A web based support for the performance portrait based controller design

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Abstract: The Performance Portrait Method enables to visualize influence of chosen control parameters on the loop performance of the selected dynamical system with given interval parameter uncertainties. The knowledge of this behavior can help to analyze and tune control algorithm and to fulfill expected requirements as far as robustness and control quality. The presented paper introduces a new web tool that in an interactive way enables to design filtered 2DOF PI controller for the integral plus dead time system models on the base of the performance portrait method. For a performance portrait calculated once in the 3-5D parameter space it enables to find optimal robust controller tuning. For given plant parameter uncertainties it yields the fastest possible transient responses satisfying with chosen tolerances the shape related constraints at the plant input and output. A web application developed to illustrate the problem offers much richer visual information than it is possible to offer by standard publications, interactivity and dynamical effects. The backend of the application is driven by Matlab software. This environment is used both for calculation of the performance portrait and for simulation of transients of the considered feedback control structure.

Keywords: PI control, performance portrait, web tool.

1. INTRODUCTION

The performance portrait method (PPM) has been developed as an extension to the parameter space method (Ackermann, 2002). Primarily it is appropriate for system, where analytical solutions either do not exist, or they are too complex. The method has been proposed in (Huba et al., 2009; Huba and Gerke, 2009) and from that time it has been used in numerous case studies, which include time delayed systems (Huba, 2010a,b, 2011c; Sóos and Huba, 2014; Huba, 2014a; Huba et al., 2016b), robustness issues (Huba, 2011a, 2012, 2013b; Sóos and Huba, 2014; Huba, 2015c), constrained control (Huba, 2011b,d), or disturbance-observer structures (Huba, 2013c, 2014b, 2015a).

1.1 Why do we need such a method?

At the beginning, the method has been developed with the aim to analyze robust and nominal tuning of several disturbance-observer based structures (Huba, 2013c,a), for which the stability oriented parameter space method and other traditional approaches based on the multiple real dominant pole method, M_s-constrained optimization, dynamics shaping, etc. did not yield satisfactory results. The multiple real dominant pole (MRDP) method leads for some of such structures (Huba, 2013c) to complex gains and time constants, which may indeed be approximated by real figures, but such a tuning seems to be too speculative (Huba, 2009). With the M_s-constrained optimization we were not able to achieve required shapes of transient responses for a broader range of the plant parameters. All this research has been carried out within the frame of developing a modular approach to constrained and robust design of single-input-single-output systems, which started several decades ago (Huba and Šimunek, 2007) and included numerous traditional and alternative control structures. Thus, its application area has rapidly expanded.

As an example we could mentioned the 2DOF PI and PID controller tuning by the MRDP method, which yields nice smooth transient responses without overshooting (Vítečková and Víteček, 2010, 2016). However, an analytical controller design is tractable just in the nominal situations and in the PID case without the derivative filter. Once wishing to deal with some parameter uncertainties, or to modify this method for responses with some overshooting, just simplified approximate solutions may be derived (Víteček and Vítečková, 2017). Their application requires tedious calculations, or use of tables. PPM enables to generate appropriate performance portrait (PP) replacing such tables and including much broader spectrum of required transient shape patterns by a systemic procedure.

As another typical application area for the PPM we could also mention the model free control (Fliess and Join, 2013) based on disturbance observers with final impulse response (FIR) filters, where the analytical solutions as, for example, the stability borders (Fliess and Join, 2013; Join et al., 2017), exist just in exceptional cases. The PPM (Huba and Bisták, 2017; Huba and Huba, 2018) enables here a more detailed analysis and design.

1.2 Limitations of the PPM

The PPM is based on checking the loop performance over a grid of loop parameters which characterize all interesting situations. Achieved information is evaluated by performance measures related directly to the shape of transients and stored within the so called performance portrait. This is accomplished by simulation experiments or directly with real-time experiments. By its nature, the main method limitations are given by the number of the grid points and number of the characteristic loop parameters. Extent of the meaningful parameter changes, together with the number of grid points determine quantization of particular parameter and lead to questions, if some interesting situations may remain hidden and unobserved just between the considered grid points. Frequently, such situations may be excluded due to some continuity of dynamical system properties. In any case, it may be useful to combine the PPM with other similar methods (as, for example, the parameter space method), which may fully eliminate occurrence of unexpected phenomena.

In dealing with the PPM, the trade-off between the result precision and time for the PP calculation, or the search speed over PP may be simply modified by skipping samples and zooming. As the last limiting moment of the method we could mention size of the used PP.

Number of the key loop parameters, which are necessary to fully characterize all interesting situations, determine dimension of the generated PP. Since already the visualization of problems dealing with 3D information encounters display issues, visualization of more dimensional PP represents one of the basic method limitations. It means that we may work with PP of any dimension, but the results may be visualized just by series of 2D, or 3D projections.

One of the main advantages of the PPM, the possibility to deal with the time delayed systems, is limited by the numerical properties of the numerical methods used for the system simulation. In this aspect, the solvers available for simulation of the time delayed systems in Matlab/Simulink constitute a serious constraint. It can be avoided by simulations in the discrete-time domain, or by use of more robust alternatives (Scilab/Scicos, OpenModelica).

In demonstrating basic properties of the method, the paper considers application of the PPM in dealing with properties of the filtered 2DOF PI control. By use of nth order binomial filters we get FPI_n controllers. We will show, how the simplified approximate solutions proposed in (Huba, 2015b; Huba et al., 2016a) may be simply tested and evaluated.

The rest of the paper is structured as follows. Section 2 introduces the IPTD plant and the relevant performance measures for its control evaluation. Sections 3 is devoted to an analytical design of the FPI_n control for an IPDT plant, Section 4 treats the same problem by application of the performance portrait method, Section 5 discusses achieved results, Section 6 gives a brief description of the developed web tool. Section 7 considers possible educational framework of the tool application. The paper results are finally summarized by Conclusions.

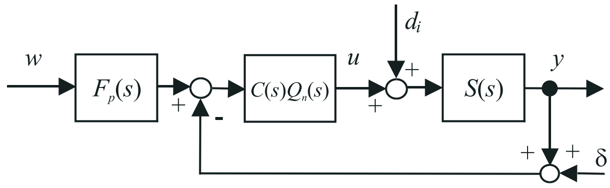

Fig. 1. Considered control structure, δ- measurement noise

2. IPDT PLANT CONTROL

We will consider FPI_n control consisting of a 2DOF PI controller $C(s)$ with a prefilter $F_p(s)$ (Huba, 2016)

$$C(s) = K_c \frac{1+T_i s}{T_i s} = K_c + \frac{K_i}{s};\ F_p(s) = \frac{bT_i s+1}{T_i s+1} \tag{1}$$

and a binomial noise-attenuation filter (Fig. 1)

$$Q_n(s) = 1/(T_f s+1)^n;\ n = 1, 2, ... \tag{2}$$

This control will be applied to the integral plus dead time (IPDT) plant with a model

$$S(s) = \frac{Y(s)}{U(s)} = \frac{K_{sm} e^{-T_{dm} s}}{s} \tag{3}$$

Where appropriate, the model will be considered to be precisely known and the index "m" will be omitted.

3. ANALYTICAL CONTROLLER+FILTER TUNING

An analytical controller tuning may be carried out by the multiple real dominant pole method. A triple real dominant pole (TRDP) s_o of the characteristic quasi-polynomial $P(s)$ (Vítečková and Víteček, 2010)

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

satisfying $P(s_o) = 0$, $\dot{P}(s_o) = 0$ and $\ddot{P}(s_o) = 0$ yields

$$s_o = -(2-\sqrt{2})/T_d \tag{5}$$

The corresponding optimal controller tuning is

$$\begin{aligned} K_o &= K_c K_s T_d = 2(\sqrt{2}-1)e^{\sqrt{2}-2} \approx 0.461 \\ \tau_{io} &= T_{io}/T_d = (2\sqrt{2}+3) \approx 5.828 \\ b_o &= \frac{1/|s_0|}{T_i} = \frac{2-\sqrt{2}}{2} \approx 0.293 \end{aligned} \tag{6}$$

Thereby, the optimal prefilter b_o has been determined to cancel one of the dominant poles s_o.

Next question is, how to derive an optimal controller for loops containing both the dead time T_{dm} (resulting from the plant identification) and a filter $Q_n(s)$ (for the measurement noise attenuation). One possibility could be to apply the "half rule" (Skogestad, 2003). An alternative solution to the same problem may start with application of the MRDP in a loop containing only the filter (2), when $T_d = 0$. It yields the triple dominant pole

$$s_n = -[2(n+1) - \sqrt{2n(n+1)}]/[(n+1)(n+2)T_f] \tag{7}$$

Next, instead of deriving the corresponding optimal parameters K_n, τ_{in} and b_n, we will look up an equivalent dead time T_e, which (after substitution for T_d into (6)) yields the same position of the dominant poles $s_o = s_n$ as $Q_n(s)$. Then, we apply the controller (6) derived for $T_d = T_e$.

Since the loop containing two dead time elements may be tuned for their sum, in loops including both the plant dead time T_{dm} and the filter $Q_n(s)$, in (6) we will consider

$$T_d = T_{dm} + T_e \tag{8}$$

It should yield transients respecting both main loop delays.

When taking into account that in the first situation the requirement $s_o = s_n$ may be achieved with

$$T_f = T_e \frac{\sqrt{2n(n+1)} - 2(n+1)}{(n+1)(n+2)(\sqrt{2}-2)]} \tag{9}$$

we may use $T_e > 0$ as a tuning parameter expressing intensity of the applied filtration. Thus, we have introduced an integrated tuning based on the identified plant parameters, T_e and n for both the controller and the noise attenuation filter. Simulations in Huba (2015b, 2016) show interesting results achieved in a broad range of T_e. The question, however, is, how far such intuitively achieved results match an optimal loop tuning. To investigate such problem, equation (9) will be modified to

$$T_e = T_f \frac{(n+1)(n+2)(\sqrt{2}-2)}{\sqrt{2n(n+1)} - 2(n+1)} \tag{10}$$

Then, for a chosen n and T_f, the controller tuning will be determined according to (8) and (6). The results will be checked by the PPM.

4. PPM BASED CONTROLLER+FILTER TUNING

Tuning of the 2DOF PI control based on the time and shape related performance measures has been presented in Huba (2013b). With respect to three loop parameters

$$\begin{array}{l} K = K_c K_s T_d \in [0.06, 0.46] \\ \tau_i = T_i/T_d \in [5, 105]\,; \quad b \in [0,1] \end{array} \tag{11}$$

the controller design has to be carried out in a 3D PP with the dimensionless parameters introduced in (6). With respect to the loop imperfections the optimal loop parameters K (and T_i) are expected to lie somewhere below (over) the optimal values (6). Then, the PP has to be augmented by the dimensions corresponding to $\tau_f = T_f/T_d$ and n. Experiments carried out over the grid of chosen parameters have been evaluated, regarding the speed of the output transient at the output $y(t)$, in terms of the integral of the absolute error IAE

$$IAE = \int_0^\infty |e(t)|\, dt\ ; \quad e = w - y \tag{12}$$

With respect to the Pareto character of the PI control, it is recommended to formulate a controller optimization problem including both the setpoint (IAE_s) and the input disturbance (IAE_d) step responses (Arrieta and Vilanova, 2011; Grimholt and Skogestad, 2012; Huba, 2013b). The cost function is composed by using the minimal $IAE_{s,min}$ and $IAE_{d,min}$ achieved by separate optimization of the setpoint and disturbance responses as

$$\begin{array}{l} J = w_s J_s + w_d J_d\,; \ w_s + w_d = 1\,; \ w_s \in \langle 0,\, 1\rangle \\ J_s = IAE_s/IAE_{s,min}\,; \ J_d = IAE_d/IAE_{d,min} \end{array} \tag{13}$$

Deviations from a monotonic setpoint response have been measured in terms of a modified (relative) total variance

$$TV_0(y) = \int_0^\infty \left| \left|\frac{dy}{dt}\right| - \frac{dy}{dt} \right| dt \approx \sum_i |y_{i+1} - y_i| - |y_\infty - y_0| \tag{14}$$

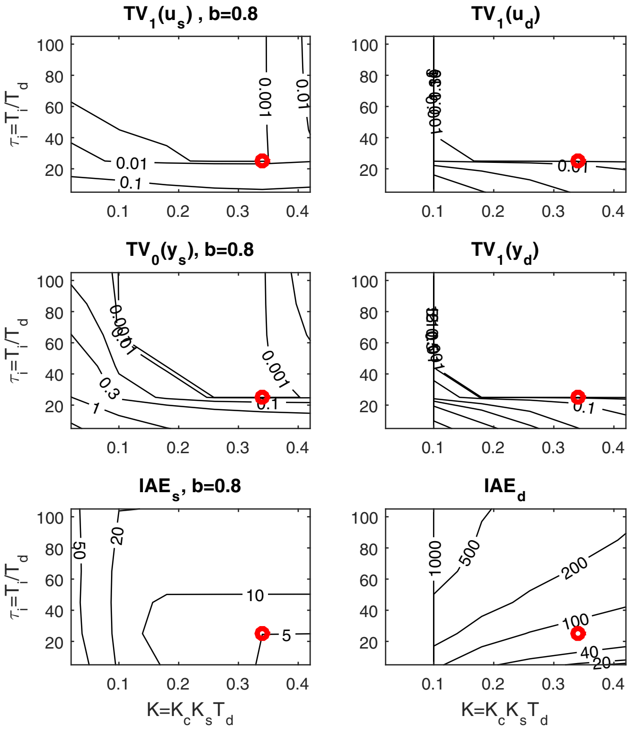

Fig. 2. Optimal working point found for $w_s = 1, w_d = 0$ in the parameter space (K, τ_i, b) (11) generated in 21x21x10 points for $K_s = 1, T_d = 1,\ T_f = 2T_d, n = 1$

Deviations from two monotonic intervals typical for the plant input transients and the output disturbance responses have been quantified by

$$TV_1(u) = \sum_i |u_{i+1} - u_i| - |2u_m - u_\infty - u_0| \tag{15}$$

Thereby, the initial and final input values are denoted as u_0 and u_∞ and $u_m \notin (u_0, u_\infty)$ represents an extreme control value separating two monotonic input intervals.

The tolerable integral deviations from ideal shapes at the plant input and output have been formulated in form of inequalities

$$\begin{array}{l} TV_0(y_s) \le \epsilon_{ys}\,; \ TV_1(y_d) \le \epsilon_{yd} \\ TV_1(u_s) \le \epsilon_{us}\,; \ TV_1(u_d) \le \epsilon_{ud} \end{array} \tag{16}$$

with

$$\epsilon = \epsilon_{ys} = \epsilon_{yd} = \epsilon_{us} = \epsilon_{ud} = 0.001 \tag{17}$$

Introduction of possible noise attenuation filter has been discussed in Huba (2013c). It has pointed out that already first order noise-attenuation filter with $T_f \approx T_d$ leads to significantly prolonged transients.

5. DISCUSSION

In comparing the analytical and PPM based tunings we have to stress much broader flexibility of the second type of tuning. For example, choice of $w_s = 1$ in (13), stressing importance of the setpoint responses, leads to a relatively sluggish disturbance response (Fig. 3. Although the analytical tuning seems to converge to the setpoint faster, it yields $IAE_{sTRDP} = 12.27 > IAE_{sPPM} = 8.74$.

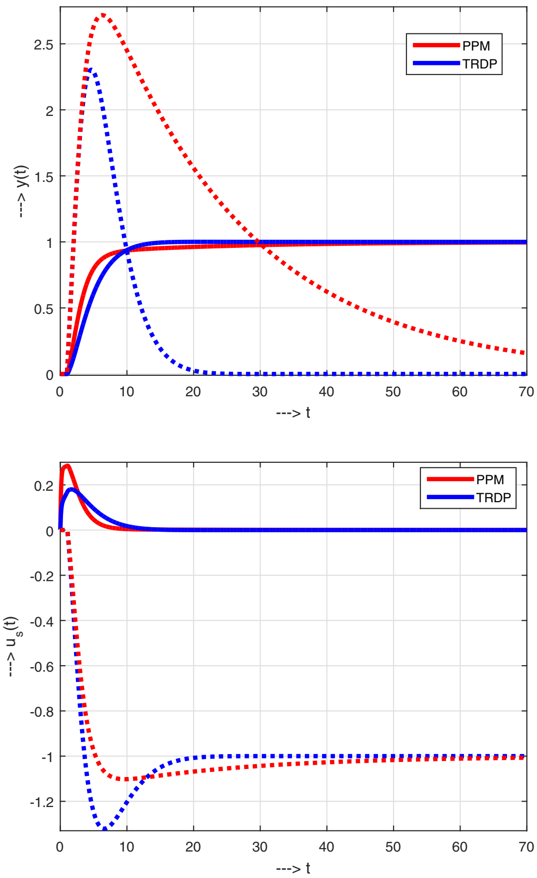

Fig. 3. Setpoint (full curves) and input disturbance step responses (dotted) corresponding to $w_s = 1, w_d = 0$

Nevertheless, it is to remember that in quantifying speed of transient processes IAE is not fully equivalent to the settling time t_s defined by a sustained achievement of a specified ε-dead-band around the reference setpoint w

$$|y(t) - w| \leq \varepsilon \quad \forall t \geq t_s;\ \varepsilon > 0 \tag{18}$$

We prefer to work with IAE because its value is not tied to ad-hoc parameter values. IAE may be calculated only once within the normalized (dimensionless) quantities, whereas the settling time has to be calculated for a set of chosen dead-band values to cover the possible area of interest. However, this will hold also for other possible approaches to the problem (Mercader and Banos, 2017).

Thus, comparison of the transients proposed with using the analytically derived delay equivalence (9)-(10) and transients found as optimal by the PPM (Figs 2-3) has “no clear winner”. It may be used in illustrating the always existing nuances in “optimal” controller tuning. With respect to this diversity, also the simplified analytical tuning shows for a broad range of T_e results satisfactory for many applications. The web application allows to show several other not illustrated aspects, for example impact of a measurement noise, which has to be omitted due to the space limitations in this paper.

6. WEB APPLICATION

The interactive web application illustrates all steps of the controller design described before. It consists of two parts - the first one shows PPM (Fig. 4) for the considered system (3) that changes according to the order of the filter (2) and the second one enables to demonstrate dynamical behavior of the system that is controlled by the proposed controller. In Fig. 5 one can see setpoint and disturbance responses corresponding to the optimal controller settings computed on the base of PP method. The comparison with other type of controllers is also possible.

The web application was built by combination of open and commercial technologies. The frontend was developed using HTML, CSS and JavaScript. Plotting of graphical dependencies was realized using D3.js and Plotly Javascript libraries. For the backend PHP programming language and MySQL database was used. In addition, Matlab simulation environment supported part of calculations that are needed for running the application. Since Matlab except of other languages (such as C/C++, Java, Fortran) has also an application programming interface (API) for Python (The MathWorks, Inc., 2017), the communication between the Matlab and web application was realized in this programming language.

Regarding functionality, the application consists of 3 parts:

- finding of performance portrait,
- determining the controller optimal parameters (done automatically immediately after the computation of performance portrait - in Fig.4 the optimal setting is illustrated by red circle),
- simulation of the system with computed controller parameters.

To ensure smooth running of the application it is also necessary to think about its velocity. Today’s young people are used to immediate responses of online applications. A longer waiting could discourage them from using them. The computation of a performance portrait takes some time. Therefore it is reasonable to calculate it in advance and to save computed values to the database. Then, they can be immediately used for plotting. Processing several portraits for various settings and control structures enables wider application usage.

Scanning the computed portrait for nominal setting of controller can be calculated in the web application, since its determining is not so computationally demanding. After its finding it has to be converted to the real optimal controller values respecting the system parameters. It is because of that the performance portrait is normalized.

The computed values can be used in simulations. In spite of the fact that numerical methods needed for realization of simulations can also be defined inside of the web application, it is much more comfortable and transparent to accomplish required simulations in some simulation environment. There exist several possibilities from the use of open solution such as Scilab or OpenModelica up to commercial alternatives e.g. Matlab or LabView. We decided to use Matlab environment because it is widely used not only at our faculty but also wordwide.

The connection with Matlab was realised via Matlab Engine API for Python. Since 2015 it enables connection to already running session of Matlab instance. This feature is very welcomed because starting new instance of Matlab

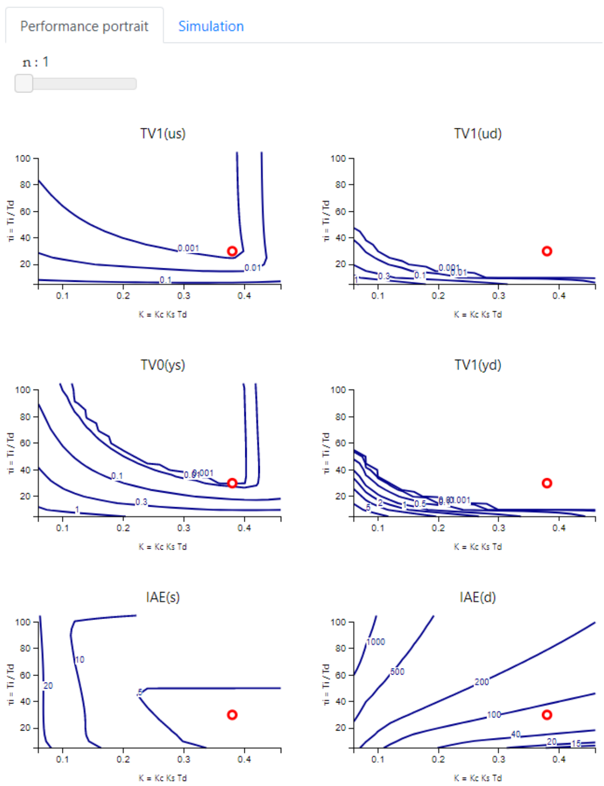

Fig. 4. Fragment from created web application: PPM and optimal working point found for b=0, w_s=1, w_d=0

at each new simulation required by the application would be not acceptable. It takes too long time.

The presented web application is available at `http://www.iolab.sk/ppm/ibce2018`.

7. EDUCATIONAL FRAMEWORK

Necessity of an appropriate filter design and application of the integrated loop tuning may be demonstrated by control of the thermal channel of the thermo-opto-mechanical system TOM1A (Huba et al., 2016a, 2017). Such a task may be included at the end of a chain of simple control tasks including measurement of the input-output steady state characteristic, loop linearization by an inverse nonlinearity (look-up table) and a pole assignment P controller design based on the first order plant models. Because of the permanent control error and impact of disturbances, such a sequence may finish with introduction of an "automatic reset" - PI control. To make the task worse, additional delays may be added to the loop, which decrease the feedback ability to eliminate the always existing model imperfections. Such a framework yields a basis for application of standard controller tuning methods, which may be concluded by the PPM application enabling an easy design and verification of the integrated filter+controller tuning.

8. CONCLUSIONS

The paper has described application of the performance portrait method in evaluating simplified integrating tuning of the filtered 2DOF PI control satisfying requirements on

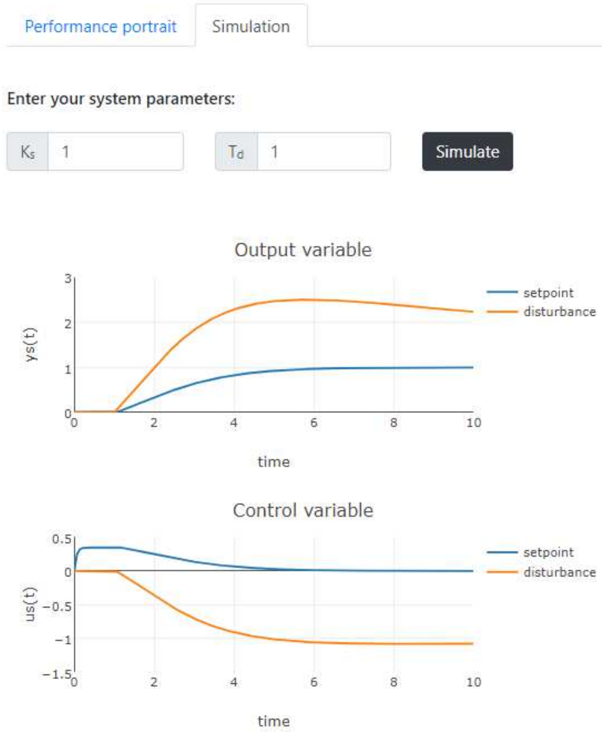

Fig. 5. Fragment from created web application: setpoint and disturbance responses corresponding to the settings in Fig. 4

the fastest possible transient responses respecting chosen shape related deviations of the setpoint and disturbance responses at the input and output. Additional nth order binomial filters (2) have been proposed to achieve an improved measurement noise attenuation, whereby the filter parameters have been included into the controller tuning. The simplified analytical tuning is much simpler than a PPM based controller design, but the spectrum of achievable dynamics is much narrower. Comparison of these two approaches in controller design may be used to demonstrate broad spectrum of "optimal" transient responses that may be required in practical applications.

Importance of the filtration problem is further stressed by the fact that its simple and reliable solution opens door to an efficient application of the derivative action as, for example, in PID, or PIDD^2 control (Huba, 2018).

REFERENCES

Ackermann, J. (2002). *Robust Control: The Parameter Space Approach - 2nd ed.* Springer, Berlin.

Arrieta, O. and Vilanova, R. (2011). Simple PID Tuning Rules with Guaranteed Ms Robustness Achievement. *IFAC World Congress Milano*, 18, 1.

Fliess, M. and Join, C. (2013). Model-free control. *International Journal of Control*, 86(12), 2228–2252.

Grimholt, C. and Skogestad, S. (2012). Optimal PI-Control and Verifcation of the SIMC Tuning Rule. *IFAC Conf. Advances in PID Control PID'12*, ThPl.1.

Huba, M. (2009). Robust design of integrating controllers for IPDT plant. In M. Fikar and M. Kvasnica (eds.), *Proc. 17th Int. Conf. Process Control '09*, 353–357. STU Bratislava, Š. Pleso.

Huba, M. (2010a). Designing robust controller tuning for dead time systems. In *Int. Conf. System Structure and Control*. IFAC, Ancona, Italy.

Huba, M. (2010b). Robust constrained pid control. In *Int. Conf. Cybernetics and Informatics*. SSKI, Vyšná Boca, Slovak Republic.

Huba, M. (2011a). Basic Fundamental Controllers of DC0. In M. Huba, S. Skogestad, M. Fikar, M. Hovd, T. Johansen, and B. Roháľ-Ilkiv (eds.), *Textbook: Selected topics on constrained and nonlinear control*, 139–186. STU Bratislava - NTNU Trondheim.

Huba, M. (2011b). Constrained pole assignment controller for sopdt plant. complex poles. In M. Huba and S. Skogestad (eds.), *Preprints of the Workshop Selected topics on constrained and nonlinear control*. STU Bratislava - NTNU Trondheim.

Huba, M. (2011c). Filtered Smith predictor tuning by the Performance Portrait method. In M. Huba, S. Skogestad, M. Fikar, M. Hovd, T. Johansen, and B. Roháľ-Ilkiv (eds.), *Preprints of the Workshop "Selected topics on constrained and nonlinear control"*, 193–200. STU Bratislava – NTNU Trondheim.

Huba, M. (2011d). Robust controller tuning for constrained double integrator. In M. Huba and S. Skogestad (eds.), *Preprints of the Workshop Selected topics on constrained and nonlinear control*, 203–211. STU Bratislava - NTNU Trondheim.

Huba, M. (2012). Setpoint versus disturbance responses of the IPDT plant. *IFAC Conf. Advances in PID Control PID'12*.

Huba, M. (2013a). Comparing 2DOF PI and Predictive Disturbance Observer Based Filtered PI Control. *Journal of Process Control*, 23, 10, 1379–1400.

Huba, M. (2013b). Performance measures, performance limits and optimal PI control for the IPDT plant. *Journal of Process Control*, 23, 4, 500–515.

Huba, M. (2013c). Performance Portrait Method: a new CAD Tool. In *10th Symposium on Advances in Control Education (ACE)*. IFAC, Sheffield, UK.

Huba, M. (2014a). Robust Tuning of the Simplest Dead Time Compensators. In *8th Int. Conf. and Exposition on Electrical and Power Eng. - EPE*. Iasi, Romania.

Huba, M. (2014b). Robustness analysis of a disturbance-observer based PI control. In *8th Int. Conf. and Exposition on Electrical and Power Eng. - EPE*. Iasi, Romania.

Huba, M. (2015a). Analyzing limits of one type of disturbance observer based PI control by the performance portrait method. In *IEEE Mediterranean Control Conference, MED'15*. Torre Molinos, Spain.

Huba, M. (2015b). Filter choice for an effective measurement noise attenuation in PI and PID controllers. In *ICM2015*. Nagoya, Japan.

Huba, M. (2015c). Robustness versus performance in PDO FPI Control of the IPDT plant. In *IEEE/IES International Conference on Mechatronics, ICM2015*. Nagoya, Japan.

Huba, M. (2016). Triple real dominant pole tuning of a filtered PI controller. In *28th Int. Conf. Cybernetics and Informatics*. Levoca, Slovakia.

Huba, M. (2018). Extending Spectrum of Filtered Controllers for IPDT Plant Models. In *Cybernetics & Informatics, IEEE 29th International Conference on*. Lazy pod Makytou, Slovakia.

Huba, M. and Bisták, P. (2017). Tuning of an iP Controller for a Time-Delayed Plant by a Performance Portrait Method. In *25th Mediterranean Conference on Control and Automation*. Valletta, Malta.

Huba, M., Bisták, P., and Huba, T. (2016a). Filtered PI and PID control of an Arduino based thermal plant. In *14th IFAC PDeS*. Lednice, Brno, Czech Rep.

Huba, M., Bisták, P., Huba, T., and Vrančič, D. (2017). Comparing filtered PID and Smith Predictor Control of a Thermal Plant. In *EDPE*. Dubrovnik, Croatia.

Huba, M. and Gerke, M. (2009). Ein auf qualitativer Analyse basierter robuster Reglerentwurf. In *16. Steirisches Seminar ueber Regelungs- technik und Prozessautomatisierung*, 29–39. TU Graz, Retzhof, Austria.

Huba, M. and Huba, T. (2018). *Modifications of Model Free Control to FOTD Plants.* Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics). Springer. APVV-0343-12, VEGA 1/0937/14.

Huba, M., Marko, Ľ., Bahník, P., and Oravec, I. (2009). Numerical issues in designing PI controller for IPDT plant. In *Proc. 17th Int. Conf. Process Control '09*, 57–64. STU Bratislava, Š. Pleso.

Huba, M., Vrancic, D., and Huba, T. (2016b). Evaluating Performance Limits in FOTD Plant Control. In *11th IFAC ACE*. Bratislava, Slovakia.

Huba, M. and Šimunek, M. (2007). Modular approach to teaching PID control. *IEEE Trans. Ind. Electr.*, 54, 6, 3112–3121.

Join, C., Delaleau, E., Fliess, M., and Moog, C. (2017). Un résultat intrigant en commande sans modele. *Automatique Control, ISTE*, 1(1), 9 p.

Mercader, P. and Banos, A. (2017). A PI tuning rule for integrating plus dead time processes with parametric uncertainty. *ISA Transactions*, 67, 246 – 255.

Skogestad, S. (2003). Simple analytic rules for model reduction and PID controller tuning. *Journal of Process Control*, 13, 291–309.

Sóos, D. and Huba, M. (2014). Experimental performance portrait based optimal controller tuning. In *15th Int. Carpathian Control Conference - ICCC*. Velké Karlovice, Czech Republic.

The MathWorks, Inc. (2017). MATLAB API for Python. `https://www.mathworks.com/help/matlab/matlab-engine-for-python.html`. Accessed: 2017-12-10.

Víteček, A. and Vítečková, M. (2017). *Metoda požadovaného modelu (The desired model method)*. VŠB - Technical University of Ostrava, Ostrava.

Vítečková, M. and Víteček, A. (2010). 2DOF PI and PID controllers tuning. In *9th IFAC Workshop on Time Delay Systems*, volume 9, 343–348. Praha.

Vítečková, M. and Víteček, A. (2016). 2DOF PID controller tuning for integrating plants. In *2016 17th Int. Carpathian Control Conf. (ICCC)*, 793–797.