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Frequency Response Based the Derivative Component Tuning Approach

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Abstract— **The controllers of PID type remain the most wide-used controllers in industrial practice. Many PID controller tuning method have been developed since Ziegler and Nichols published their technique, but they are not so widely used as the Ziegler and Nichols methods. The majority of presented tuning methods usually skips tuning of the derivative component, or they use set the derivative component parameter to be proportional to the integrative component parameter. The new approach to the derivative component tuning is presented in the paper.**

I. Introduction

CONTROLLERS of PID type are the most used in almost all industrial branches [2]. It is easy to explain why they are in favour so much, even when there are many better algorithms in existence, and a new or improved algorithm emerges almost every month (some of the recent improvements are control error reference course control [20] and new model-based tuning rules [10]). The reason is that the PID controller is easy to implement. No deep mathematical theory is necessary to understand how the PID controller works, so everybody is able to imagine what is happening inside the controller during the control process [21].

Many tuning algorithms have been presented, e.g. [3], [4], [9], [12], [18], but they are mostly based on a model of the controlled process/device. Incredible number of PID tuning rules was collected in [14] and some were added to them in [15]. Majority of existing tuning rules is model-based, only a few of them are model-free. Because that, the more than 50-year-old Ziegler-Nichols method [28] is still the most-used controller tuning method. It is known that the control loops tuned with the Ziegler and Nichols tuning rule are oscillatory with low damping. The same statement is valid as for the relay method in its basic version [1] as for many of its modifications, e.g. [7], [13], [17], [19]. The disadvantage of the Ziegler and Nichols method and also of the relay method is the necessity to break the control function of controller and its problematic use to tune controllers of MIMO controlled plants [27]. This was a motivation to develop new controller tuning method that does not have these disadvantages. During the development the question how to tune properly the derivative component occurred. Among the existing method, even model based tuning methods skip the derivative component tuning, e.g. method described in [22]. The majority of model-free tuning method does not solve derivative component tuning (e.g. [5], [11], [16]) eventually uses fixed derivative component setting according to the integrative component setting, usually $T_D = \frac{1}{4} T_I$ is chosen (e.g. [6], [8]). The derivative component of PID controller is a small mystery and it still not so satisfactory explained when the derivative action is useful and when it is better that the controller works like PI controller only [2].

Because the goal of PID controller tuning is to tune it fully with no restriction to fix the derivativative component setting to the integrative component setting, an attempt to find such a tuning rule that fulfils the demands of our tuning methods was made.

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II. Frequency Response Evaluation Based Tuning

Our tuning method is based on on-line frequency response evaluation and the control quality indicators are computed consequently [23]. Then, the new controller parameters are computed in dependence on the actual and desired values of control quality indicators. Even the control quality indicators are connected with open loop behaviour characteristics, they are evaluable also in closed control loop.

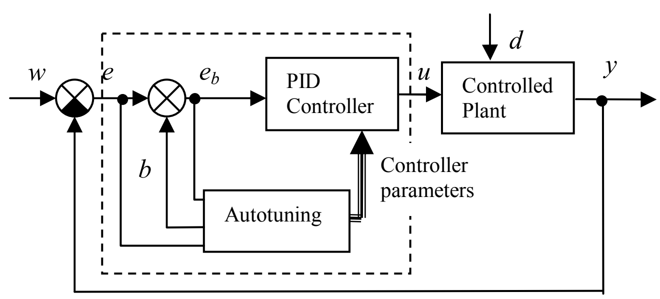

Fig. 1. Scheme of a control circuit with an added autotuning mechanism.

The scheme of the closed control loop with the added autotuning based on open loop control quality indicators is shown in Figure 1.

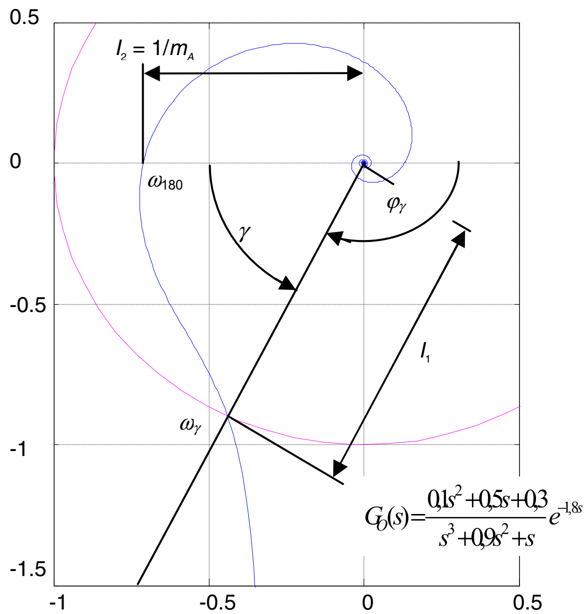

Fig. 2. Nyquist plot with marked main control quality indicators.

The PID controller is in the form

$$G_R(s) = \frac{r_D s^2 + r_0 s + r_I}{s} \tag{1}$$

where $r_D = r_0 T_D$ and $r_I = r_0 / T_I$.

The method uses non-linear controller parameter iterative tuning rules, which can be of the following structure:

$$r_{0(k)} = r_{0(k-1)} \frac{I_{2D}}{I_{2(k-1)}} \tag{2}$$

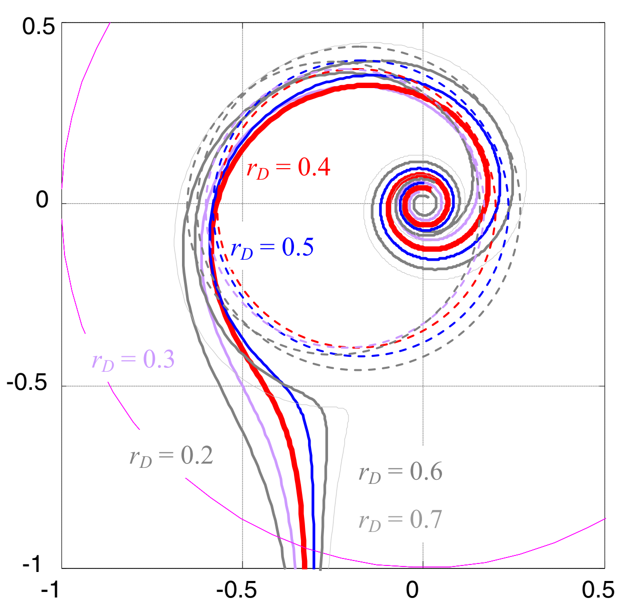

Fig. 3. Nyquist plots for PID controller with various r_D setting

$$r_{I(k)} = r_{I(k-1)} \frac{I_{1D}}{I_{1(k-1)}} \tag{3}$$

where I_{1D} and I_{2D} are desired values of the control quality indicators, k is the step of iterative tuning.

In a comparison with other model-free tuning techniques it produces usable controller parameters [25]. Currently, the algorithm is being tested on small-scale biomass fired boiler [24]. More details about the tuning method are presented in [26].

III. The Derivative Component Tuning Approach

The form of the derivative component iterative tuning rule is given by form of existing proportional and integrative component iterative tuning rules (2) and (3).

The derivative component tuning rule is derived with the use of linear control theory and Nyquist plot and it is derived similarly like Magnitude Margin and Phase Margin. The general principle is demonstrated using the model with transfer function $G_S(s) = \frac{e^{-1,8s}}{s^2 + 0{,}9s + 1}$ controlled with a PID controller with transfer function $G_R(s) = \frac{r_D s^2 + 0{,}5s + 0{,}3}{s}$ (parameter r_D is variable). When comparing the Nyquist plots and the courses of disturbance response and when the criteria are 1) the lowest overshoot, and 2) the shortest control process, we can see that the Nyquist plot corresponding to the response of these two criteria has following property: The circumscribed circle with the center on real axis around the top part of Nyquist (corresponding to phase shift between -180° to -360°) has the smallest diameter. When the value of r_D value is smaller or bigger than the optimal one, the circumscribed circle diameter is always bigger. If it is possible to get more circles with the same diameter, the circle with the center closest to the origin should be taken into account.

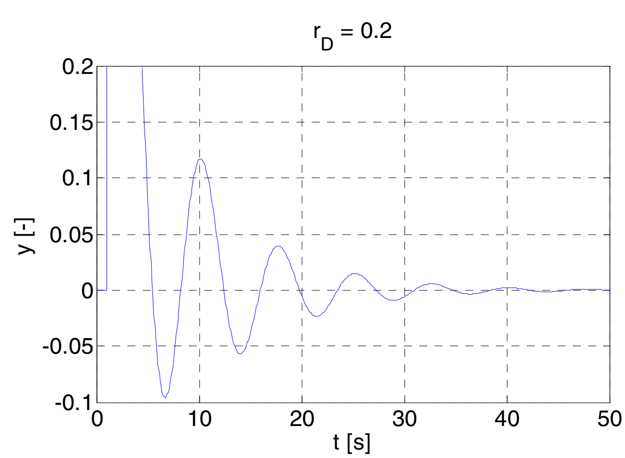

Fig. 4. Disturbance response course when $r_D = 0.2$ (the first peak of size 0.35 is not shown in full size in the figure as it has no illustrative value, it occurs always in the same size due the presence of time delay).

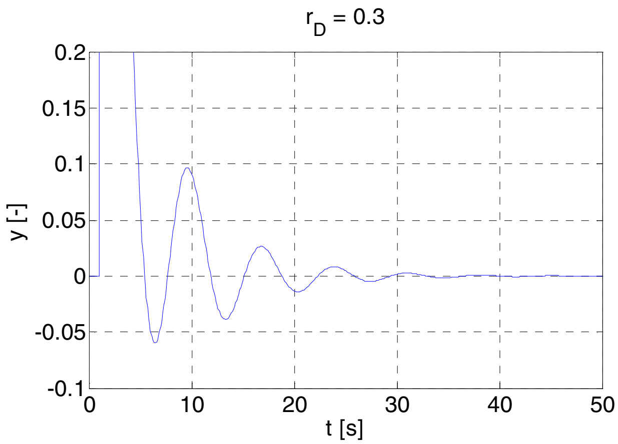

Fig. 5. Disturbance response course when r_D = 0.3 (the first peak of size 0.35 is not shown in full size in the figure).

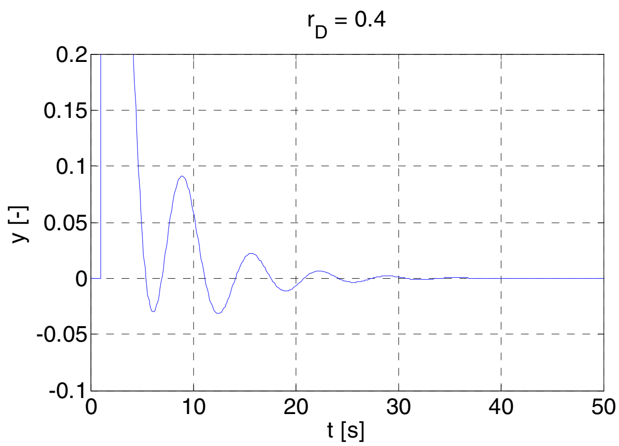

Fig. 6. Disturbance response course when r_D = 0.4 (the first peak of size 0.35 is not shown in full size in the figure).

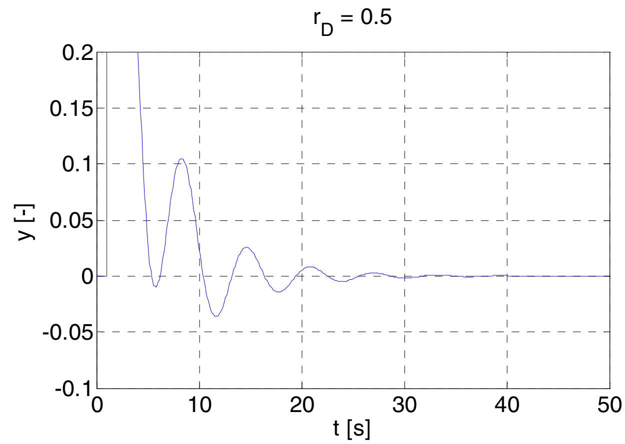

Fig. 7. Disturbance response course when r_D = 0.5 (the first peak of size 0.35 is not shown in full size in the figure).

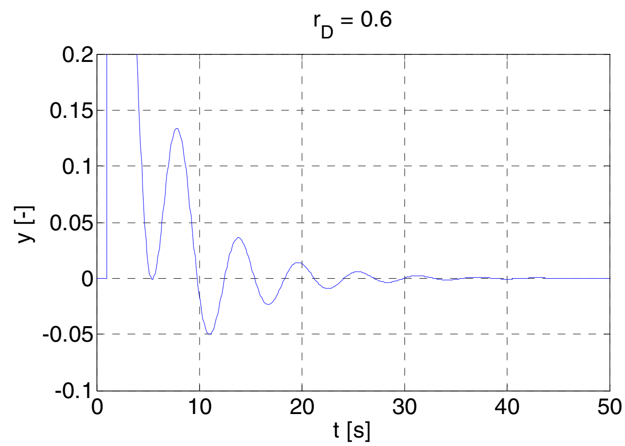

Fig. 8. Disturbance response course when r_D = 0.6 (the first peak of size 0.35 is not shown in full size in the figure).

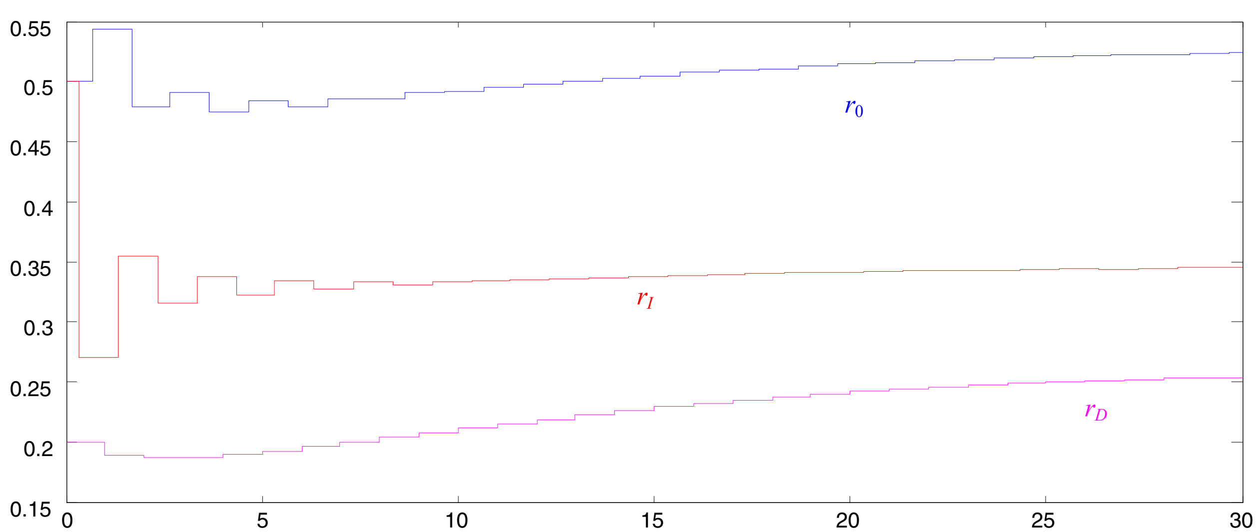

Fig. 9. Example of PID controller tuning $\left(G_{PID} = r_0 + \frac{r_I}{s} + r_D s\right)$.

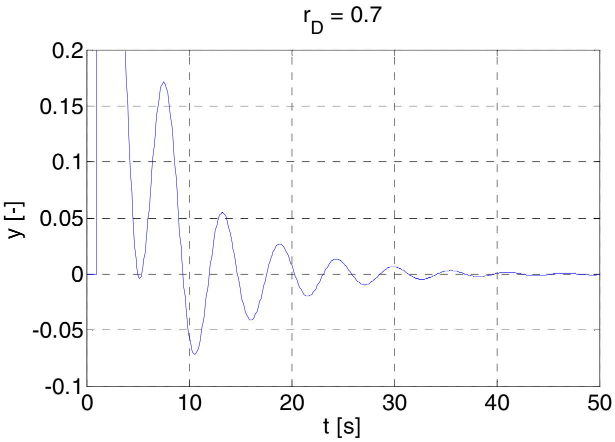

Fig. 10. Disturbance response course when $r_D = 0.7$ (the first peak of size 0.35 is not shown in full size in the figure).

Figures 4 to 8 and Figure 10 show example of responses on disturbance for various r_D parameter values (values of parameters r_0 and r_I remain the same). We can see that when the value of r_D increases to 0.5, the oscillations decreasing, the third and fourth peaks become lower. The response time shorts with growing r_D value. When the value of parameter r_D increases to values over 0.5, the oscillations grow, the third and fourth peaks become higher and the response time grows.

However, to find the diameter of circumscribed circle is time demanding task, because it depends on the Nyquist plot shape and more points of frequency response are needed to

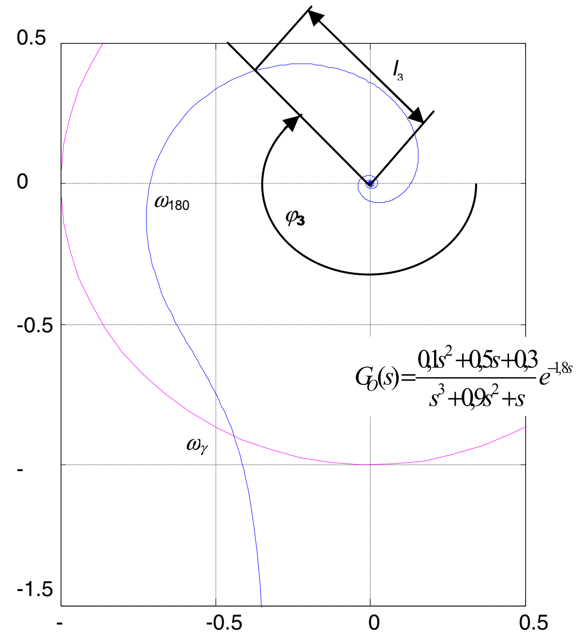

Fig. 11. Nyquist plot with marked derivative component related control quality indicator.

be evaluated. To simplify the tuning rule, one point of Nyquist plot is chosen that should leave on the specified distance from origin. The simplified iterative rule used in the tuning method then is

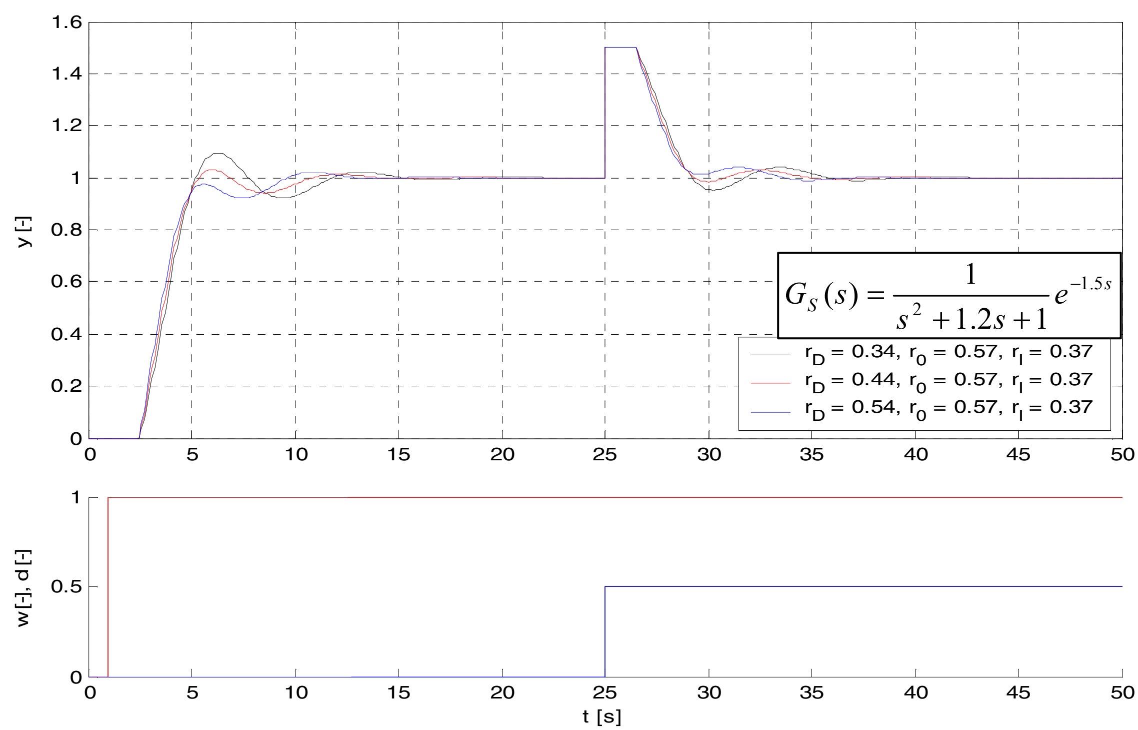

Fig. 12. Example of control process using the controller with setting obtained with the presented derivative component tuning rule (slightly better courses with higher r_D values than the found one are shown for comparison)

$$r_{D(k)} = r_{D(k-1)} \frac{I_{3D}}{I_{3(k-1)}} \quad (4)$$

This simplification does not produce the optimal setting but it is close to the optimal setting. According to experiments, the choice of point corresponding to phase shift of -240° gives good results.

The use of rule (4) needs to choose the value of I_{3D} carefully. Exceeding its minimal possible value causes parameter r_D converging to zero. To prevent this, it is necessary to test if increase of r_D causes increase of I_3. If not, it is necessary to use alternative rule

$$r_{D(k)} = r_{D(k-1)} \frac{I_{3(k-1)}}{I_{3D}} \quad (5)$$

It ensures that value of r_D reaches its minimal value only if desired value I_{3D} is not chosen properly or the initial value of $r_{D(0)}$ is too big.

The example of PID controller tuning course is shown in Figure 9. The course of control process with the obtained controller setting using the derivative component tuning rule presented here when the used model is $G_S(s) = \frac{e^{-1,5s}}{s^2 + 1,2s + 1}$ is shown in Figure 12. The courses obtained with only slightly better controller setting are shown in the same figure for comparison.

IV. Stability Analysis

There are two consideration for stability features. First consideration is that the derivative component tuning presented here should be used as a part of tuning method tuning all controller parameters, and the second that it can be used to improve the derivative component performance when the controller is tuned already.

When presented method is used to improve derivative component performance stability is guaranteed when

$$\frac{r_{D(k)} I_{3(k-1)}}{r_{D(k-1)} I_{3(k)}} \to 1 \quad (6)$$

because then bigger changes in controller parameter value causes smaller changes in control quality indicator value and then it is guaranteed that more than one iteration step is necessary to get desired value of I_3.

If the method is used as a part of tuning of all controller parameters, unsignificant instability can be compensated by other parameter value changes.

V. Conclusions

The new derivative component tuning approach is presented in this paper. In simulation results, it proved the ability to obtain suitable derivative component parameter value that is very close to the optimal value. In actual state, the tuning rule does not reflect the presence of noise. The improvement reflecting the presence of noise is planed in future.

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