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Interactive Disturbance Observer Based Filtered PID Controller Design

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Abstract: The paper shows Matlab based interactive tool for noise attenuation motivated filtered PD and disturbance observer based filtered PID controller performance analyses and design. The user can set several control loop parameters (plant model parameters and their uncertainty, measurement noise, controller, filter parameters) and evaluate various performance measures. The comparison with traditional linear PID controller design methods can be made.

Keywords: Disturbance observer, PID control, performance, robustness, noise attenuation, Matlab/Simulink, interactive tool

1. INTRODUCTION

New modular filtered PD and disturbance observer (DO) based filtered PID (DO-FPID) controller design allowing an easy filter specification for an appropriate noise attenuation has been proposed in Huba (2013b,a). This paper describes an interactive computer tool enabling users to interact with controller design treated in these papers and to explore in depth features of particular controller and filter tunings. Similar tools are available for large area of control related tasks (see e.g.Dormido et al. (2011); Rodriguez et al. (1996); Kroumov et al. (2003); Carrero et al. (2010)).

The paper is organized as follows The performance measures used to evaluate the considered control performance are discussed in Section 1.1. Filtered PD and DO-PID controllers (FPD/DO-FPID) are presented in section 1.2. Pole assignment control of filtered PD control is briefly treated in Section.1.3. Possible solutions to the problem of dynamics specification and noise attenuation by an equivalence of time delays is described in Section 1.4. Possible extensions of the proposed time constant equivalence derived for integral plants is mentioned in Section 1.5. The interactive tool features are described in section 2. Possible tasks appropriate for the tool application are discussed in Section 3. Contributions of the paper are summarized in Conclusions.

1.1 Performance measures

Speed of the transients at the plant output will be quantified by means of the IAE (Integral of Absolute Error)

$$IAE = \int_0^\infty |e(t)|\, dt \tag{1}$$

For evaluating deviations from ideal shapes of the setpoint responses at the plant input and output (Huba, 2013b), relative measures for deviations from monotonic (MO), one-pulse (1P) and two-pulse (2P) shapes may be proposed (Huba, 2010, 2013c). Deviations from strictly MO shape of the plant output $y(t)$ with the initial value y_0 and the final value y_∞ may be characterized by

$$yTV_0 = \sum_i |y_{i+1} - y_i| - |y_\infty - y_0| \tag{2}$$

$yTV_0 = 0$ just for strictly MO response, else $yTV_0 > 0$.

Contribution of the superimposed oscillations in 1P dominant control (typical for the output disturbance step responses) are for $y_m = max\{y\}$ expressed by

$$yTV_1 = \sum_i |y_{i+1} - y_i| - |2y_m - y_\infty - y_0| \tag{3}$$

$yTV_1 = 0$ just for strictly 1P response, else for control signals with superimposed higher harmonics $yTV_1 > 0$.

Integral deviations from an ideal 2P input shape with two extreme points u_{m1}, u_{m2} may be characterized by

$$uTV_2 = \sum_i |u_{i+1} - u_i| - |2u_{m1} - 2u_{m2} - u_\infty - u_0| \tag{4}$$

Again, for ideal 2P control functions $u(t)$, $uTV_2 = 0$.

In evaluating disturbance response one has to note that immediately after a disturbance step the plant output starts to rise (fall). The controller needs some time to balance its effect and to reverse output to move back to the reference value. So, the evaluation of MO output increase (decrease) may start just after its turnover, which requires to evaluate deviations from 1P shapes by yTV_1 measure. Thereby, MO areas for disturbance response are in general different from those corresponding to the setpoint steps and the controller design has to compromise these differences.

1.2 Filtered PD and DO-PID Control

In designing filtered PD and DO-FPID controllers, a dominant 2nd-order plant dynamics is considered, with an

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input disturbance d_i, $\mathbf{x} = (y, \dot{y})'$, $\dot{x} = dy/dt$ and y being the plant state and output

$$\ddot{y} = K_s(u_r + d_i) - a_1\dot{y} - a_0 y \tag{5}$$

In working with stable, integral and unstable systems, this plant description leads to the "pole-zero form" transfer function

$$F(s) = \left[\frac{Y(s)}{U_r(s)}\right]_{d_i=0} = \frac{K_s}{s^2 + a_1 s + a_0} \tag{6}$$

that is more universal than the usual "static-gain-time-constant" form. Plant approximation (5) used above for design of the controller itself is not sufficient for its reliable tuning. Some constraints on set of admissible closed loop poles may be derived just by considering additional loop dynamics comprising the inherently included nonmodelled dynamics together with the intentionally introduced dynamics of different filters used to get a proper controller, to increase robustness and to attenuate measurement noise.

In determining loop approximations including the non-modelled dynamics one may work with several types of time delays. Most frequently (Åström and Hägglund, 1995, 2006; Hägglund, 2012; Larsson and Hägglund, 2012; Segovia et al., 2014) 2nd and 3rd order linear models, or the first order linear model with dead time are used. In order to develop a consistent approach covering all possible situations met in practice, this set will yet be extended by higher order approximations. In order to keep the number of unknown parameters as low as possible, just two (or, more precisely, three) parameter loop model $S_n(s)$ with K_s, n and T_n will be preferred, when a_1, a_0 have been neglected

$$\begin{aligned} S_n(s) &= \frac{K_s}{(s^2 + a_1 s + a_0)(T_n s + 1)^n}; \\ F_n(s) &= \frac{1}{(T_n s + 1)^n} \\ 0 < T_n &<< T_p = \sqrt{1/|a_0|};\ n = 1, 2, \ldots \end{aligned} \tag{7}$$

For determining parameters of these approximations there exist huge number of methods based e.g. on measuring and evaluating step responses, ultimate sensitivity experiments, relay experiments, etc. and fulfilling different performance specifications. Furthermore, in Huba (2012) it has been shown that for the first order plants and increasing n the loop performance approaches that of the loop with an equivalent dead time, which enables to simplify the overall treatment. Thereby, use of higher order filters may significantly improve the closed loop performance Huba (2015a).

1.3 FPD controller

For stepwise constant setpoint values r, under pole assignment control of the plant (6) one can require the setpoint-to-output relation characterized by the closed loop poles α_1, α_2, or the corresponding time constants $T_{ri} = -1/\alpha_i$ as

$$F_r(s) = \frac{Y(s)}{R(s)} = \frac{1}{(T_{r1}s + 1)(T_{r2}s + 1)} \tag{8}$$

When considering plant (5) and solving for u one gets

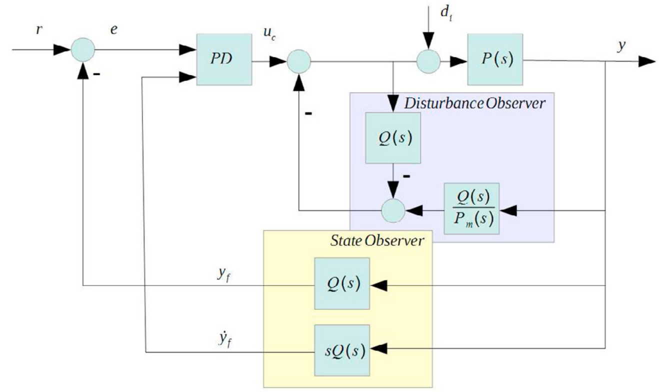

Fig. 1. DO-FPID control using equal filtration of all channels of the state observer (SO) and of the disturbance observer (DO)

$$\begin{aligned} u &= K_P e + K_P T_D \dot{e} + u_\infty = K_P e + K_D \dot{e} + u_\infty \\ e &= r - y\ ;\ \ u_\infty = a_0 r/K_s - d_i \\ K_P &= \frac{\alpha_1\alpha_2 - a_0}{K_s} \\ T_D &= -\frac{\alpha_1 + \alpha_2 + a_1}{\alpha_1\alpha_2 - a_0} \\ K_D &= -\frac{\alpha_1 + \alpha_2 + a_1}{K_s} \end{aligned} \tag{9}$$

Thereby, the static feedforward control u_∞ is necessary for keeping the output in a steady state at the required reference value r under influence of a constant disturbance d_i.

Closed loop with PD-controller (9) remains stable, when its poles remain negative, i.e.

$$K_P K_s + a_0 > 0;\ K_P K_s T_D + a_1 > 0 \tag{10}$$

For stable and marginally stable plants ($a_i \geq 0$) this holds for any $K_P K_s > 0$, $T_D > 0$ and stability will be satisfied by any $0 < T_r < \infty$. For unstable plants with $a_0 < 0$ it must hold

$$T_r < \sqrt{-1/a_0} = T_p \tag{11}$$

i.e. the controller gain K_P cannot be arbitrarily decreased (the closed loop time constant T_r cannot be arbitrarily increased), just to a value fulfilling (11).

Introduction of filters $F_n(s)$ into the closed loop makes the above pole assignment controller tuning unusable. The question is, how to organize the closed loop tuning in such a way that it allows to interact with the choice of an appropriate filter order influencing the noise attenuation without changing dynamics of the required closed loop transients.

1.4 Time Constants Equivalence

For a simple noise attenuation tuning by filters with an order n one needs a method allowing to keep a nearly constant performance independently from the chosen filter order. This may be derived by analyzing closed loops including either the filter F_n with a time constant T_n, or a pure dead time T_d. In this way, several equivalences of these time delays may be established (Huba, 2013b,a). The simplest open loop delay equivalence $T_n = T_d/n$