Robust stabilization of interval plants by means of two feedback controllers

Radek Matušů

***Abstract*—**The main aim of this paper is to present an approach for robust stabilization of interval plants by means of closed-loop control systems with two feedback controllers. The control synthesis is based on the polynomial technique and subsequent graphical robust stability analysis utilizes the combination of the value set concept with the zero exclusion condition. The presented set of examples for second and third order interval plants illustrates design and tuning of various controllers and elucidates investigation of robust stability through the graphical tests. Finally, the obtained results are confirmed by the control simulations.

***Keywords*—**Two Feedback Controllers, Interval Systems, Polynomial Method, Robust Stability Analysis.

I. Introduction

The control system with two feedback controllers represents a relatively general structure in which the weight coefficients for two individual controllers can be selected [1], [2]. Two extreme cases of this choice then correspond either to classical one-degree-of-freedom (1DOF) control loop or (under some presumptions) to two-degree-of-freedom (2DOF) configuration. Thus, this structure offers more facilities in controller tuning. However, the robustness of the loop with two feedback controllers and some family of controlled plants has not been studied in many research works so far (for some robustness problems see e.g. [3] – [5]).

The principal goal of this paper is to demonstrate utilization of a graphical robust stability analysis for closed control loops with two feedback controllers and interval plants. The applied control design method is based on the polynomial approach [1], [2] and solution of Diophantine equations [6]. Subsequent robust stability tests of the resulting closed-loop characteristic polynomials with affine linear uncertainty structure employ the well known combination of the value set concept and the zero exclusion condition [7]. The simulation examples show design and tuning of various sets of two feedback controllers for the second and third order interval plants, followed by graphical robust stability analysis and control simulation for several "sampled" representatives of the controlled plant family with interval uncertainty. A previous version of this paper was presented at the conference [8].

The paper is organized as follows. In Section 2, the control structure with two feedback controllers is briefly described. The Section 3 then offers the fundamentals on applied polynomial approach to control design and tuning. A graphical technique for robust stability analysis of systems with parametric uncertainty is outlined in Section 4. Further, several simulation examples for second and third order interval plants are presented in the extensive Section 5. And finally, Section 6 provides some conclusion remarks.

The work was performed with financial support of research project NPU I No. MSMT-7778/2014 by the Ministry of Education of the Czech Republic and also 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.

Radek Matušů is 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, 76001 Zlín, Czech Republic (e-mail: rmatusu@fai.utb.cz).

II. Control Systems with Two Feedback Controllers

The diagram of the control system with two feedback controllers adopted from [1], [2] with referred original inspiration in [9] is depicted in Fig. 1.

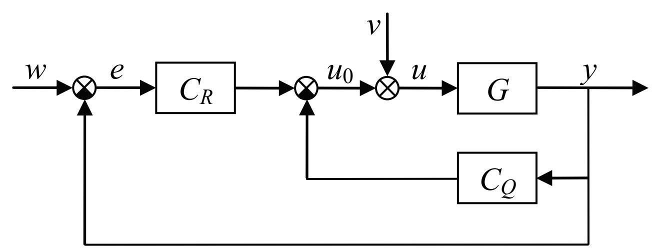

Fig. 1 control loop with two feedback controllers

The blocks C_R and C_Q represent two controllers and G stands for a controlled plant. The symbols of the signals have the following meaning: w – reference signal, e – tracking (control) error, u_0 – difference of controllers' outputs, u – control signal, y – controlled signal (output), v – load disturbance.

The controllers are supposed to be described by transfer functions:

$$C_Q(s) = \frac{\tilde{q}(s)}{\tilde{p}(s)} \tag{1}$$

$$C_R(s) = \frac{r(s)}{\tilde{p}(s)} \tag{2}$$

and controlled plant is given by:

$$G(s) = \frac{b(s)}{a(s)} \tag{3}$$

III. Control Design

A polynomial method is used for control design [1], [2]. It should fulfill the basic requirements such stability and internal properness of the control system, asymptotic tracking of the reference signal and load disturbance rejection.

Laplace transforms of basic signals from Fig. 1 can be obtained as follows [2]:

$$Y(s) = \frac{b(s)}{d(s)}\left[r(s)W(s) + \tilde{p}(s)V(s)\right] \tag{4}$$

$$E(s) = \frac{1}{d(s)}\left\{\left[a(s)\tilde{p}(s) + b(s)\tilde{q}(s)\right]W(s) - b(s)\tilde{p}(s)V(s)\right\} \tag{5}$$

$$U(s) = \frac{a(s)}{d(s)}\left[r(s)W(s) + \tilde{p}(s)V(s)\right] \tag{6}$$

where $d(s)$ is the closed-loop characteristic polynomial:

$$d(s) = a(s)\tilde{p}(s) + b(s)\left[r(s) + \tilde{q}(s)\right] \tag{7}$$

Simple substitution

$$t(s) = r(s) + \tilde{q}(s) \tag{8}$$

leads to the Diophantine equation:

$$a(s)\tilde{p}(s) + b(s)t(s) = d(s) \tag{9}$$

which is critical for control design.

Stability of control loop from Fig. 1 is guaranteed for polynomials $\tilde{p}(s)$ and $t(s)$ obtained as a solution of the Diophantine equation (9) with a stable right-hand polynomial $d(s)$.

In this paper, both reference w and load disturbance v are supposed as stepwise signals with general Laplace transforms:

$$W(s) = \frac{w_0}{s}, \quad V(s) = \frac{v_0}{s} \tag{10}$$

Under this scenario, the asymptotic tracking and load disturbance rejection are ensured by divisibility of both terms $\left[a(s)\tilde{p}(s) + b(s)\tilde{q}(s)\right]$ and $\tilde{p}(s)$ from tracking error equation (5) by the term s. Obviously, it is fulfilled for the following forms of polynomials $\tilde{p}(s)$ and $\tilde{q}(s)$:

$$\tilde{p}(s) = sp(s), \quad \tilde{q}(s) = sq(s) \tag{11}$$

Consequently, the controllers' transfer functions (1) and (2) can be written as:

$$C_Q(s) = \frac{q(s)}{p(s)} \tag{12}$$

$$C_R(s) = \frac{r(s)}{sp(s)} \tag{13}$$

Since the transfer functions of all components of the control system are supposed to be proper, the following inequalities must hold true:

$$\begin{aligned} \deg q &\le \deg p \\ \deg r &\le \deg p + 1 \end{aligned} \tag{14}$$

The Diophantine equation (9) can be simply rewritten to:

$$a(s)sp(s) + b(s)t(s) = d(s) \tag{15}$$

and the polynomial t (8) can be expressed as:

$$t(s) = r(s) + sq(s) \tag{16}$$

The degrees of polynomials in equations (15) and (16) can be derived (assuming their solvability) [2]:

$$\begin{aligned} \deg t &= \deg r = \deg a \\ \deg q &= \deg a - 1 \\ \deg p &\ge \deg a - 1 \\ \deg d &\ge 2\deg a \end{aligned} \tag{17}$$

The forms of polynomials $t(s)$, $r(s)$ and $q(s)$ are:

$$\begin{aligned} t(s) &= \sum_{i=0}^{n} t_i s^i \\ r(s) &= \sum_{i=0}^{n} r_i s^i \\ q(s) &= \sum_{i=1}^{n} q_i s^{i-1} \end{aligned} \tag{18}$$

with basic relations among their coefficients [2]:

$$\begin{aligned} &r_0 = t_0 \\ &r_i + q_i = t_i \quad \text{for } i = 1, \dots, n \end{aligned} \tag{19}$$

Coefficients of the polynomials $r(s)$ and $q(s)$ can be obtained on the basis of calculated polynomial $t(s)$ and adjustable coefficients $\gamma_i \in \langle 0,1 \rangle$ according to:

$$\begin{aligned} &r_i = \gamma_i t_i \quad \text{for } i = 1, \dots, n \\ &q_i = (1 - \gamma_i)t_i \quad \text{for } i = 1, \dots, n \end{aligned} \tag{20}$$

Obviously, the coefficients γ_i represent the weights for numerators of transfer functions (12) and (13). The unit parameters γ_i for all i reduce the control system (Fig. 1) to standard 1DOF configuration ($C_Q(s)=0$). On the other hand, if all $\gamma_i = 0$ and moreover reference and load disturbance are stepwise signals, the control system corresponds to 2DOF control structure [2].

Primarily, the control behaviour can be influenced by selection of right-hand polynomial $d(s)$ in Diophantine equation (15). In this contribution, just the simplest method with multiple real roots will be utilized.

IV. Systems with Parametric Uncertainty: Robust Stability Analysis

Systems with parametric uncertainty suppose known fixed structure but on the other hand imprecise knowledge of real physical parameters. Typically, such parameters are bounded by intervals with minimal and maximal possible values. General transfer function describing a system with parametric uncertainty has a form:

$$G(s,q) = \frac{b(s,q)}{a(s,q)} \tag{21}$$

where $b(s,q)$ and $a(s,q)$ are polynomials with coefficients depending on vector of real uncertain parameters q which is typically bounded by some uncertainty bounding set (frequently by using L_∞ norm).

A common practically used case of system with parametric uncertainty is represented by an interval plant:

$$G(s,b,a) = \frac{\sum_{i=0}^{m}\left[b_i^-;b_i^+\right]s^i}{\sum_{i=0}^{n}\left[a_i^-;a_i^+\right]s^i} \tag{22}$$

with mutually independent parameters defined by means of their lower and upper limits.

The main object of interest from the viewpoint of robust stability is uncertain closed-loop characteristic polynomial:

$$p(s,q) = \sum_{i=0}^{n}\rho_i(q)s^i \tag{23}$$

where $\rho_i(q)$ are coefficient functions. Corresponding family of closed-loop characteristic polynomials can be written as:

$$P = \{p(s,q): q\in Q\} \tag{23}$$

The robust stability of this family of polynomials means that $p(s,q)$ is stable for all $q \in Q$. However, direct calculation of roots could take extremely long computation times and thus the more sophisticated methods are studied. The choice of specific technique for robust stability analysis depends mainly on the uncertainty structure. The higher level of relation among coefficients yields more complicated investigation and usually requires more powerful and effective tools. Nonetheless, there is a graphical method based on combination of the value set concept and the zero exclusion condition available [7]. It is applicable for the wide range of uncertainty structures, including the very complicated ones.

According to [7], the value set at given frequency $\omega \in \mathbb{R}$ is:

$$p(j\omega,Q) = \{p(j\omega,q): q\in Q\} \tag{24}$$

Practical creation of the value sets can be performed by substituting s for $\omega \in \mathbb{R}$, fixing $\omega \in \mathbb{R}$ and letting q range over Q.

The zero exclusion condition for Hurwitz stability of family of continuous-time polynomials (23) is defined [7]: Suppose invariant degree of polynomials in the family, pathwise connected uncertainty bounding set Q, continuous coefficient functions $\rho_k(q)$ for $k = 0,1,2,\ldots,n$ and at least one stable member $p(s,q^0)$. Then the family P is robustly stable if and only if:

$$0 \notin p(j\omega,Q) \quad \forall \omega \geq 0 \tag{25}$$

The detailed information on robust stability analysis under parametric uncertainty can be found in [7] and subsequently e.g. in [10], [11].

V. Simulation Examples

A. Second Order Interval Plant

Initially, suppose a controlled plant described by the second order interval transfer function:

$$G(s,b,a) = \frac{[0.4,1.6]}{[0.4,1.6]s^2 + [0.4,1.6]s + [0.4,1.6]} \tag{26}$$

The nominal system, used for a controller design, is assumed to have the average values:

$$G_N(s) = \frac{1}{s^2+s+1} \tag{27}$$

so the interval family contains all parameter perturbations of the size $\pm 60\%$.

The Diophantine equation (15) takes the form:

$$\left(s^2+s+1\right)s\left(p_1 s + p_0\right) + \left(t_2 s^2 + t_1 s + t_0\right) = \left(s+m\right)^4 \tag{28}$$

i.e. it is considered as a polynomial with quadruple roots.

First, the roots are chosen as -0.85, which means $m = 0.85$. Besides, the coefficients from (20) are supposed $\gamma_1 = \gamma_2 = 0.5$.

Thus, the final controllers are:

$$C_Q(s) = \frac{0.4675s + 0.0283}{s + 2.4} \tag{29}$$

$$C_R(s) = \frac{0.4675s^2 + 0.0283s + 0.522}{s^2 + 2.4s} \tag{30}$$

The corresponding family of closed-loop characteristic polynomials (with affine linear uncertainty structure) is:

$$\begin{aligned} p_{CL}(s,a,b) &= a_2 s^4 + \left(2.4a_2 + a_1\right)s^3 + \cdots \\ &+ \left(2.4a_1 + a_0 + 0.935b_0\right)s^2 + \left(2.4a_0 + 0.0565b_0\right)s + 0.522b_0 \end{aligned} \tag{31}$$

where $a_2, a_1, a_0, b_0 \in \langle 0.4, 1.6 \rangle$ are taken from (26).

The value sets for the family of polynomials (31) and frequency range from 0 to 3 with step 0.05 are depicted in Fig. 2 while its zoomed version (in order to see better a closer neighborhood of the complex plane origin) is shown in Fig. 3.

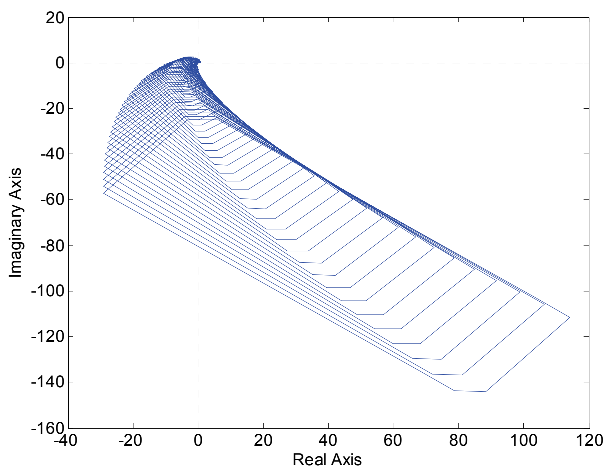

Fig. 2 value sets for family of closed-loop characteristic polynomials (31) – full view

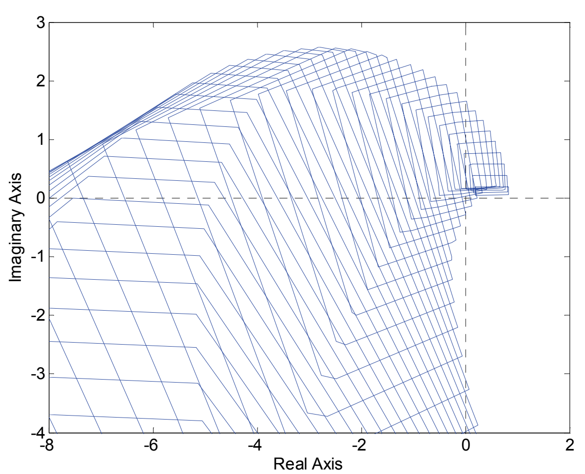

Fig. 3 value sets for family of closed-loop characteristic polynomials (31) – zoomed view

It is clearly distinguishable (Fig. 3) that the zero point is included in the value sets. Consequently, the family of closed-loop characteristic polynomials (31) is not robustly stable.

The Fig. 4 shows the simulations of the output signals of 256 "sampled plants" from the interval family (26). All four interval parameters were divided into 3 subintervals of the equal size and so the obtained 4 values for 4 parameters lead to $4^4 = 256$ plants for simulation. Moreover, the red curve represents the output signal of the nominal plant (27). Besides, the stepwise reference signal changing from 1 to 2 in the first third of the simulation time and step load disturbance -0.5 affecting the input to the controlled plant during the last third of simulation are supposed.

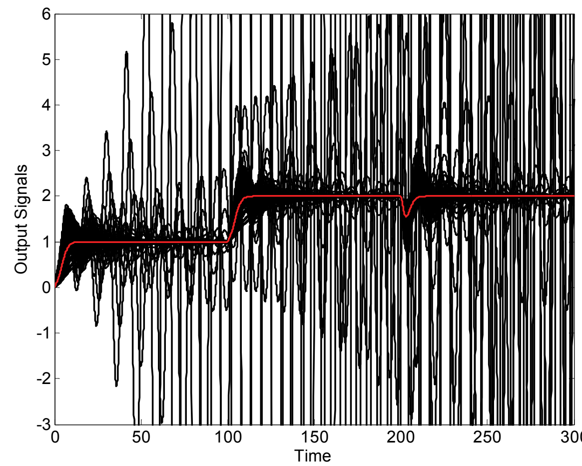

Fig. 4 control of "sampled plants" from interval family (26) by two feedback controllers (29) and (30)

As can be seen from Fig. 4, although some members of the family (26) are robustly stabilized (e.g. nominal system) by two feedback controllers (29) and (30), the other members are not so the system is really robustly unstable as had been already proven by Figs. 2 and 3.

The selection of coefficients γ_i do not influence the robust stability of the control loop with two feedback controllers as the polynomial $t(s)$ remains the same. It would change "only" control performance but the system remains either robustly stable or robustly unstable for all possible γ_i.

Now, different quadruple roots are supposed, i.e. $m = 1.3$. The weight coefficients are considered again as $\gamma_1 = \gamma_2 = 0.5$. This results in controllers:

$$C_Q(s) = \frac{2.47s + 2.294}{s + 4.2} \tag{32}$$

$$C_R(s) = \frac{2.47s^2 + 2.294s + 2.8561}{s^2 + 4.2s} \tag{33}$$

and subsequently in the family of closed-loop characteristic polynomials:

$$p_{CL}(s,a,b) = a_2 s^4 + (4.2a_2 + a_1)s^3 + \cdots + (4.2a_1 + a_0 + 4.94b_0)s^2 + (4.2a_0 + 4.588b_0)s + 2.8561b_0 \quad (34)$$

with $a_2, a_1, a_0, b_0 \in \langle 0.4, 1.6 \rangle$ from (26).

The value sets for this new polynomial family (34) (for frequency 0:0.05:4) are shown in Fig. 5 while the closer look near the complex plane origin can be seen in Fig. 6.

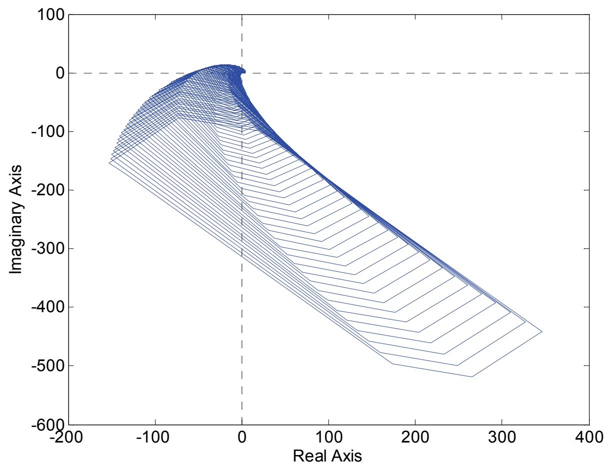

Fig. 5 value sets for family of closed-loop characteristic polynomials (34) – full view

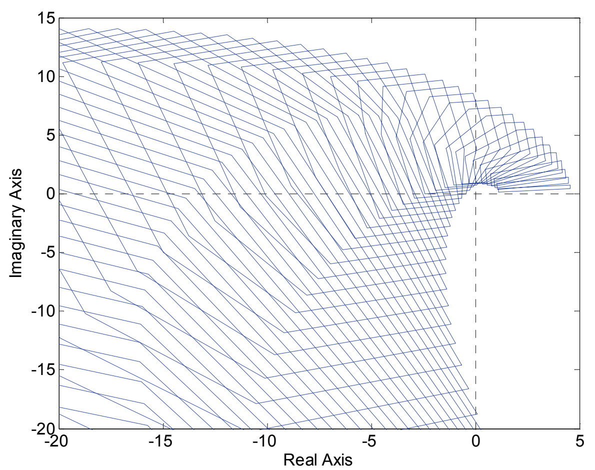

Fig. 6 value sets for family of closed-loop characteristic polynomials (34) – zoomed view

In this case, the Figs. 5 and 6 reveal that the complex plane origin is excluded from the value sets. Moreover, the family contains a stable member so one can conclude that the closed-loop characteristic polynomial (34) is robustly stable.

The output signals simulated under the same conditions as for the previous controller are shown in Fig. 7. As can be seen, all “sampled plants” are really stabilized by two feedback controllers (32) and (33).

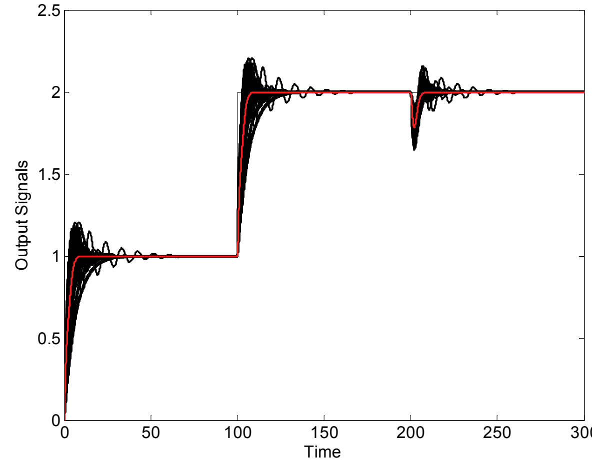

Fig. 7 control of “sampled plants” from interval family (26) by two feedback controllers (32) and (33)

Obviously, a different choice of coefficients γ_i would not change the robust stability, again. However, the control performance can be influenced by their alteration. For example, suppose the same controlled (26) and nominal (27) plant, the same quadruple roots $m = 1.3$, but the weight coefficients are modified to $\gamma_1 = \gamma_2 = 1$. This leads to the new controllers:

$$C_Q(s) = 0 \quad (35)$$

$$C_R(s) = \frac{4.94s^2 + 4.588s + 2.8561}{s^2 + 4.2s} \quad (36)$$

which corresponds to standard 1DOF control configuration. The simulations of the output signals are shown in Fig. 8. As can be seen, they really behave in an expected 1DOF way (more “aggressive” responses with higher overshoots).

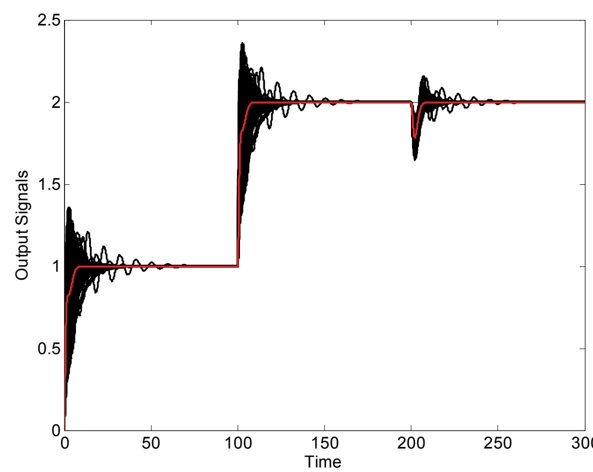

Fig. 8 control of “sampled plants” from interval family (26) by two feedback controllers (35) and (36)

The second extreme selection of weight coefficients $\gamma_1 = \gamma_2 = 0$ corresponds to 2DOF configuration (as the reference and load disturbance are stepwise signals). The related feedback controllers are now:

$$C_Q(s) = \frac{4.94s + 4.588}{s + 4.2} \tag{37}$$

$$C_R(s) = \frac{2.8561}{s^2 + 4.2s} \tag{38}$$

The corresponding simulations of the output signals are depicted in Fig. 9. The interesting outcome is that the worst case responses for the previously tuned controllers (32) and (33) (for $\gamma_1 = \gamma_2 = 0.5$) have the lower overshoots then the worst case responses for this purely 2DOF configuration with controllers (37) and (38).

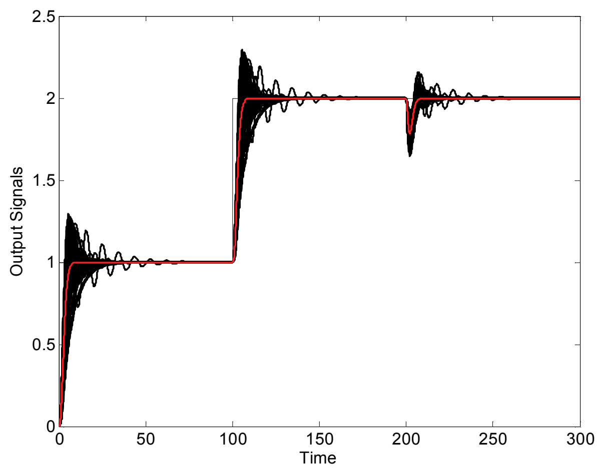

Fig. 9 control of “sampled plants” from interval family (26) by two feedback controllers (37) and (38)

B. *Third Order Interval Plant*

In the second example, the third order interval plant adopted from [7] is considered:

$$G(s,b,a) = \frac{[0.75, 1.25]s + [0.75, 1.25]}{s^3 + [2.75, 3.25]s^2 + [8.75, 9.25]s + [0.75, 9.25]} \tag{39}$$

The mean-valued nominal system for a controller design is:

$$G_N(s) = \frac{s+1}{s^3 + 3s^2 + 9s + 5} \tag{40}$$

and thus, the Diophantine equation (15) can be written as:

$$\begin{gathered}\left(s^3 + 3s^2 + 9s + 5\right)s\left(p_2 s^2 + p_1 s + p_0\right) + \cdots \\ + (s+1)\left(t_3 s^3 + t_2 s^2 + t_1 s + t_0\right) = (s+m)^6\end{gathered} \tag{41}$$

First, $m = 1.5$ and $\gamma_1 = \gamma_2 = \gamma_3 = 0.5$ are selected which results in the controllers:

$$C_Q(s) = \frac{0.8711s^2 - 4.1328s + 4.5664}{s^2 + 6s + 5.0078} \tag{42}$$

$$C_R(s) = \frac{0.8711s^3 - 4.1328s^2 + 4.5664s + 11.3906}{s^3 + 6s^2 + 5.0078s} \tag{43}$$

The corresponding family of (sixth order) closed-loop characteristic polynomials is:

$$\begin{aligned} &p_{CL}(s,a,b) = s^6 + (a_2 + 6)s^5 + \cdots \\ &+ (a_1 + 6a_2 + 1.7422b_1 + 5.0078)s^4 + \cdots \\ &+ (a_0 + 6a_1 + 5.0078a_2 - 8.2656b_1 + 1.7422b_0)s^3 + \cdots \\ &+ (6a_0 + 5.0078a_1 + 9.1328b_1 - 8.2656b_0)s^2 + \cdots \\ &+ (5.0078a_0 + 11.3906b_1 + 9.1328b_0)s + 11.3906b_0 \end{aligned} \tag{44}$$

where parameters a_i and b_i can vary according to uncertain parameters from the plant (39).

The value sets for the family of polynomials (44) (frequency range 0:0.05:5.5) going successively through six quadrants are depicted in Fig. 10. Then, Fig. 11 shows its zoomed version.

Since the zero point is included in the value sets, the family of closed-loop characteristic polynomials (44) is robustly unstable. This is demonstrated also by the Fig. 12 where the simulations of the output signals for $3^5 = 243$ “sampled plants” from the interval family (39) are plotted. As in the previous example, the red curve represents the output signal of the nominal plant (40). Besides, the step load disturbance -2 affecting the input to the controlled plant during the last third of simulation is assumed.

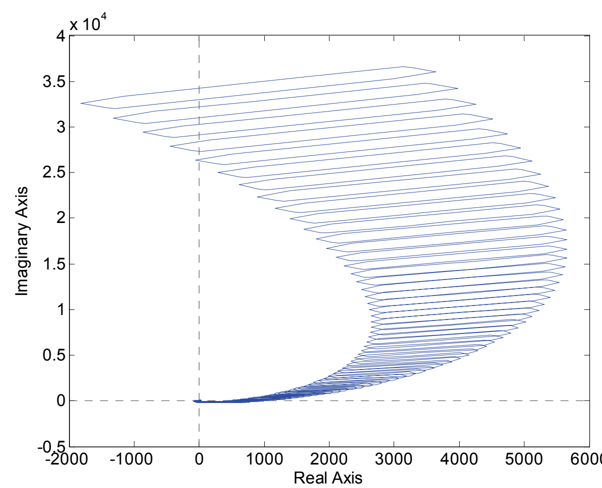

Fig. 10 value sets for family of closed-loop characteristic polynomials (44) – full view

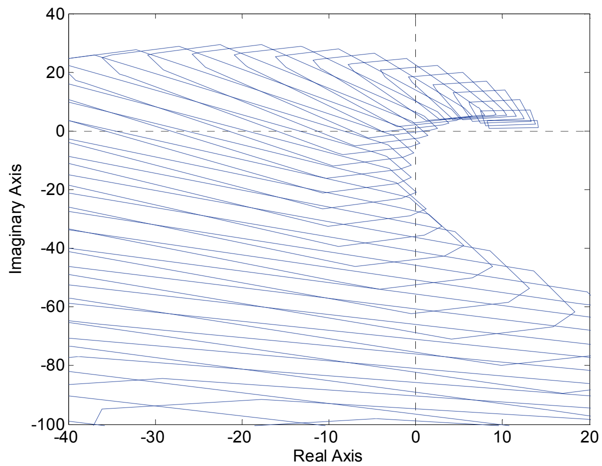

Fig. 11 value sets for family of closed-loop characteristic polynomials (44) – zoomed view

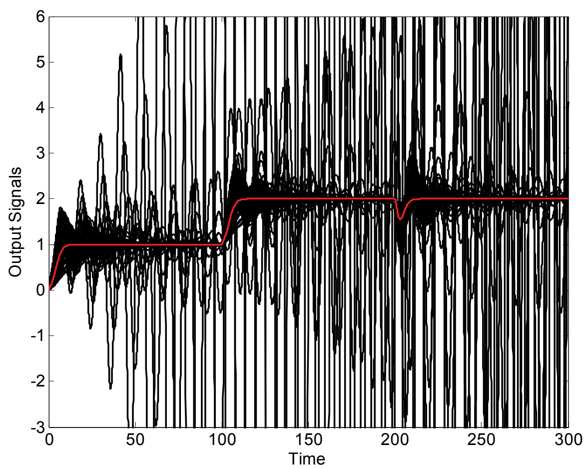

Fig. 12 control of "sampled plants" from interval family (39) by two feedback controllers (42) and (43)

The Fig. 12 clearly confirms that really only some members of the family (39) are stabilized but the other ones are not and so the family as a whole is robustly unstable.

Next, $m = 2.1$ and $\gamma_1 = \gamma_2 = \gamma_3 = 0.5$ are supposed. So the controllers are:

$$C_Q(s) = \frac{9.4321s^2 + 23.2492s + 55.9255}{s^2 + 9.6s + 9.4858} \tag{45}$$

$$C_R(s) = \frac{9.4321s^3 + 23.2492s^2 + 55.9255s + 85.7661}{s^3 + 9.6s^2 + 9.4858s} \tag{46}$$

and the corresponding family of closed-loop characteristic polynomials is:

$$\begin{aligned} p_{CL}(s,a,b) &= s^6 + (a_2 + 9.6)s^5 + \cdots \\ &+ (a_1 + 9.6a_2 + 18.8642b_1 + 9.4858)s^4 + \cdots \\ &+ (a_0 + 9.6a_1 + 9.4858a_2 + 46.4984b_1 + 18.8642b_0)s^3 + \cdots \\ &+ (9.6a_0 + 9.4858a_1 + 111.851b_1 + 46.4984b_0)s^2 + \cdots \\ &+ (9.4858a_0 + 85.7661b_1 + 111.851b_0)s + 85.7661b_0 \end{aligned} \tag{47}$$

with the uncertain parameters from (39).

Finally, the full and nearer views of the value sets for the family (47) are shown in Figs. 13 and 14, respectively (frequency range 0:0.05:8). The existence of a stable member and the plotted value sets clearly prove the robust stability of (47).

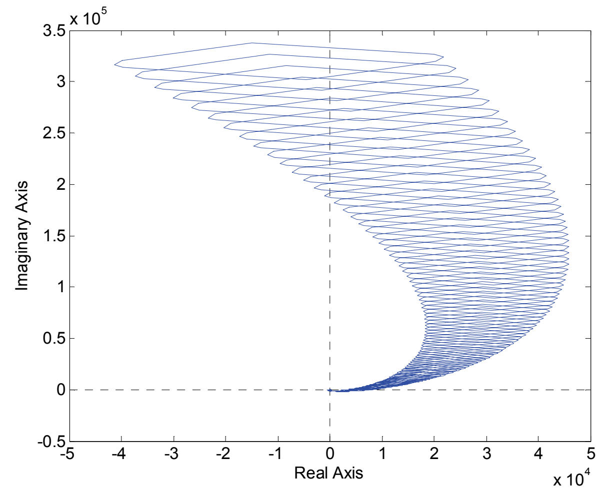

Fig. 13 value sets for family of closed-loop characteristic polynomials (47) – full view

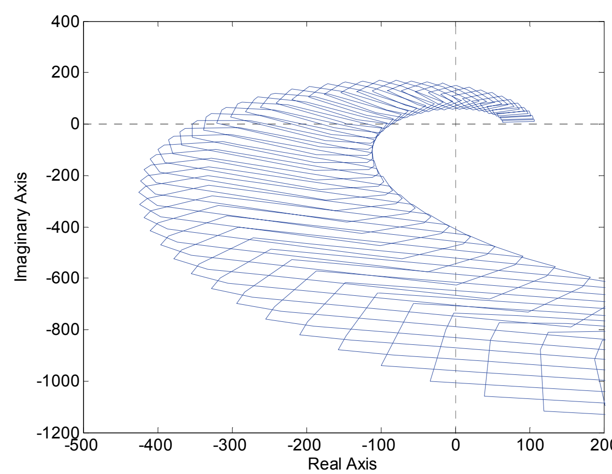

Fig. 14 value sets for family of closed-loop characteristic polynomials (47) – zoomed view

The set of corresponding simulations of the output signals is visualized in Fig. 15.

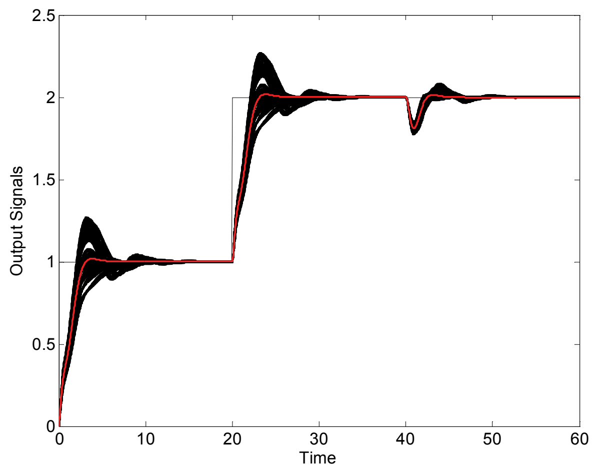

Fig. 15 control of "sampled plants" from interval family (39) by two feedback controllers (45) and (46)

VI. Conclusion

The contribution has been focused on investigation of robust stability for closed-loop control systems containing two feedback controllers and interval plants by means of plotting the value sets and subsequent application of the zero exclusion condition. The controller design itself is based on the polynomial approach. The computational examples have demonstrated analysis and simulation of robustly stable or unstable control loops with second or third order interval plant. The paper has also shown that the choice of weight coefficients for numerators of the individual feedback controllers influences "only" control performance but has no impact on the robust stability or instability.

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Radek Matušů was born in Zlín, Czech Republic in 1978. Currently, 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. The main fields of his professional interest include robust systems and application of algebraic methods to control design.