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Discussion on the short sightedness phenomenon of the conditioning technique

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Abstract: The article deals with anti-windup protection in constrained closed-loop control. In particular, it examines the conditioning technique, which is a commonly used anti-windup method, and the so-called short sightedness phenomenon. The study shows that the conditioning technique is an efficient anti-windup method and that the short sightedness phenomenon can also occur when using controllers without internal dynamics. The main conclusion of the discussion is that the short sightedness phenomenon is not related to the anti-windup protection and should be mitigated by other means.

Keywords: anti-windup, conditioning technique, short-sightedness, constrained control, PID control.

1. INTRODUCTION

Integral windup is a phenomenon when the controller output (usually due to the integrating (I) term of the controller) becomes excessively high when the controller output signal is constrained (e.g., the calculated controller output signal is higher than the signal fed to an actuator - a process). This usually happens during large reference (set-point) changes. Due to the constrained process input, the process output changes slower than in an unlimited case, and the control error is higher for longer time. The integral term (and other controller dynamic terms) accumulates higher control error and changes significantly (therefore the term "integrator windup"). Typical consequence of such constrained control action is the process output overshoot and/or long settling times of the process (Åström and Hägglund, 1995; Peng *et al*., 1996; Vrančić, 1997; Vrančić *et al*., 2001).

The integral windup phenomenon can be mitigated by applying an anti-windup (AW) protection (Åström and Hägglund, 1995; Hanus *et al*., 1987; Peng *et al*., 1998) which, in most cases, decrease the control error fed to the integral term when the controller signal is constrained (Vrančić *et al*., 2001). One of the AW techniques is the conditioning technique (Hanus *et al*., 1987) which has been very efficient in eliminating the windup phenomenon.

However, one of the reported disadvantages of the conditioning technique is its so-called "short-sightedness" (Walgama *et al*., 1992). Namely, some process overshoots may occur when using the conditioning technique and when the opposite (upper and lower) limitations occur. It is reported that this shortcoming in inherent in the conditioning technique (Walgama *et al*., 1992). The "short-sightedness" phenomenon of the conditioning technique was later on mentioned in several other papers (e.g., Chen and Perng, 1998, Hoo *et al*., 2015; Horla, 2011), where they cited the original paper by Walgama *et al*. (1992).

In the present discussion it will be demonstrated that the so called "short-sightedness" phenomenon has no direct relation to the applied AW protection.

2. THE INTEGRATOR WINDUP

Each control system in practice is limited, usually due to the actuators (valve cannot open more than 100% or less than 0%, motor has a limited speed, etc.). When a limitation occurs, the closed-loop starts to behave as an open-loop. If the controller has an integral term, the increased control error will cause exaggerated integral term output. Therefore, the integral term becomes too high or it "winds up" (Åström and Hägglund, 1995). The windup problem, therefore, exists due to the integral term of the controller (and/or some other controller terms with dynamics).

The windup phenomenon will be illustrated on the following second-order process:

$$G_P(s) = \frac{1}{(1+s)(1+0.02s)}. \tag{1}$$

The closed-loop control scheme without windup phenomenon is shown in Figure 1, where the P, the PI and the PID controller transfer functions, $G_C(s)$, are:

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$$P: G_C(s) = K_P$$
$$PI: G_C(s) = \frac{K_I + K_P s}{s},$$
$$PID: G_C(s) = \frac{K_I + K_P s + K_D s^2}{s(1 + sT_F)}, \tag{2}$$

where K_I, K_P, K_D and T_F are the integral gain, proportional gain, derivative gain and the controller filter time constant, respectively.

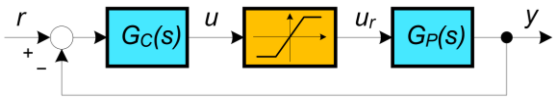

Fig. 1. The constrained closed-loop configuration with the controller and the process.

The orange block in Figure 1 represents the limitation of the signal u:

$$u_r = \begin{cases} U_{max} & u > U_{max} \\ u & U_{min} \leq u \leq U_{max} \\ U_{min} & u < U_{min} \end{cases} \tag{3}$$

Let us use the PI controller with the following parameters:

$$K_P = 50,\ K_I = 50. \tag{4}$$

If the process input signal (u_r) is not limited (U_{max}=∞, U_{min}=-∞), the process closed-loop responses are shown in Figure 2 (blue line). The closed-loop response has an overshoot below 20 % and a relatively short settling time. If the process input signal is restricted to (U_{max}=2, U_{min}=-∞), the closed-loop response changes, accordingly, as depicted by green broken line in Figure 2. We can see larger overshoot and much longer settling times after the process output reaches the set-point.

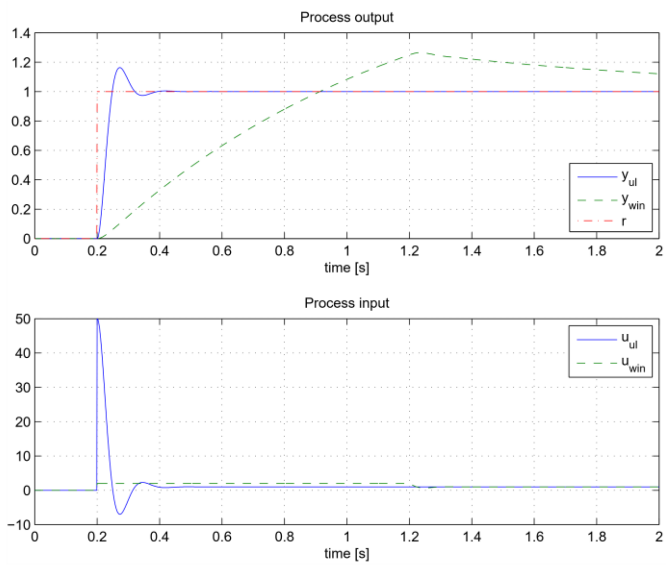

Fig. 2. The closed-loop process responses without limitations (blue line), and with limitations (green broken line).

3. THE CONDITIONING TECHNIQUE

As already mentioned, the conditioning technique (Hanus *et al.*, 1987) is a relatively successful method for eliminating windup phenomenon. The method main idea is an inventive block manipulation of the controller, where $G_C(s)$ in Fig. 1 is divided it into the static gain (K_0) and strictly proper dynamic part of the controller, $G_{FB}(s)$, as shown in Figure 3 (Hanus *et al.*, 1987; Vrančić, 1995; Huba *et al.*, 2020). Gain K_0 and dynamic part $G_{FB}(s)$ are calculated so as that realisations in Figs. 1 and 3 are equivalent in linear region (u_r=u)

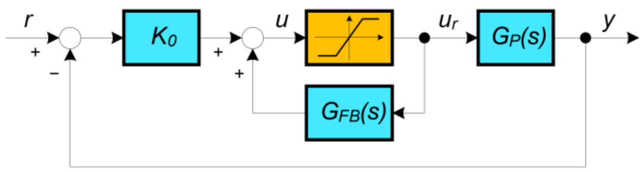

Fig. 3. The controller transfer function block manipulation according to the conditioning technique.

The realisation of the P, the PI, and the PID controllers with the conditioning technique (Fig. 3) is the following (note that the PIDA controller realisation is given in Huba *et al.*, 2020):

$$P: K_0 = K_P, \qquad G_{FB}(s) = 0$$
$$PI: K_0 = K_P, \qquad G_{FB}(s) = \frac{K_I}{K_I + K_P s},$$
$$PID: K_0 = \frac{K_D}{T_F}, \qquad G_{FB}(s) = \frac{K_I + s\left(K_P - \frac{K_D}{T_F}\right)}{K_I + K_P s + K_D s^2} \tag{5}$$

Remark 1: For non-strictly proper controller transfer functions, see possible practical realisations in Huba *et al.* (2020).

When using the conditioning technique (5), the limited closed-loop response is shown by red lines in Figure 4. The overshoot is smaller and the settling times are significantly reduced compared to the green broken line in Figure 2.

The closed-loop response seems to be good, but is it *optimal* in the sense of AW protection? The optimal AW protection is the one which does not “wind-up” the integral and/or the other dynamic terms of the controller. How can we be certain that the integral term or the other dynamic terms do not “wind-up” during constrained control? The answer is to use a controller without any integral and/or other dynamic terms. Such controller is proportional (P). Since it does not contain any dynamics, it cannot exhibit windup effect.

We can, therefore, find a P controller which gives the most similar unlimited responses to the applied PI controller (4) in Figures 2 and 4 (see blue lines). The problem in finding the appropriate P controller is twofold. First, since the P controller does not contain integral term, there is a control error in the steady-state. This can be solved by applying a modified reference (r_P) to the P controller:

$$r_P = \frac{1 + K_{PR}K_P}{K_{PR}K_P} r, \qquad (6)$$

so as that the final process output becomes equal to the reference (r). In expression (6) K_{PR} is the process steady-state gain (in our case K_{PR}=1), and K_P is the gain of the P controller. Second problem is to find such gain of the P controller which will make similar unlimited closed-loop responses. By trial and error, the following gain of the P controller is chosen:

$$K_P = 50. \qquad (7)$$

The closed-loop responses of the unlimited P controller are given by broken green lines in Figure 4. The responses are almost indistinguishable from the responses of the unlimited PI controller (see blue lines in Figure 4). Note that the magnified view of the process output closed-loop response from Fig. 4 is given in Fig. 5. Therefore, the chosen P controller is a good candidate to show us what should be the optimal response under limitations. When applying the same control limitations (U_{max}=2, U_{min}=-∞) as on the PI controller, the obtained closed-loop responses of the P controller are shown with broken cyan lines in Figure 4 (see the magnified view in Figure 5). It is obvious that the responses of the P controller, and the PI controller with conditioning technique AW protection (red lines in Figure 4) practically coincide. Therefore, the conditioning technique seems to give the optimal constrained closed-loop response by completely eliminating windup effect. Some other aspects why the conditioning technique is the most optimal AW solution are elaborated in Vrančić *et al.* (2001).

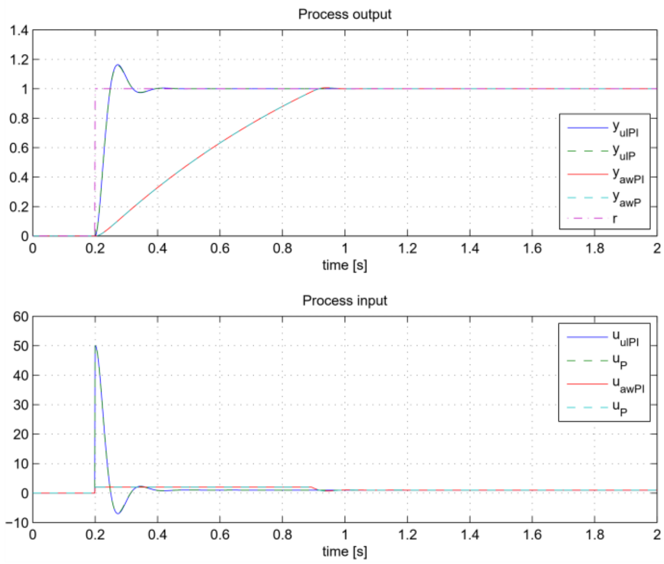

Fig. 4. The unlimited closed-loop responses (blue lines and green broken lines), and limited closed-loop responses with PI controller realised by Figure 3 (red line), and P controller (cyan broken line).

4. SHORT SIGHTEDNESS OF THE CONDITIONING TECHNIQUE

As already stated in introduction, one of the frequently stated disadvantages of the conditioning technique is the so called "short-sightedness", originally studied in Walgama *et al.* (1992) and later on mentioned by some other authors (usually citing the original paper).

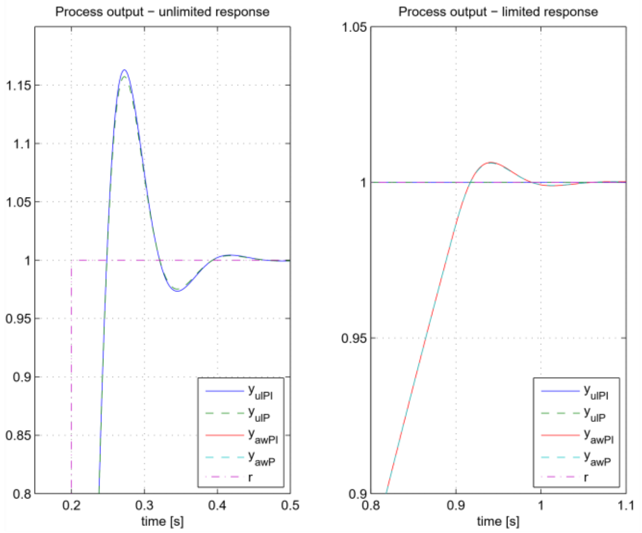

Fig. 5. The enlarged views of the process output closed-loop responses from Figure 4.

When the opposite (upper and lower) limitations are active during the constrained closed-loop control or the limitation happens some time interval after the set point changes, the conditioning technique, reportedly, "takes into account the present situation only, and under the implicit assumption that only one saturation level exists. The conditioning controller thus suffers from a 'short-sightedness' problem" (Walgama et al., 1992).

Let us illustrate such situation by using the control limitations U_{max}=40, U_{min}=-1. Using the same PI controller as before with the conditioning technique (5), the process closed-loop response is shown in Figure 6 (see red lines). It can be seen that the overshoot is now significantly larger than in the unlimited case (blue lines). However, practically the same response is obtained when using the P controller which *cannot exhibit* any windup phenomenon (see green broken lines). This means that the "short-sightedness" phenomenon cannot be related to the applied AW controller strategy.

5. CONCLUSIONS

The comparison of the constrained control of P and PI controller showed that the conditioning technique successfully eliminates the windup phenomenon and give the optimal AW responses under constraints.

The last experiment with double limitations showed that reported "short-sightedness" should not be related to the windup phenomenon or the applied AW strategy. The effect happens due to limitations in the closed-loop control and is present also when using controllers without dynamic terms. The phenomenon is similar to the closed-loop limit cycles when using high control gains in the constrained control loop, which can also appear when using P controller.

Therefore, the problem of “short sightedness” should not be mitigated by changing the AW strategy, but by preventing this phenomenon from happening in the first place. This can be done either by reducing the controller gains, applying adaptive filtering of the reference signal, or by using some other control strategies, like control of process moments instead of the process output (Vrančić *et al*., 2024).

In future research we are planning to investigate some new adaptive filtering strategies to reduce the “short sightedness” phenomenon.

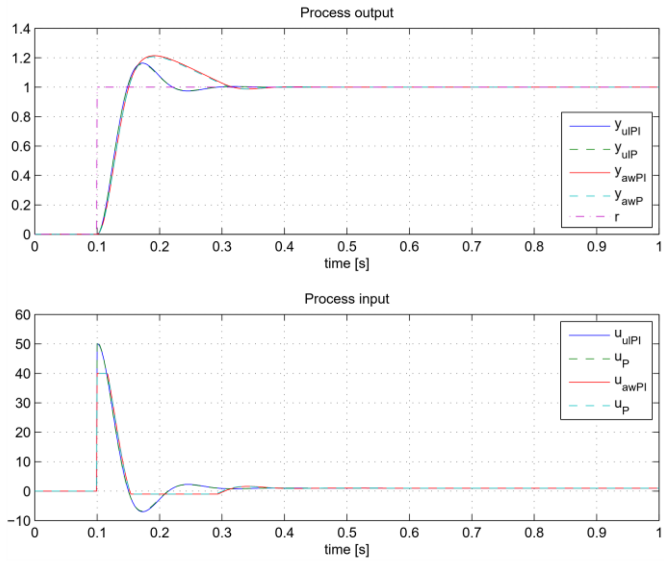

Fig. 6. The unlimited closed-loop responses (blue lines and green broken lines), and limited closed-loop responses with PI controller realised by Figure 3 (red line), and P controller (cyan broken line).

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