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NUMERICAL ISSUES IN DESIGNING PI CONTROLLER FOR IPDT PLANT

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Abstract: This paper deals with numerical issues arising in robust design of PI controller for the Integral Plus Dead Time plant (IPDT) under robust tuning based on regions of parameters corresponding to non-overshooting, monotonic, or monotonic & one-pulse control achieved by computer simulation.

Keywords: Pole assignment control, Proportional control, Dead time.

1 INTRODUCTION

Control design for IPDT plant

$$F(s) = \frac{K_s}{s} e^{-T_d s} \tag{1}$$

was already treated by different approaches in many papers, see e.g. [2], [6], [9] to mention just few of them. However, majority of available methods offers just transient responses with overshooting that are not acceptable in many control problems occurring e.g. in mechatronics. For such performance definition, tuning of the PI controller [7], [8] based on triple real dominant pole and on the setpoint weighting with the control algorithm

$$U(s) = K_R[bW(s) - Y(s)] + \frac{K_R}{sT_i}[W(s) - Y(s)] \tag{2}$$

that can be shown to be equivalent to using prefilter

$$F_p(s) = \frac{bT_i s + 1}{T_i s + 1} \tag{3}$$

with T_i being the integral time constant gives excellent results. It is based on solving closed loop characteristic equation for a triple pole s_0 of characteristic polynomial $A(s)$ that requires fulfilling

$$A(s_0) = 0 \text{ ; } \dot{A}(s_0) = 0 \text{ ; } \ddot{A}(s_0) = 0 \tag{4}$$

$$\begin{aligned} A(s) &= s^2 T_i e^{T_d s} + K_R K_s (T_i s + 1) \\ \dot{A}(s) &= 2sT_i e^{T_d s} + s^2 T_d T_i e^{T_d s} + K_R K_s T_i \\ \ddot{A}(s) &= 2T_i e^{T_d s} + 4sT_d T_i e^{T_d s} + s^2 T_d^2 T_i e^{T_d s} \end{aligned} \tag{5}$$

Solution of the last equation in (4) yields root

$$s_0 = -\left(2 - \sqrt{2}\right)/T_d \tag{6}$$

for which from the first two equations in (4) one gets stable tuning with parameters

$$\begin{aligned} K_R &= 2\left(\sqrt{2} - 1\right)e^{\sqrt{2}-2} / (K_s T_d) \approx 0.461/(K_s T_d) \\ T_i &= \left(2\sqrt{2} + 3\right)T_d \approx 5.828 T_d \end{aligned} \tag{7}$$

For the root $s_0 = -\left(2 + \sqrt{2}\right)/T_d$ the resulting values $K_R = -0.1588/(K_s T_d); T_i = 0.17157 T_d$ with negative loop gain do not guarantee the closed loop stability.

Zero of the closed loop transfer function

$$F_{wy}(s) = \frac{K_s K_R (T_i s + 1)}{s^2 e^{T_d s} + K_R K_s (T_i s + 1)} \tag{8}$$

can be cancelled by the prefilter denominator in (3) that removes overshooting typical for one degree of freedom PI controllers. Simultaneously, one of the triple real poles (6) will be cancelled by the prefilter numerator (3) that further accelerates the transient responses. It gives the setpoint weighting coefficient

$$b = \frac{1/|s_0|}{T_i} = \frac{2 - \sqrt{2}}{2} \approx 0.293 \tag{9}$$

So, fast and smooth responses are achieved both in regulatory as well as tracking control tasks that are much better than e.g. those reported in [2], [6], [9].

2 NEEDS FOR ROBUST CONTROLLER DESIGN

The most serious and principal disadvantage of the proposed design is that it guarantees excellent properties just in the nominal case representing a single point in the space of controller parameters. But, real plants have just exceptionally properties that can be characterized by fixed completely known point. E.g. in level control the dead time behavior that is caused by long pipelines between the pump and the container varies, whereby the resulting delay is not only proportional to its length but it is also influenced by the control signal. For low flow rates the resulting delay is larger than for the relatively large ones.

Similarly, in transporting material by belt conveyers the delay is proportional to their length and to the control signal (amount of material transported), but in the opposite way as above. For low control signal values the belt velocity is higher than for fully loaded belt, what leads to reverse delay dependence on control values.

Both above examples explain, why the traditional methods of controller tuning based on nominal transfer functions are just rarely used in practice. In both above cases it is mostly required to design controller in such a way that will guarantee specified performance for interval plants having parameters given in the form

$$K_s \in \langle K_{s\min}, K_{s\max} \rangle;\ K_{s\max} \geq K_{s\min} > 0 \qquad (10)$$

$$T_d \in \langle T_{d\min}, T_{d\max} \rangle;\ T_{d\max} \geq T_{d\min} > 0 \qquad (11)$$

The aim of this paper is to expand the optimal tuning (7-9) giving interesting dynamical properties, but corresponding just to a single nominal point to plants with interval uncertainty (10-11).

3 CLOSED LOOP PERFORMANCE

From the technology point of view, the expected dynamics is frequently specified by requiring non-overshooting plant output (Non-Overshooting control, NO), monotonic plant output control (Monotonic Output control, MO), or monotonic plant output achieved under one smooth pulse of control (plant input) having after a step change of setpoint signal just one extreme point at the controller output (plant input) and no further local extremes of control signal showing tendency to oscillations. Such a combination of monotonic output with smooth control signal at the plant input will here be briefly denoted as One-Pulse control (1P).

The output transients represented by the setpoint step response values $y(t)$, $y(0)=0$ measured over interval t_{sim} (that should be larger than maximal possible settling time) are classified according to

$$0 \leq [w - y(t)]sign(w), \forall t \in (0, t_{sim}) \qquad (12)$$

as NO. In case of fulfilling (10) and relations

$$0 \leq [y(t_2) - y(t_1)]sign(w);\quad 0 \leq t_1 < t_2 \leq t_{sim} \qquad (13)$$

it is denoted as MO and in case of fulfilling (13) and simultaneously also (14)

$$\begin{aligned} & sign(\dot{u}(t_1))sign(u(t_m)) \geq 0, \forall t_1 \in \langle 0, t_m \rangle \cup \\ & \cup\, sign(\dot{u}(t_2))sign(u(t_m)) \leq 0, \forall t_2 \in \langle t_m, t_{sim} \rangle \end{aligned} \qquad (14)$$

it will be denoted as 1P. For all that $u(t_m)$; $t_m \geq 0$ corresponds to the maximal control signal amplitude during transient.

In practice, but also in case of computer simulation, it has sense to weaken the above conditions by introducing some tolerable overshooting defined by

$$\varepsilon > 0 \qquad (15)$$

ε being a small positive number and in this way to find controller parameters corresponding to

$$-\varepsilon \leq [w - y]sign(w - y_0),\ \forall t_1 \in (0, t_{sim}) \qquad (16)$$

or to

$$\begin{aligned} & -\varepsilon \leq [y(t_2) - y(t_1)]sign(w - y_0) \\ & \forall 0 \leq t_1 < t_2 \leq t_{sim} \end{aligned} \qquad (17)$$

E.g. by choosing $\varepsilon = 0.01$ and considering setpoint step responses with the maximal step $w = 1$ it means that overshooting up to 1% of the setpoint value w will be tolerated and included under denotation as the NO. This approach will only be used for $\varepsilon \approx 0.01$, because step responses with larger overshooting may be achieved also in other ways (e.g. without using setpoint weighting) and so the design should consider also other alternatives. But it is no real limitation of this procedure, since usual measurement precision in practice is in the range 1-5%.

All above mentioned properties are, however, just rarely in focus of contemporary control research. Latest review on PID control [5] is e.g. mentioning just NO for control loops without dead time and without distinguishing two other important specifications MO and 1P. This is consequence of the development of last decades, when methods applied were dominated by the mathematical convenience and concentrated mostly on traditional performance indices like gain margin, phase margin, maximum sensitivity, H_∞ norm, ISE, etc. Because of lacking analytical tools, the controller will be robustly tuned by using numerically derived areas of parameters corresponding to NO, MO, or 1P.

By its specification, 1P is subset of MO. This is subset of NO that represents subset of stable control.

Because the settling time used for characterizing speed of output transient strongly depends on the defined measurement precision (given e.g. by ε), for quantitative evaluation of responses more frequently IAE (Integral of Absolute Error) or the ISE (Integral of Squared Error) performance indices are used that do not depend on ε so strongly

$$IAE = \int_0^\infty |e(t)| dt \qquad ISE = \int_0^\infty e(t)^2 \, dt \tag{18}$$

To evaluate control effort required to achieve the required output behavior, Total Variance (TV) criterion is used [6]. This was defined as

$$TV = \int_0^\infty \left| \frac{du}{dt} \right| dt \approx \sum_i |u_{i+1} - u_i| \tag{19}$$

All these values are computed by simulation after discretization with small sampling period.

Optimal values corresponding to the PI controller with the nominal tuning for the triple real pole (7-9) and unit reference step $w = 1$, or unit disturbance step $v = 1$ are as follows

$$\begin{aligned} &IAE_w = 4.1204\,; ISE_w = 2.8482\,; TV_w = 0.4343 \\ &IEA_v = 12.6421\,; ISE_v = 17.657\,; TV_v = 1.6925 \end{aligned} \tag{20}$$

4 ROBUST PI CONTROLLER DESIGN

4.1 Determining prefilter coefficient

After introducing loop parameter

$$\Omega_c = K_R K_s T_d \tag{21}$$

that is specifying the P action gain, parameter

$$\Omega_f = T_d / T_i \tag{22}$$

specifying scaled integral time constant and

$$\sigma = sT_d \;\; ; \;\; T_d > 0 \tag{23}$$

specifying new independent (complex) variable, the closed loop characteristic polynomial and its derivatives can be written as

$$\begin{aligned} A(\sigma) &= \sigma^2 e^\sigma + \Omega_c \sigma + \Omega_c \Omega_f \\ \dot{A}(\sigma) &= \left(\sigma^2 + 2\sigma\right) e^\sigma + \Omega_c \\ \ddot{A}(\sigma) &= \left(\sigma^2 + 4\sigma + 2\right) e^\sigma \end{aligned} \tag{24}$$

The question is how the controller design developed originally for guaranteeing triple real dominant pole can be extended to more general situation. Numerically, the first critical point in such a new approach will be given by looking for real root σ_0 of the transcendent characteristic equation

$$A(\sigma_0) = 0 \tag{25}$$

It is possible to show that for each $\Omega_c, \Omega_f > 0$ there exist at least one real root of (25). But, for some values there exist 3 such roots and the task is to choose that one corresponding to minimal IAE, or ISE values. This root finally determines the setpoint weighting coefficient

$$b = -\frac{1}{s_0 T_i} = -\frac{T_d / T_i}{s_0 T_d} = \frac{\Omega_f}{\sigma_0} \tag{26}$$

and together with coefficients Ω_c, Ω_f (21-23) also the complete control algorithm (2).

4.2 Uncertainty line segments and trapezoids

After evaluating (21) and (22) for interval values (10-11), it is obvious that in general, we should find controller solution for

$$\begin{aligned} &0 < \Omega_{c\min} \le \Omega_c \le \Omega_{c\max}\,; \\ &0 < \Omega_{f\min} \le \Omega_f \le \Omega_{f\max} \end{aligned} \tag{27}$$

Geometrically, it is, however, not rectangle, but trapezoid, or in a limit case a line segment. When dealing with interval values just for the plant gain K_s, whereas the dead time value is known exactly, in the parameter plane (Ω_c, Ω_f) such situation corresponds to a horizontally oriented uncertainty line segment with vertices

$$\begin{aligned} &A = (\Omega_{c\min}, \Omega_f);\; B = (\Omega_{c\max}, \Omega_f) \\ &\Omega_{c\min} = K_R K_{s\min} T_d\,; \Omega_{c\max} = K_R K_{s\max} T_d \end{aligned} \tag{28a}$$

On the other side, having interval values just for the plant dead time T_d, whereas the plant gain value K_s is known exactly, it corresponds to a skew uncertainty line segment with vertices

$$\begin{aligned} &A = (\Omega_{c\min}, \Omega_{f\min});\; B = (\Omega_{c\max}, \Omega_{f\max}) \\ &\Omega_{c\min} = K_R K_s T_{d\min}\,; \Omega_{c\max} = K_R K_s T_{d\max} \\ &\Omega_{f\min} = T_{d\min} / T_i\,; \Omega_{f\max} = T_{d\max} / T_i \end{aligned} \tag{28b}$$

For both parameters given in the interval form (27) in the parameter plane (Ω_c, Ω_f) one gets *trapezoid uncertainty set (US)* with vertices

$$
\begin{aligned}
A &= \left(K_R K_{s\min} T_{d\min}, T_{d\min}/T_i\right);\\
B &= \left(K_R K_{s\min} T_{d\max}, T_{d\max}/T_i\right);\\
C &= \left(K_R K_{s\max} T_{d\min}, T_{d\min}/T_i\right);\\
D &= \left(K_R K_{s\max} T_{d\max}, T_{d\max}/T_i\right)
\end{aligned}
\tag{28c}
$$

So, using experimental approach based on identification of NO, MO, or 1P areas, it will be necessary:

1. to choose grid of parameters Ω_c, Ω_f over US (28),
2. for each point of this grid to derive setpoint weighting coefficient b given by real negative pole $\sigma_0 = s_0 T_d$ (9), (23) equation (25),
3. to run simulations under derived PI control,
4. to check fulfillment of conditions (12-14), or of the weakened conditions (16-17) and
5. to evaluate performance criteria (18-19).

Doing so over whole grid of parameters Ω_c, Ω_f, it is possible to get information about corresponding control properties that can later be used in robust tuning of the controller. This will be based on information about possible plant gains (10) and possible dead time values (11).

After choosing some controller tuning K_R, T_i, one gets uncertainty set (US) (28). It is expected that the robust design with given performance specification can be fulfilled just if the whole US (28) can be located within the specified parameter area. Furthermore, the weighting coefficient b will be defined by its minimal value corresponding to given position of US. Due to this, for all other parameters transient responses will be slower than for nominal tuning, but without overshooting.

5 NUMERICAL DETERMINATION OF SETPOINT WEIGHTING

For solving transcendent characteristic equation (23) according to σ different algorithms may be used. Fundamental problems are related to existence and uniqueness of the solution. Since there are available just iterative solutions, practical problems are associated with their convergence and speed, with achieved precision and dependence on initial conditions. The only exception enabling explicit evaluation corresponds to the triple real pole (6) written as

$$\sigma_{00} = \sqrt{2} - 2 \tag{29}$$

According to (7) and (19-20) it is corresponding to point $\Omega_{00} = (\Omega_{c0}, \Omega_{f0})$

$$
\begin{aligned}
\Omega_{c0} &= 2\left(\sqrt{2} - 1\right)e^{\sqrt{2}-2}\\
\Omega_{f0} &= 1/\left(2\sqrt{2} + 3\right) = 3 - 2\sqrt{2}
\end{aligned}
\tag{30}
$$

5.1 *Existence and uniqueness of real solution of (23)*

Lemma 1: The function $A: \mathbf{R} \to \mathbf{R}$, $A(\sigma) = \sigma^2 e^{\sigma} + \sigma\Omega_c + \Omega_c\Omega_f$ is smooth function with derivatives

$$\dot{A}: \mathbf{R} \to \mathbf{R}, \dot{A}(\sigma) = \left(\sigma^2 + 2\sigma\right)e^{\sigma} + \Omega_c$$

and

$$\ddot{A}: \mathbf{R} \to \mathbf{R}, \ddot{A}(\sigma) = \left(\sigma^2 + 4\sigma + 2\right)e^{\sigma}$$

Lemma 2: $\lim_{\sigma\to-\infty} A(\sigma) = -\infty$, $\lim_{\sigma\to\infty} A(\sigma) = \infty$, $\lim_{\sigma\to-\infty} \dot{A}(\sigma) = \Omega_c$, $\lim_{\sigma\to\infty} \dot{A}(\sigma) = \infty$.

Lemma 3: The derivative $\dot{A}(\sigma)$ is increasing function on intervals $\left(-\infty, -\sqrt{2} - 2\right) \cup \left(\sqrt{2} - 2, \infty\right)$ and decreasing function on interval $\left(-\sqrt{2} - 2, \sqrt{2} - 2\right)$ with relative maximum value at the point $\sigma = -\sqrt{2} - 2$

$$\dot{A}\left(-\sqrt{2} - 2\right) = 2\left(1 + \sqrt{2}\right)e^{-\sqrt{2}-2} + \Omega_c > \Omega_c > 0$$

and relative minimum value at the point $\sigma = \sqrt{2} - 2$

$$\dot{A}\left(\sqrt{2} - 2\right) = 2\left(1 - \sqrt{2}\right)e^{\sqrt{2}-2} + \Omega_c < \Omega_c$$

Lemma 4: If $\dot{A}\left(\sqrt{2} - 2\right) \ge 0$, then $\dot{A}(\sigma) > 0$ for all $\sigma \in \mathbf{R}$ (may be with exception of $\sigma = \sqrt{2} - 2$), i.e. function $A(\sigma)$ has unique simple negative zero point.

Lemma 5: Closed loop characteristic polynomial of delay free plant

$$A(s) = s^2 + \Omega_c s + \Omega_c\Omega_f;\ \Omega_c, \Omega_f > 0 \tag{31}$$

has real roots

$$s_{0_{1,2}} = \left(-\Omega_c \pm \sqrt{\Omega_c^2 - 4\Omega_c\Omega_f}\right)/2;\ \Omega_c \ge 4\Omega_f \tag{32}$$

Theorem 1: For any $\Omega_c > 0$ and $\Omega_f > 0$, there exist at least one real negative zero $\sigma_0 < 0$ of (23).

Proof:

Existence of the solution follows from Lemma 2.

For $\dot{A}\left(\sqrt{2} - 2\right) = 2\left(1 - \sqrt{2}\right)e^{\sqrt{2}-2} + \Omega_c \ge 0$ the uniqueness of the solution results from Lemma 4. For $\dot{A}\left(\sqrt{2} - 2\right) < 0$ there might exist also several real solutions of (23).

It is an interesting conclusion of Lemma 5 and Theorem 1 that conditions on existence of real root of (23) are more relaxed in the case of dead time system than for the delay free system (32).

5.2 *Convergence of solutions*

We know that for $\Omega_c > 0$ and $\Omega_f > 0$ (23) has at least one real solution $\sigma_0 < 0$, the question, however, is, what to do in situations when there exists several real solutions.

E.g. for $\Omega_c = 0.17$, $\Omega_f = 0.0438$ one gets 3 different real negative roots of (23) shown in Tab. 1 together with the corresponding performance indices.

Tab. 1 Roots of (23) used in (24) and corresponding performance indices of resulting control

Root s0	IAE	ISE	TV
-2.8267	3.5359	0.3356	0.0658
-0.1254	4.4333	0.7482	0.1324
-0.0725	5.9271	1.5535	0.2202

It is evident that the minimal values of IAE/ISE correspond to root s_0 that is maximally shifted to the left on real axis. This must then be respected by choosing initial condition for computation, e.g. by means of Matlab offering for solving nonlinear equations of form $f(x) = 0$ (that includes also (23)) function *fsolve*.

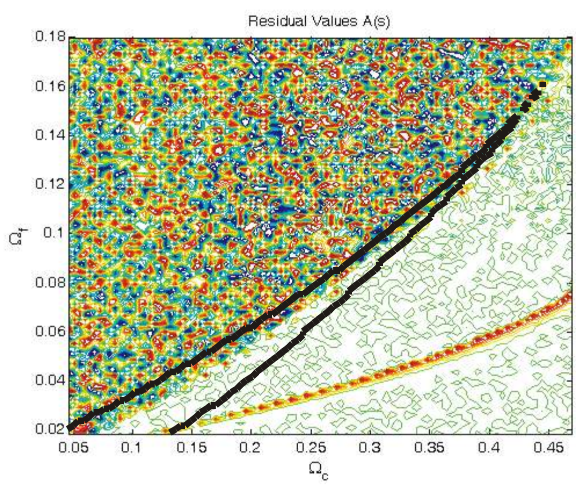

Fig. 1 Contours of residual polynomial values corresponding to levels defined by vector v=[-3e-17 -2e-17 -1e-17 0 1e-17 2e-17 3e-17], 1P area that is coinciding with MO and NO areas (full)

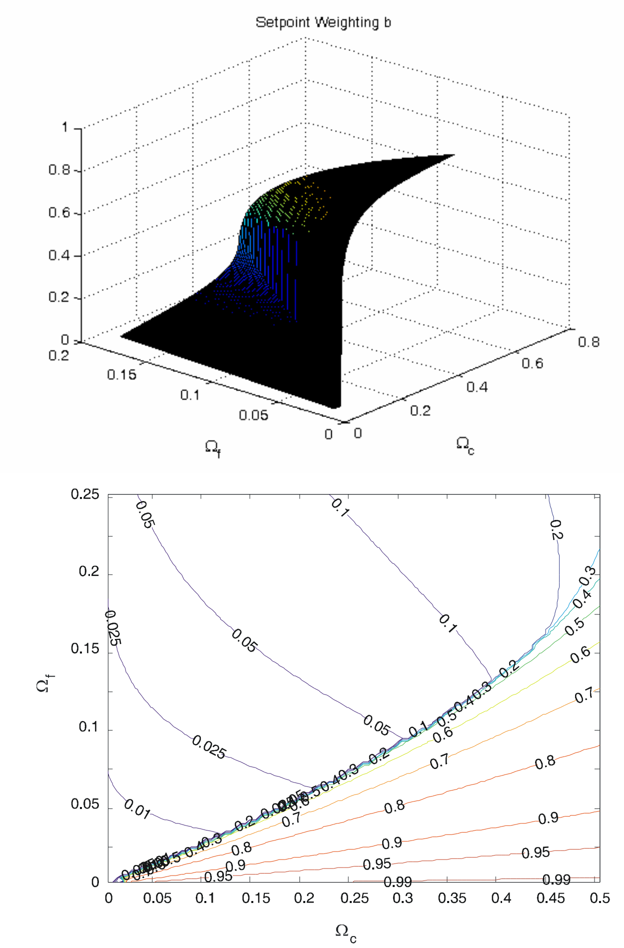

Fig. 2 Setpoint weighting values *b* in 3D (above) and in 2D (below)

In function it is possible to set by using *options* = *optimset* options like 'TolFun' – termination tolerance on $f(x)$ values, or 'TolX' - termination tolerance on x values, or to display algorithm used by setting output item 'algorithm'.

It is also possible to define initial value for the solution: in order to eliminated dependence on choice of initial values for computation.

From Fig. 1 it is obvious that the residual polynomial values are related with the character of the transient responses. The optimal point (29-30) is situated just at the corner of the 1P area (see also Fig. 3), so that it is not possible to include it in practically usable uncertainty box (28) with variable plant gain K_s.

Usable results may be achieved just for variable dead time and fixed plant gain K_s when for appropriately chosen integral time constant T_i US given as skew line segment (28b) may be more easily located into 1P area. Since this has not convex shape, in general, such line segment with vertices lying in 1P does not necessarily belong to 1P also by its internal points, so one has to be careful in placing US close to the optimal point (30).

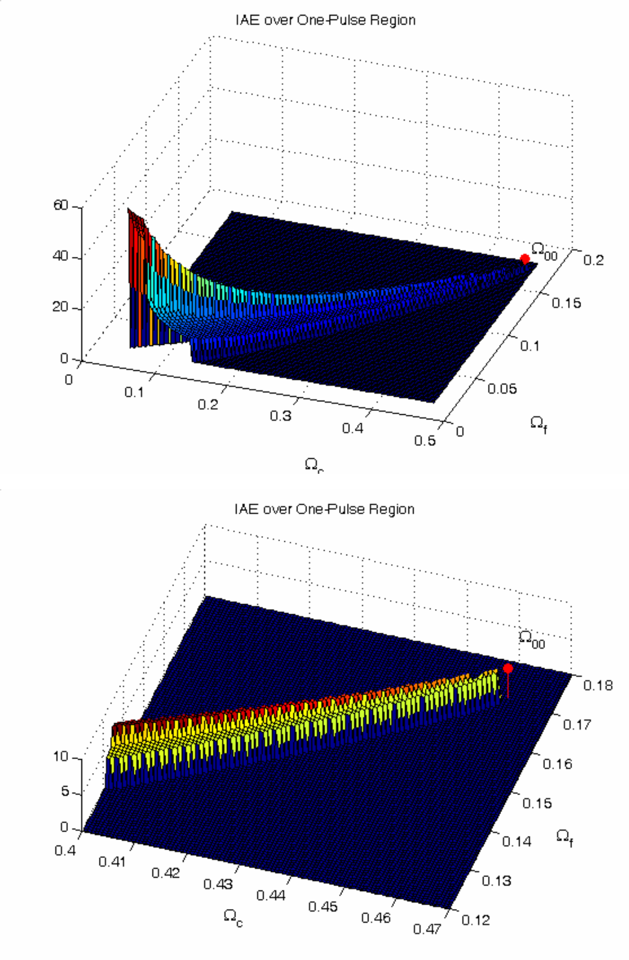

Fig. 3 Optimal point Ω_{00} corresponding to triple real pole (30); 1P area and IAE values defined over it (above) and detailed view (below); increasing level of red corresponds to increasing IAE values

4.3 *Numerical issues in determining parameter areas*

When determining for a setpoint step NO, MO, or 1P areas according to (10-13), for $\varepsilon = 0$ all melt together into a relatively narrow strip (Fig. 1, 3, 4). Differences occur just after introducing certain tolerance $\varepsilon > 0$ (13) into areas identification by inequalities (14-15). Although already for $\varepsilon = 10^{-5}$ areas corresponding to weaken MO and 1P are reasonably larger than for strictly MO and 1P, further they vary with increasing ε just slightly. NO area, however, increases reasonably fast. It means that the requirement on strictly MO and 1P puts tight constraints on admissible plant uncertainty – much stronger than in using the disturbance observe based PI_1 controller [4].

Broader plant uncertainty can be allowed just in the case when tolerating some small overshooting (Fig.4). Examples show uncertainty box (28) corresponding to values

$$\begin{aligned}
&T_{d\,\min} = 1;\ T_{d\,\max} = 2;\ K_{s\,\min} = 1.33;\ K_{s\,\max} = 2\\
&K_R = 0.1048;\ T_i = 23.3137;\\
&\Omega_{cA} = 0.1397;\ \Omega_{cB} = 0.2795;\\
&\Omega_{cC} = 0.2096;\ \Omega_{cD} = 0.4192;\\
&\Omega_{fA} = 0.0429;\ \Omega_{fB} = 0.0858;\\
&\Omega_{fC} = 0.0429;\ \Omega_{fD} = 0.0858
\end{aligned} \tag{33}$$

with dead time changes $T_{d\,\max} / T_{d\,\min} = 2$ and $K_{s\,\max} / K_{s\,\min} = 1.5$.

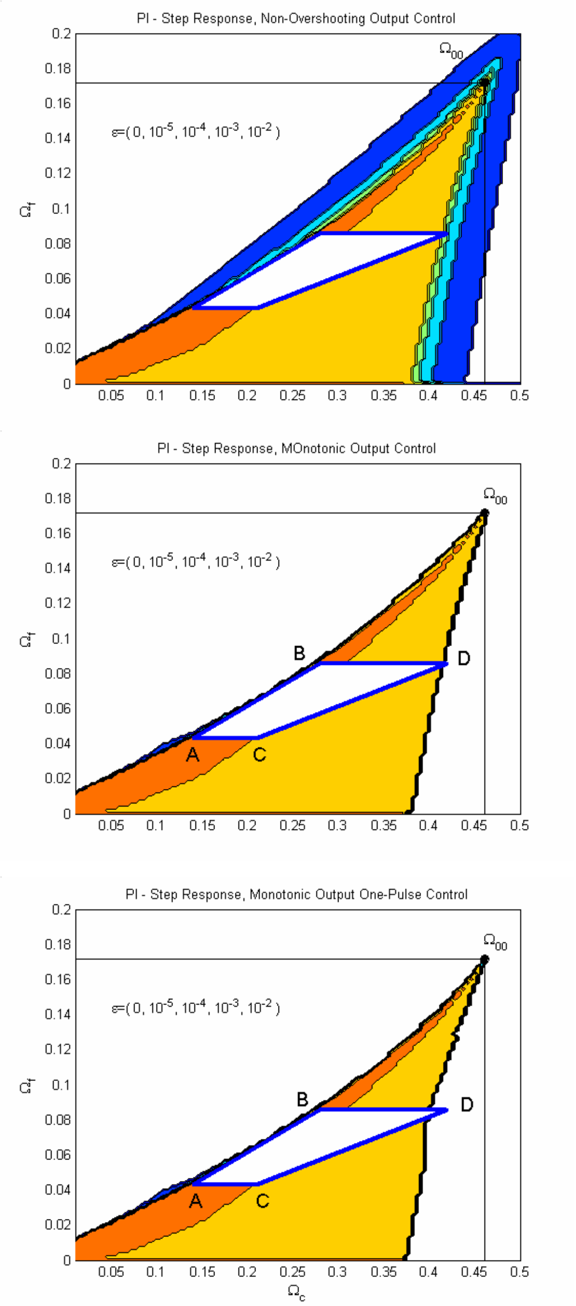

Fig. 4 Performance portrait with NO, MO and 1P areas corresponding to different values of ε and identified using (14-15) for grid of 100x100 points; Ω_{00} - optimal tuning (30), example of locating uncertainty box (28) into NO and MO areas corresponding to $\varepsilon = 10^{-5}$

It is to see if Fig. 4 that US satisfying for $\varepsilon = 10^{-5}$ NO and MO requirements does not already fulfill requirements on 1P. Transient responses in Fig. 5 correspond to minimal value of parameter b identified over uncertainty set as

$$b_{\min} = 0.0065 \qquad (34)$$

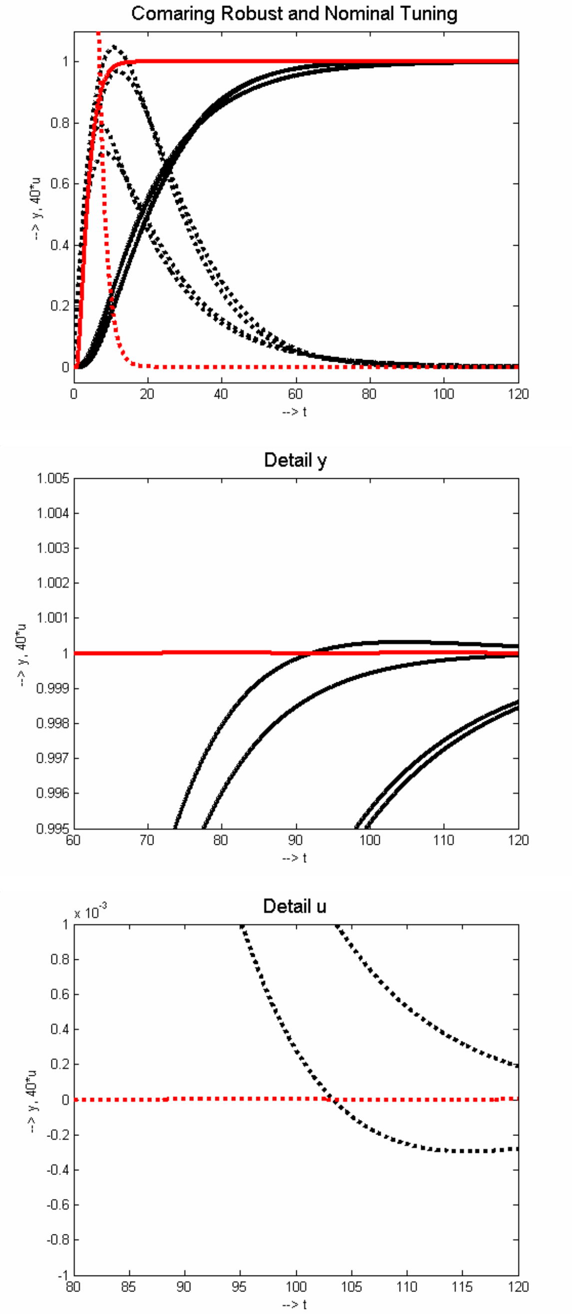

Fig. 5 Setpoint step responses corresponding to vertices of US from Fig. 4 (black) with $b = b_{\min}$ (34) and optimal transients corresponding to (30) (red); to see differences in robust tuning, scaling for u was enlarged times 40, but then the one pulse of optimal control signal is not shown fully)

Due to use of minimal value of prefilter coefficient over US (34) that contributes to slowing down transients and to decreasing overshooting, achieved overshooting values are smaller than supposed in the design. This conservatism could be partially reduced by a two-step procedure using corrective identification of performance portrait corresponding not to variable, but to fixed value of prefilter coefficient (34), but this is a generic disadvantage of using PI controller with setpoint weighting instead of DOB based PI controller [4].

It is yet to remind that identified areas corresponding to the setpoint step and to the disturbance step will be, in general, different. Tuning fulfilling requirements put on both setpoint as well as disturbance response should then be found by intersection of corresponding areas.

6 CONCLUSIONS

Analysis of new robust PI controller tuning approach based on experimental identification of plant performance portrait with areas corresponding to loop parameters guaranteeing non-overshooting, monotonic and one-pulse control showed that the two-degree-of-freedom PI controller design [7], [8] may also be extended to interval plants by respecting specified qualitative requirements.

Whereas it seems that we have all numerical problems of such design, for practical application it still would be necessary to analyze also the problem of control signal constraints.

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