ROBUST PROCESS CONTROL WITH SATURATED CONTROL INPUT

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ABSTRACT

The contribution presents a methodology to design a robust control loop in case of the saturated control input. The control system design is based on the polynomial approach resulting in the pole-placement problem to be solved. This task is addressed numerically by means of standard MATLAB functions to meet both the constraints on the control input and robustness of the resultant loop. New control quality criteria are suggested for this purpose. The proposed methodology is illustrated practically on a simple simulation example with a classical feedback set-up and one optimized parameter. The presented preliminary results show applicability of the suggested approach.

INTRODUCTION

When designing control systems nowadays it is common to use various simulation tools. It allows to make experiments safely prior to the implementation under real conditions and it saves both time and costs. In some cases, e.g. designing safe control systems for various reactors and unstable processes, it can even save lives when done properly. A simulation model of the process to be controlled is the key crucial point in the designing procedure. It has to contain the main important properties of the process with respect to control. Generally, the more information about the process the better for the control system design. However, a complicated model is not practical for both implementation and control system design as it leads to more complex controllers. Therefore a good process model has to be a trade-off between model complexity and practicability. The fact that only an approximate model of a real nonlinear process is used for the control system design has to be kept in mind and solved using e.g. the adaptive or robust control approach. The adaptive control systems (e.g. Åström and Wittenmark 1995) are generally more complex as they must readjust to new process operating conditions. Robust control systems (e.g. Morari and Zafirou 1989; Barmish 1994; Bhattacharya et al. 1995) generally use simpler fixed controllers capable of meeting the control requirements not only for one particular process model but for a certain class of them. Practically the robust controllers are more often used in the industrial practice due to their simpler structure although the achieved control quality may be worse compared to the adaptive control approach.

In practical control applications there are always limits. The most crucial are the constraints on the manipulated variable - the so called control input signal which is used to obtain the desired course of the controlled variable. This signal is always represented by a certain physical quantity, such as a flow rate, electric current or voltage etc which obviously has some limits. Besides amplitude limitations of the manipulated variables there are very often limits on the achievable speed of changes of the variables due to the used actuators, e.g. valves. These facts have to be carefully considered in the control system design procedure and simulation testing. Not respecting these limits can lead to serious consequences, especially when dealing with hardly controllable processes, e.g. unstable, with significant time-delay or with an inverse response (Stein 2003). In the literature there is a great number of classic methods dealing with this problem, often called anti-wind-up techniques applicable mainly to popular PI and PID controllers (e.g. Saberi et al. 2000; Glattfelder and Schaufelberger 2003). Among modern control approaches the predictive control concept is also effective and popular in this field nowadays (Camacho and Bordons 2004; De Doná et al. 2000), although it is more computationally demanding.

Although there are many sources devoted to the robust control systems design and to the constrained control separately, simultaneous solutions of both these problems are still quite rare (e.g. Campo and Morari 1990; Miyamoto and Vinnicombe 1996; Huba 2010). This paper represents a contribution to this interesting and practically important topic. The methodology fruitfully utilized in this contribution is based on the systematic algebraic control concept transforming the control system design problem to the solution of polynomial equations (e.g. Kučera 1993; Hunt 1993; Anderson 1998). After formulation of basic control requirements the polynomial approach enables to find both suitable structure and parameters of controllers. Generally it can lead to more complicated structures of the resultant controllers than the classical PI or PIDs but this does not seem a serious problem nowadays when most of industrial controllers are implemented using PLCs.

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A natural part of the procedure for finding a suitable controller using the polynomial approach is the pole-placement problem solution (e.g. Kučera 1994). In this paper this task is solved numerically using the standard MATLAB functions for nonlinear constrained optimization. The resultant poles (free parameters) of the control loop are optimized with respect to both robustness and constraints on the control input signal. For this purpose new control quality criteria and a corresponding procedure are suggested. The whole methodology is illustrated on a simple representative example with the help of simulation means, namely the MATLAB/Simulink environment.

The presented paper is structured as follows: after this introductory section the contribution starts by recalling basics from the algebraic control theory utilized in this work. Next part introduces the control quality criteria for subsequent optimization which is described in detail in the section later. Further parts present the illustrative example, analyse the achieved results and suggest possible areas of future work.

THEORETICAL FRAMEWORK

This section recalls basics of the employed polynomial approach and prepares the space for the methodology respecting both control input limitations and robustness of the resultant loop.

Assume the classical feedback control system of Fig. 1, where G denotes a plant to be controlled by a controller C and the signals w, e, u, and y stand for the reference (set point), control error, control input (manipulated variable), and a process (controlled) variable, respectively. Signals v_u and v_y represent general disturbances.

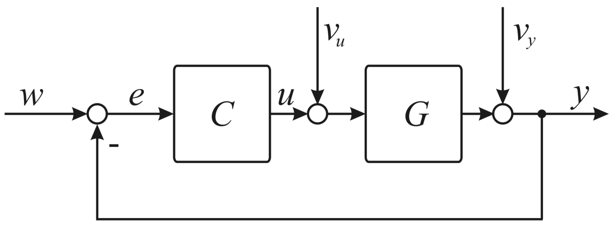

Figure 1: Control System Configuration

Further suppose that in the continuous-time domain both the plant and the controller can be approximated by transfer functions $G(s)$, $C(s)$ with coprime polynomials $b(s)$, $a(s)$ and $q(s)$, $p(s)$ according to (1)-(2) satisfying (3)-(4), i.e. the plant is generally assumed to be strictly proper while the controller is supposed to be proper (the argument s is the complex variable of the Laplace transform).

$$G(s) = \frac{b(s)}{a(s)} \tag{1}$$

$$C(s) = \frac{q(s)}{p(s)} \tag{2}$$

$$\deg a(s) > \deg b(s) \tag{3}$$

$$\deg p(s) \geq \deg q(s) \tag{4}$$

The basic requirements for the control system introduced above are formulated as follows:

- Stability
- Asymptotic tracking of the reference signal
- Disturbances attenuation
- Inner properness

Besides the above-mentioned general requirements, the control system should also be robust to cope with the real nonlinear plant (not only with the adopted linear model) and possible disturbances. In addition the controller has to respect the given physical limitations of its manipulated variable. All these tasks are discussed and solved further in this paper.

From the scheme of Fig. 1 and assuming (1)-(2), it is easy to derive following relationships between the controlled variable $y(t)$ ($Y(s)$ in the complex domain) and the input signals $w(t)$, $v_u(t)$, and $v_y(t)$ ($W(s)$, $V_u(s)$, and $V_y(s)$ similarly); the argument s is omitted in these formulas to keep them more compact and readable:

$$\begin{aligned} Y &= \tfrac{GC}{1+GC}W + \tfrac{G}{1+GC}V_u + \tfrac{1}{1+GC}V_y = \\ &= \tfrac{bq}{ap+bq}W + \tfrac{bp}{ap+bq}V_u + \tfrac{ap}{ap+bq}V_y = \\ &= \tfrac{bq}{d}W + \tfrac{bp}{d}V_u + \tfrac{ap}{d}V_y = \\ &= TW + S_uV_u + SV_y. \end{aligned} \tag{5}$$

Here, d denotes a characteristic polynomial of the closed loop defined as

$$ap + bq = d. \tag{6}$$

Symbols S, T, and S_u represent important transfer functions of the loop known as the sensitivity function, the complementary sensitivity function, and the input sensitivity function, respectively. The sensitivity function S is further used to make the designed control system robust.

Similarly, it is straightforward to derive the formula (7) for the control error $e(t)$ ($E(s)$ in the complex domain):

$$E(s) = \frac{p}{d}\left[aW(s) - bV_u(s) - aV_y(s)\right]. \tag{7}$$

Control System Stability

From (5), it is clear that the control system of Fig. 1 will be stable if the characteristic polynomial $d(s)$ given by (6) is stable. This polynomial equation, after a proper choice of the stable polynomial $d(s)$, is used to compute the unknown controller polynomials $q(s)$

and $p(s)$. Roots of the characteristic polynomial $d(s)$ are known as *poles* of the closed loop. Their proper placement influences not only stability of the loop but also the achieved control quality, i.e. a settling-time, overshoots, control input course etc. Therefore the so-called pole-placement problem is a natural part of the polynomial approach to control system design. In this work the poles are optimized numerically to respect both limitations on the control input and robustness of the resultant loop. The procedure is described in detail further in the paper.

Asymptotic Tracking of the Reference Signal and Disturbance Attenuation

Let us assume, as it is a common case, that the reference signal, $w(t)$, can be well approximated by a step function defined in the complex domain as

$$W(s) = \frac{w_0}{s}, \tag{8}$$

for some real w_0 and further, suppose that both disturbances $v_u(t)$ and $v_y(t)$ can be also approximated by the following step functions:

$$V_u(s) = \frac{v_{u0}}{s}, V_y(s) = \frac{v_{y0}}{s}, \tag{9}$$

for some reals v_{u0}, v_{y0}. Then, substituting (8) and (9) into (7) yields

$$E(s) = \frac{p}{d}\left(a\frac{w_0}{s} - b\frac{v_{u0}}{s} - a\frac{v_{y0}}{s}\right). \tag{10}$$

If we suppose $a(0), b(0) \neq 0$ (the common case of proportional systems) then it is obvious that to guarantee zero-control error in the steady state (despite both disturbances), the denominator polynomial of the controller $p(s)$ needs to be divisible by the s term, i.e. the controller has to include an integrator, which will be fulfilled for its denominator polynomial in the following form:

$$p(s) = s\,\tilde{p}(s). \tag{11}$$

Then the controller (2) can be written as

$$C(s) = \frac{q(s)}{s\,\tilde{p}(s)}, \tag{12}$$

and the polynomial equation (6) defining stability will be as follows:

$$as\tilde{p} + bq = d. \tag{13}$$

Inner Properness of the Control System

The inner properness of the control system is satisfied if all its parts (transfer functions) are proper. With regard to the strictly proper plant transfer function (1),(3), proper controller (2), (4) and taking into account the solvability of (6) and (13), it is possible to derive the following formulas for the degrees of the unknown polynomials q, $\tilde{p}$, and d:

$$\begin{aligned} &\deg\, q(s) = \deg\, a(s) \\ &\deg\, \tilde{p}(s) \geq \deg\, a(s) - 1 \\ &\deg\, d(s) \geq 2\deg\, a(s). \end{aligned} \tag{14}$$

For practical purposes, when seeking the most simple controller structures fulfilling the given requirements, equalities are taken into account in the inequalities above.

Pole-Placement Problem

For practical computation of the controller's polynomials $q(s)$, $\tilde{p}(s)$ (their coefficients) it is necessary to choose a suitable stable polynomial $d(s)$ appearing on the right side of the polynomial equation (6), (13). This is the so called pole-placement problem mentioned earlier (e.g. Kučera 1994). Therefore we are seeking suitable poles p_i of the designed loop to fulfil the given requirements. Hence the polynomial $d(s)$ can be expressed as:

$$d(s) = \prod_{i=1}^{\deg d} (s - p_i) \tag{15}$$

for some poles (its roots) p_i. Then the control design procedure transforms to the optimization problem of finding the right poles providing the required control quality. When working in the continuous-time domain it is well known the all the poles have to be in the left half of the complex plane to enable stable behaviour, i.e. their real parts have to be negative:

$$\mathrm{Re}\,[p_i] < 0 \ \ \forall i. \tag{16}$$

Besides this it is also well known that complex poles lead to oscillatory behaviour, therefore, it is recommended to employ only real poles for aperiodic (non-oscillatory) behaviour of the system, i.e. it is desirable to have imaginary parts of the poles equal to zero:

$$\mathrm{Im}\,[p_i] = 0 \ \ \forall i. \tag{17}$$

Therefore the optimization problem here can be formulated as to find suitable poles of the loop characteristic polynomial (15) respecting their stability (16) and aperiodic sense (17). The methodology for this task ensuring both loop robustness and limitations on the manipulated controller variable is introduced further in the next section. Based on the information presented above it is suggested to choose the characteristic polynomial of the closed loop $d(s)$ as

$$d(s) = \prod_{i=1}^{\deg d} (s + \alpha_i) \tag{18}$$

for some real constants $\alpha_i > 0$. This ensures both stability of the closed loop (all poles will be negative, i.e. stable, at positions $p_i = -\alpha_i$) and aperiodic behaviour as the poles are real numbers. Now the optimization task is to find optimal values of the free tuning parameters $\alpha_i > 0$.

METHODOLOGY

This section describes the used procedure for optimization of the poles to meet the required control quality, i.e. loop robustness and limitation on the control input. First suitable control quality criteria are suggested and then the methods and procedure of optimization is clarified.

Control Quality Criteria

The solved optimization problem can be formulated as follows:

$$\min_{\alpha} J_{rob}(\alpha) \text{ such that } \alpha_i > 0 \text{ and } J_u(\alpha) = 0, \quad (19)$$

where J_{rob} is the sub-criterion for assessing the loop robustness, J_u the criterion for evaluating demands on the manipulated variable, i.e. control input signal $u(t)$, and α is the vector of optimized parameters α_i. As far as the loop robustness is concerned, a peak gain of the sensitivity function frequency response given by the infinity norm H_∞ is a good measure for this purpose, e.g. (Skogestad and Postlethwaite 2005). Therefore it is suggested to use the sensitivity function S from (5) and its infinity norm H_∞ to assess the loop robustness. The sensitivity function is according to (5) given as:

$$S = \frac{1}{1+GC} = \frac{ap}{ap+bq} = \frac{ap}{d}, \quad (20)$$

then, the first sub-criterion describing robustness reads:

$$J_{rob} = \|S\|_\infty = \sup_{\omega} |S(j\omega)|, \quad (21)$$

where ω is the frequency. The second criterion J_u describes the demands on the manipulated variable $u(t)$ and is formed as follows. Let us define the achievable limits of the manipulated variable (control input) as U_{min} and U_{max} where the first one denotes the minimum allowed value of the signal and the latter one the maximum allowed value of the variable. Therefore the control input has to be in the following defined interval:

$$u(t) \in \langle U_{min}; U_{max} \rangle \ \ \forall t. \quad (22)$$

Further denote $\triangle u(t)_{max}$ as the maximum overshoot of the manipulated variable above the given limit U_{max} and correspondingly $\triangle u(t)_{min}$ the maximum undershoot of the manipulated variable under the given limit U_{min}. Then the sub-criterion J_u is computed according to this simple formula:

$$J_u = \triangle u(t)_{max} + \triangle u(t)_{min}. \quad (23)$$

It is evident that the sub-criterion is equal to zero if the manipulated variable is within the desired limits and it is positive with higher values for control input out of the required range. The situation is well illustrated in the following picture, Fig. 2, with the limits chosen as $U_{min} = -1$ and $U_{max} = 1$.

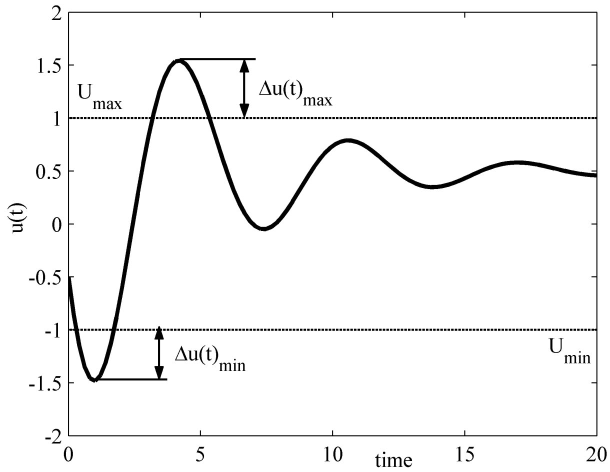

Figure 2: Explanation of the Sub-Criterion J_u

It is obvious that achieved values of the control quality criteria in (19) explained above depends on the placement of the closed-loop poles in (15), i.e. on the choice of the free tuning parameters $\alpha_i > 0$ in (18). This is solved with the help of simulation means using the procedure described in the next section.

Optimization Procedure

First, let us scale the loop variables so that both the controlled output $y(t)$ and correspondingly also the reference signal $w(t)$ are within the range from zero to one, i.e.

$$y(t), w(t) \in \langle 0; 1 \rangle. \quad (24)$$

Then the worst-case behaviour of the control system (regarding the changes in the reference signal) can be analysed by considering the reference change of magnitude one. Therefore the designed control system is analysed facing this condition and the control quality criteria in (19) are assessed for different values of the free tuning parameters $\alpha_i > 0$. This is done with the help of simulation means, namely the MATLAB environment and its toolboxes for simulation and optimization. The procedure can be briefly described as follows:

1. choose number of optimized parameters α_i (the closed-loop poles $p_i = -\alpha_i$ can be different or multiple);
2. for every α_i choose an interval for optimization;
3. find a solution of the problem specified in (19), i.e. find a minimum of the sub-criterion J_{rob} subject to

the conditions such that $J_u = 0$ on the given region of α_i from the previous point;

4. record the resultant parameters α_i and verify if they fulfil the given requirements.

If the algorithm for solution of the problem fails then there may not be such combination of α_i (under the given conditions) to respect the limits of the control input $u(t)$. Then the designer has several basic possibilities: try to increase the number of optimized parameters α_i, use different control structures (e.g. the 2DoF control set-up with a pre-filter of the reference signal), or has finally no other way than enlarging the prescribed limits on the manipulated variable $u(t)$.
The algorithm for the optimization uses a standard MATLAB function for nonlinear constrained minimization (nonlinear programming) *fmincon*. It is a gradient-based method — the trust-region-reflective algorithm based on the interior-reflective Newton method, described in detail in, e.g. (Coleman and Li 1996). For this algorithm it is necessary to choose also a starting point (initial estimate) of the optimization. With no prior information, this is usually the middle of the interval from the point 2 of the optimization procedure described above.

Next section illustrates the suggested methodology using a simulation study — robust control system design with a saturated input signal applied to a given representative simulation model.

ILLUSTRATIVE EXAMPLE

Consider a system described by the following transfer function in the continuous-time domain:

$$G(s) = \frac{b(s)}{a(s)} = \frac{18400}{s^2 - 2.418s - 3998}. \quad (25)$$

This transfer function approximates behaviour of the magnetic levitation system CE 152, the product of TQ Education and Training Ltd designed for studying system dynamics and experimenting with control algorithms. The system consists of a coil levitating a steel ball in the magnetic field with the position sensed by an inductive linear sensor connected to an A/D converter. The coil is driven by a power amplifier connected to a D/A converter. A basic control task is to control the position of the ball freely levitating in the magnetic field of the coil. From the control theory point of view, the magnetic levitation system is a nonlinear unstable system with one input and one output and relatively fast dynamics. Detailed description of the apparatus can be found in e.g. (Gazdoš et al. 2009). The model (25) represents a linear approximation of the system levitating the ball in the middle of the space. Following the polynomial approach methodology described in the previous sections a suitable controller for this system is designed in the following general form:

$$C(s) = \frac{q(s)}{p(s)} = \frac{q(s)}{s\tilde{p}(s)} = \frac{q_2 s^2 + q_1 s + q_0}{s(\tilde{p}_1 s + \tilde{p}_0)}, \quad (26)$$

hence, it is a real (filtered) PID controller. Unknown coefficients of the controller are obtained by the solution of the polynomial equiation (13) for a given stable characteristic polynomial $d(s)$. This polynomial, in the general form (15),(18), must be according to (14) of the 4^{th} degree and it is suggested in the following simple form:

$$d(s) = (s + \alpha)^4, \quad (27)$$

for some real parameter $\alpha > 0$ subject to optimization. Then the closed-loop has 4 identical poles located at $p_{1,2,3,4} = -\alpha$ which will guarantee both stable and aperiodic behaviour. Although this simple choice limits possibilities of achievable control quality it enables simple tuning of the loop and it is used here to illustrate simply the methodology introduced in this paper. Now the one free tuning parameter α is optimized numerically according to the procedure suggested in the previous section to respect both robustness of the loop and limitations on the control input signal $u(t)$ which are in this case defined as:

$$u(t) \in \langle -1; 1 \rangle \ \ \forall t. \quad (28)$$

In this simple case of only one tuning parameter it is possible to obtain easily the course of the sub-criterion J_u (23) assessing the control input signal with respect to the given limitations (28), depending on the parameter α. It is recorded in the following picture, Fig. 3.

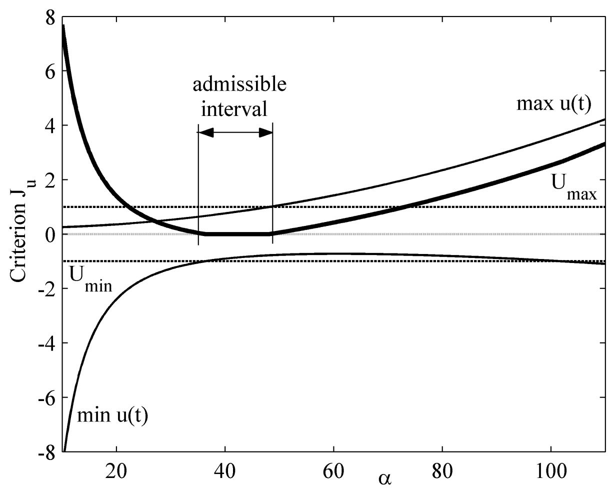

Figure 3: Sub-Criterion J_u with α

From the plot, it is obvious that there exists an interval where $J_u = 0$, i.e. there are values of α for which the given control input limitations are respected. Further inspection of the results shows that this interval is for $\alpha \in \langle 36.4; 48.1 \rangle$ approximately. If we choose several values of the parameter from and outside of the admissible interval to test the results, it is possible to obtain the recorded simulation of the control input $u(t)$ as presented in the next figure, Fig. 4.

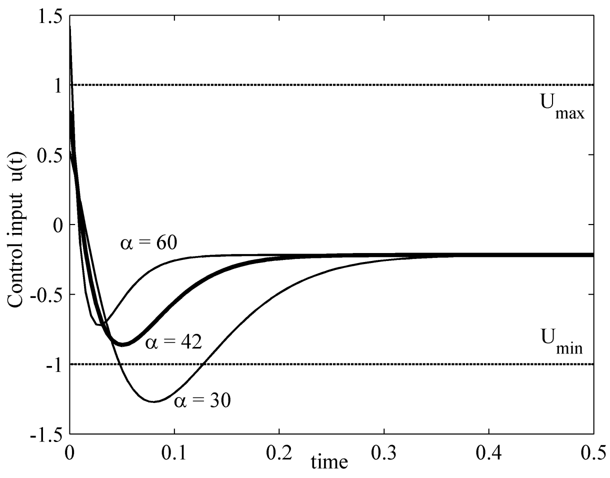

Figure 4: Control Input $u(t)$ with α

From the graph, it is clear that for α from the suggested interval ($\alpha = 42$) the control input is in the prescribed limits while for $\alpha = 30$ and $\alpha = 60$ (outside the interval) it is out of the required range $\langle -1; 1 \rangle$.
Next figure, Fig. 5, shows the course of the sub-criterion J_{rob} (21) assessing the loop robustness on the admissible interval of the parameter α.

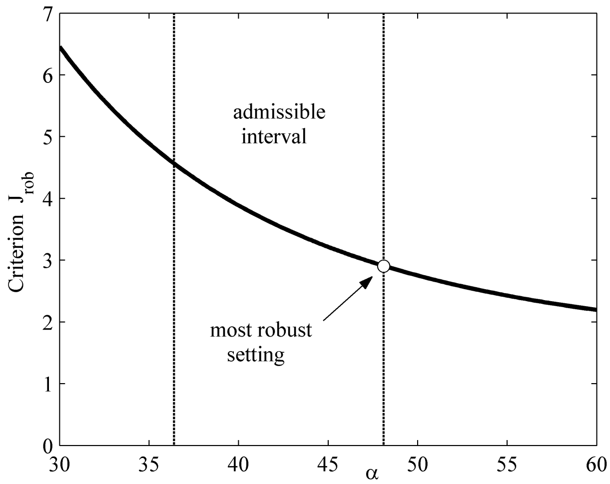

Figure 5: Sub-Criterion J_{rob} with α

The figure reveals that the most robust setting respecting the given control input limits is on the right end of the admissible interval. Therefore it is for $\alpha = 48.1$ approximately. For safety reasons the *optimal* value of this parameter is suggested a bit smaller, for $\alpha = 48$. This value respects the control input limitations and leads to the most robust setting of the designed control system, under given conditions (conrol set-up, number of optimized closed-loop poles, given limits on the control input signal). Simulated responses of the controlled variable and control input signal are presented in the next graphs, Fig. 6 and Fig. 7. In these experiments step-disturbances of 10% amplitude were injected at times $t = 1$ (acting on the control input $u(t)$) and $t = 3$ (acting on the controlled variable $y(t)$) to test robustness of the designed loop. Two settings of the optimized parameter are recorded to asses the robustness: $\alpha = 48$ (suggested optimal setting - most robust) and $\alpha = 37$ (less robust setting, see Fig. 5).

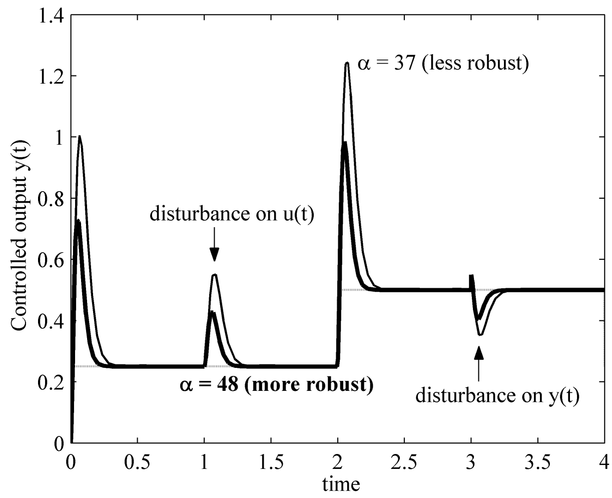

Figure 6: Controlled Output Response

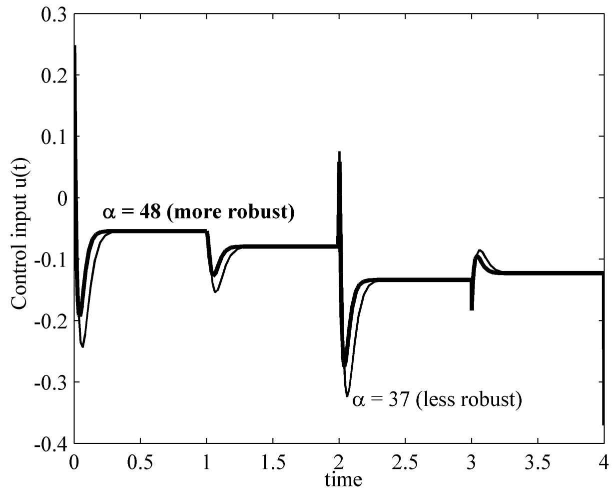

Figure 7: Control Input Response

The graphs show that the controlled variable tracks its desired value stably without a steady-state control error. Although there are relatively high overshoots the response is aperiodic, both disturbances are compensated and the control input is in the prescribed limit $\langle -1; 1 \rangle$. When comparing the robustness of the designed loop for the suggested *optimal* setting ($\alpha = 48$) to another one, not so robust ($\alpha = 37$) it is obvious that the recommended *optimal* setting provides better results - with smaller overshoots, faster settling-time, better compensation of both disturbances and less demands on the manipulated variable.
Concerning the higher amplitude of overshoots in the presented control responses - it is attributable to the fact that i) the system is unstable (such systems are

more difficult to control), ii) most robust setting of the loop respecting limits on the control input is desired (this results in responses of worse control quality with bigger overshoots and longer settling-times), iii) the classical feedback control set-up was employed (another control configurations with, e.g. a filter of the reference signal can lead to comparably smaller overshoots). Therefore for future work is recommended to use e.g. the 2DoF (2 degrees-of-freedom) control set-up with one feedback and one feedforward controller filtering the reference signal. This will decrease the overshoots and enables to achieve better control quality while respecting the limits on the manipulated variable. It is also expected that higher number of optimized parameters α_i (consequently, also closed-loop poles p_i) enables to achieve better results for both control quality and robustness.

CONCLUSIONS

This paper investigates and presents one possible way how to design a robust control system in the presence of constraints on the control input signal. For this purpose the systematic polynomial approach is fruitfully exploited resulting in a solution of polynomial equations. Robustness and input constraints are solved numerically using standard MATLAB functions for nonlinear constrained optimization and new suggested criteria. Optimal poles of the designed loop are the results of this optimization procedure which is based on the usage of simulation means. Presented preliminary results show the potential of the suggested methodology even though the illustrated example is simple with only one optimized parameter. Better results are expected in case of optimizing more parameters and with usage of different control configuration which is the course of future works. An extension to cover not only control input amplitude limitations but also constraints on the speed of changes of this signal is relatively simple. Usage of the suggested procedure for MIMO (Multi-Input Multi-Output) systems is also open.

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