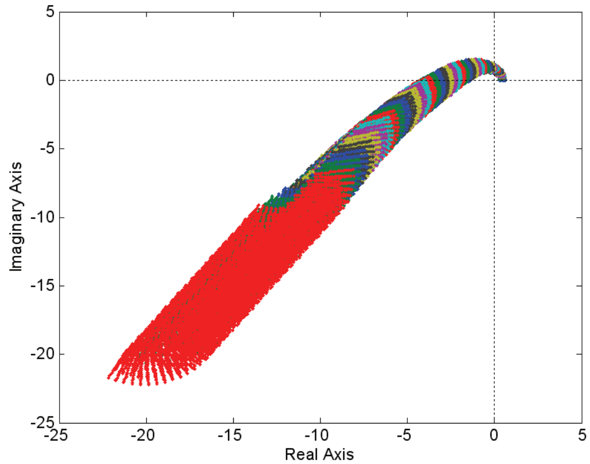

Fig. 5 the value sets – controller (12)

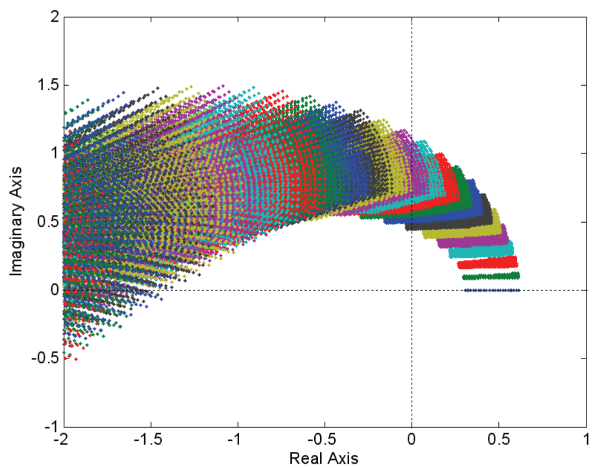

Fig. 6 the zoomed value sets – controller (12)

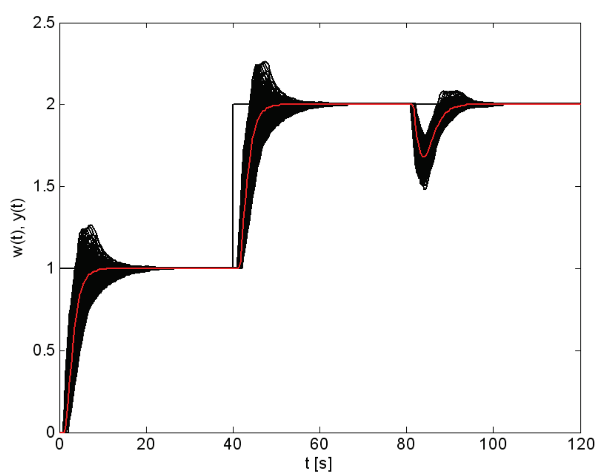

Fig. 7 set of output signals – controller (12)

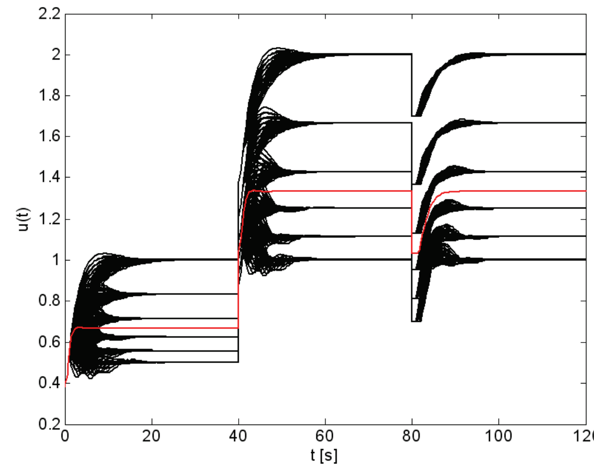

Fig. 8 set of manipulated variables – controller (12)

C. The Third Controller

Finally, the controller with coefficients (13) which was calculated by using the tuning parameter $m = 1.5$ is considered.

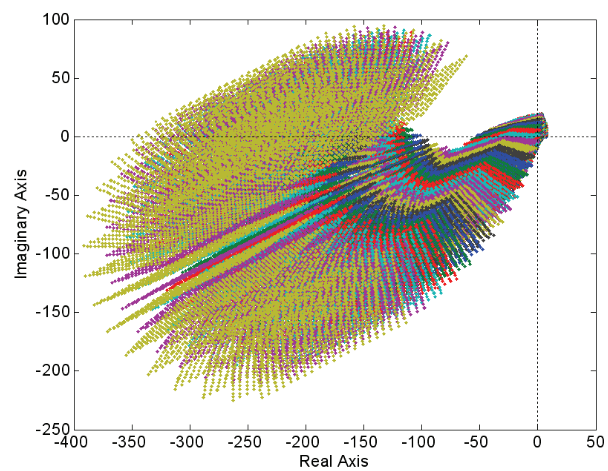

Fig. 9 the value sets – controller (13)

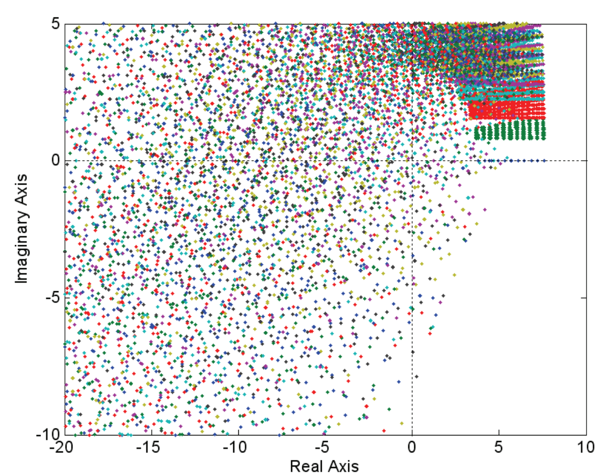

Fig. 10 the zoomed value sets – controller (13)

In this case, the value sets of quasi-polynomial family are depicted for $\omega = 0:0.1:4$ in fig. 9 with the detailed view in fig. 10. Obviously, the origin of the complex plane is included in the value sets and so the family is robustly unstable. The confirming simulation results for "representative" set of controlled systems are given in fig. 11 (control outputs) and fig. 12 (manipulated variables). As can be seen, the nominal plant (represented by the red curve) is stabilized but the plant family is not.

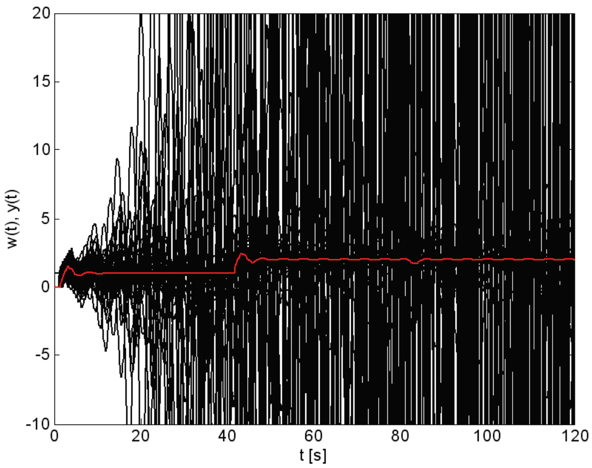

Fig. 11 set of output signals – controller (13)

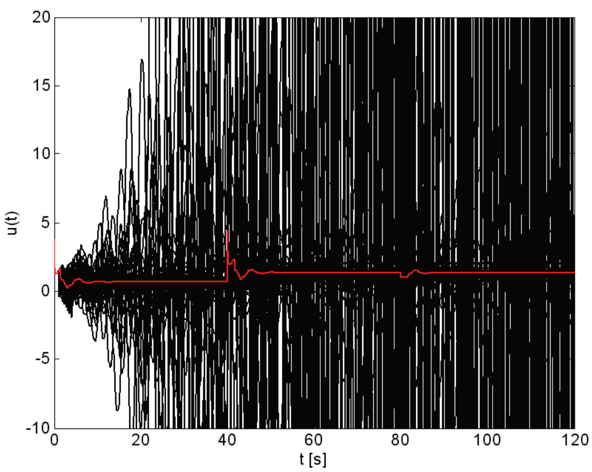

Fig. 12 set of manipulated variables – controller (13)

VI. Illustrative Simulation Examples – Second Order Plant

Now, the control loops with the family of second order time-delay plants (4), (5) + one of the regulators with parameters (16) or (17) and their robust stability will be analyzed.

In this section, the value set for each fixed frequency consists of $11^4 = 14641$ points as the uncertain parameters are sampled $K, T_1, T_2, \Theta = 1:0.1:2$. A "representative" set of systems used for simulations has $4^4 = 256$ members ($K, T_1, T_2, \Theta = 1:1/3:2$). Moreover, the red curves in simulation figures represent the results for the nominal plant (6). Again, the step load disturbance –0.3 was injected into the input of the controlled plant during the last third of simulation.

A. The First Controller

The controller (15) tuned with $m = 0.45$, that is with parameters (16), is employed for controlling the family of systems (4), (5). The value sets of the family of quasi-polynomials (19) for $\omega = 0:0.05:1.2$ are depicted in fig. 13 and the zoomed view is provided by fig. 14.

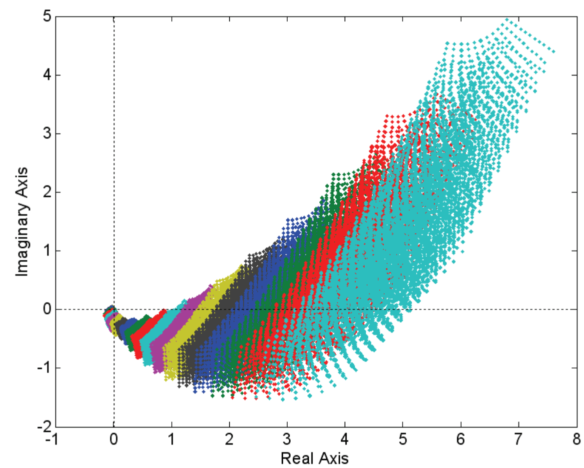

Fig. 13 the value sets – controller (16)

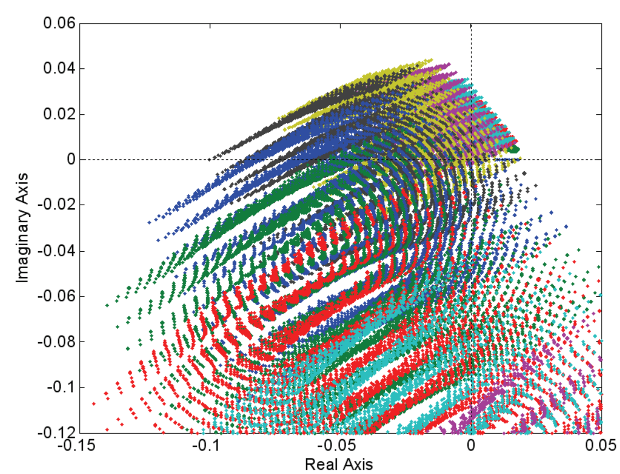

Fig. 14 the zoomed value sets – controller (16)

Obviously, the origin of the complex plane is included in the value sets and for this reason the family of closed-loop characteristic quasi-polynomials is robustly unstable. The corresponding control outputs for "representative" set of systems are plotted in fig. 15 and the set of manipulated variables in fig. 16.

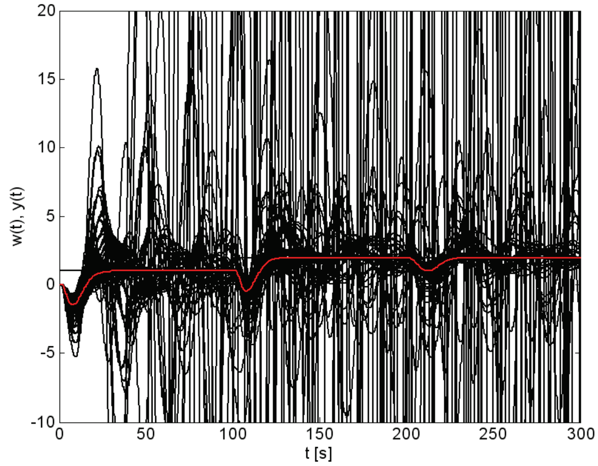

Fig. 15 set of output signals – controller (16)

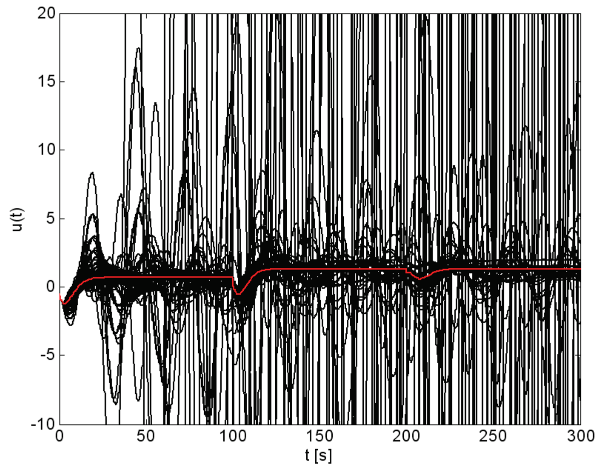

Fig. 16 set of manipulated variables – controller (16)

B. *The Second Controller*

Finally, it was assumed the tuning parameter $m = 0.65$ which results in the controller (17). The figs. 17 and 18 show the value sets for $\omega = 0:0.05:2.2$.

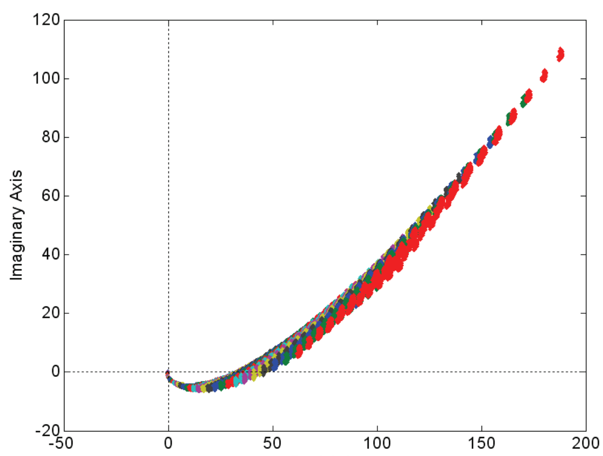

Fig. 17 the value sets – controller (17)

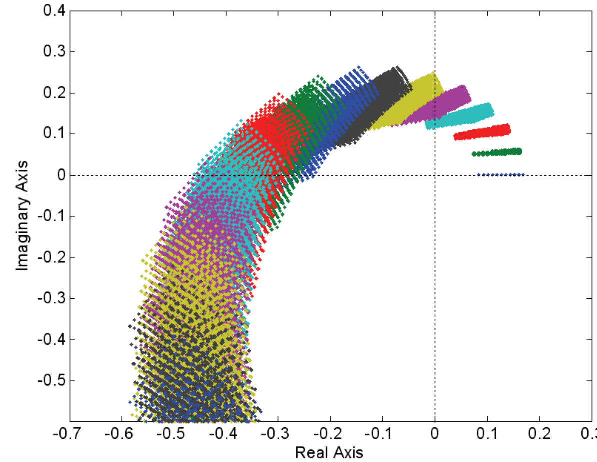

Fig. 18 the zoomed value sets – controller (17)

The "representative" set of output signals, and "representative" set of manipulated variables are depicted in figs. 19 and 20, respectively. All the figures demonstrate the robust stability of the closed control loop.

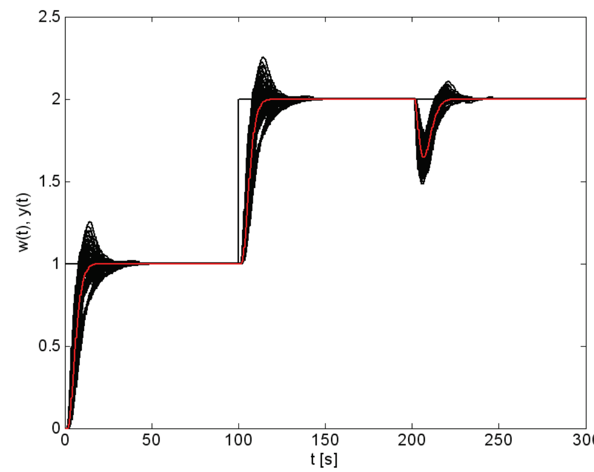

Fig. 19 set of output signals – controller (17)

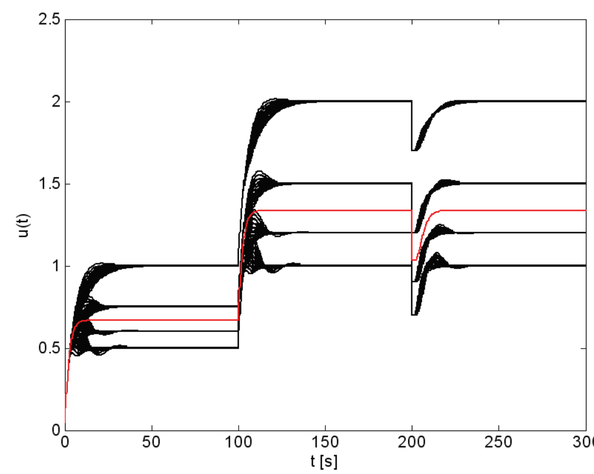

Fig. 20 set of manipulated variables – controller (17)

VII. CONCLUSION

The principal aim of the paper has been to show a possible method for control of single-input single-output time-delay systems with parametric uncertainty. The control design technique based mainly on general solutions of Diophantine equations in R_{PS} was accompanied by graphical investigation of robust stability using the value set concept and the zero exclusion condition. Within the paper, three realistic PID controllers tuned by means of single parameter were applied to the controlled first-order time-delay plant and two more general (third-order) controllers were applied to the controlled second-order time-delay plant. The obtained results of robust stability analysis and control simulations were compared and discussed.

REFERENCES

[1] L. Pekař, and R. Prokop, "Stabilization of a Delayed System by a Proportional Controller" *International Journal of Mathematical Models and Methods in Applied Sciences*, vol. 4, no. 4, pp. 282-290, 2010.

[2] L. Pekař, and E. Kurečková, "Rational Approximations for Time-Delay Systems: Case Studies" presented at the 13th WSEAS International Conference on Mathematical and Computational Methods in Science and Engineering, Catania, Italy, 2011.

[3] L. Pekař, R. Matušů, P. Dostálek, and J. Dolinay, "The Nyquist Criterion for LTI Time-Delay Systems" presented at the 13th WSEAS International Conference on Automatic Control, Modelling and Simulation, Lanzarote, Spain, 2011.

[4] Y.-Ch. Chang, and S. S. Chen, "Static Output-Feedback Simultaneous Stabilization of Interval Time-Delay Systems" *WSEAS Transactions on Systems*, vol. 7, no. 4, pp. 185-194, 2008.

[5] R. Matušů, and R. Prokop, "Control of Periodically Time-Varying Systems with Delay: An Algebraic Approach vs. Modified Smith Predictors" *WSEAS Transactions on Systems*, vol. 9, no. 6, pp. 689-702, 2010.

[6] T. Hashimoto, and T. Amemiya, "Stabilization of Linear Time-varying Uncertain Delay Systems with Double Triangular Configuration" *WSEAS Transactions on Systems and Control*, vol. 4, no. 9, pp. 465-475, 2009.

[7] B. Makki, and B. Makki, "Control Design for Uncertain Singularly Perturbed Systems with Discrete Time Delay" *WSEAS Transactions on Systems and Control*, vol. 6, no. 12, pp. 456-465, 2011.

[8] É. Gyurkovics, and T. Takács, "Output Feedback Guaranteeing Cost Control by Matrix Inequalities for Discrete-Time Delay Systems" *WSEAS Transactions on Systems*, vol. 7, No. 7, pp. 645-654, 2008.

[9] K. J. Åström, and T. Hägglund, *PID Controllers: Theory, Design and Tuning*. Research Triangle Park, North Carolina, USA: Instrument Society of America, 1995.

[10] A. O'Dwyer, *Handbook of PI and PID Controller Tuning Rules*. London, UK: Imperial College Press, 2003.

[11] M. Vidyasagar, *Control system synthesis: a factorization approach*. Cambridge, Massachusetts, USA: MIT Press, 1985.

[12] V. Kučera, "Diophantine equations in control – A survey" *Automatica*, vol. 29, no. 6, pp. 1361-1375, 1993.

[13] R. Prokop, and A. Mészáros, "Design of robust controllers for SISO time delay systems" *Journal of Electrical Engineering*, vol. 47, no. 11-12, pp. 287-294, 1996.

[14] R. Prokop, and J. P. Corriou, "Design and analysis of simple robust controllers" *International Journal of Control*, vol. 66, no. 6, pp. 905-921, 1997.

[15] R. Prokop, P. Husták, and Z. Prokopová, "Simple robust controllers: Design, tuning and analysis" presented at the 15th IFAC World Congress, Barcelona, Spain, 2002.

[16] R. Matušů, and R. Prokop, "Single-parameter tuning of PI controllers: Theory and application" *Journal of the Franklin Institute*, vol. 348, no. 8, pp. 2059-2071, 2011.

[17] B. R. Barmish, *New Tools for Robustness of Linear Systems*. New York, USA: Macmillan, 1994.

[18] M. Šebek, "Robustní řízení", PDF slides for course "Robust Control", Czech Technical University in Prague, Czech Republic, Available from URL: http://dce.felk.cvut.cz/ror/prednasky_sebek.html or http://www.polyx.com/_robust/. (In Czech).

[19] R. Matušů, and R. Prokop, "Graphical analysis of robust stability for systems with parametric uncertainty: an overview" *Transactions of the Institute of Measurement and Control*, vol. 33, no. 2, pp. 274-290, 2011.

[20] R. Matušů, R. Prokop, and L. Pekař, "Uncertainty Modelling in Time-Delay Systems: Parametric vs. Unstructured Approach" presented at the 13th WSEAS International Conference on Automatic Control, Modelling and Simulation, Lanzarote, Spain, 2011.

[21] R. Matušů, R. Prokop, and L. Pekař, "Parametric and unstructured approach to uncertainty modelling and robust stability analysis" *International Journal of Mathematical Models and Methods in Applied Sciences*, vol. 5, no. 6, pp. 1011-1018, 2011.

[22] R. Matušů, R. Prokop, and J. Korbel, "Uncertain Quasipolynomials: Robust Stability of Time-Delay Systems" presented at the 18th International DAAAM Symposium, Zadar, Croatia, 2007.

[23] R. Matušů, and R. Prokop, "Robust control of uncertain time-delay systems" presented at the 11th international research/expert conference "Trends in the development of machinery and associated technology", Hammamet, Tunisia, 2007.

[24] R. Matušů, R. Prokop, "Robust Stabilization of First-Order Time-Delay Systems with Parametric Uncertainty" presented at the 16th WSEAS International Conference on Systems, Kos, Greece, 2012.

[25] R. Matušů, R. Prokop, "Time-Delay Systems with Uncertain Parameters: An Algebraic Approach to Control Design" presented at the 14th WSEAS International Conference on Mathematical and Computational Methods in Science and Engineering, Malta, 2012.

Radek Matušů was born in Zlín, Czech Republic in 1978. He is a Researcher at Faculty of Applied Informatics of Tomas Bata University in Zlín, Czech Republic. He graduated from Faculty of Technology of the same university with an MSc in Automation and Control Engineering in 2002 and he received a PhD in Technical Cybernetics from Faculty of Applied Informatics in 2007. He worked as a Lecturer from 2004 to 2006. The main fields of his professional interest include robust systems and application of algebraic methods to control design.

Roman Prokop, born in 1952, is a Vice-Dean and a Full Professor at Faculty of Applied Informatics of Tomas Bata University in Zlín, Czech Republic. He graduated from Czech Technical University in Prague in 1976 and received a PhD from Slovak University of Technology in Bratislava in 1983. He was an Associate Professor from 1996 and a Full Professor from 2004. He aims his pedagogical and research work to automatic control theory, algebraic methods in control design and optimization. The main interests of the latest period are uncertain and robust systems, autotuning of controllers and time-delay systems.