# ANTI-WINDUP DEAD-TIME COMPENSATION FOR STABLE AND INTEGRATIVE FIRST-ORDER DEAD-TIME PROCESSES

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**Abstract**— This work proposes an anti-windup structure for the filtered Smith predictor (FSP) which belongs to a class of dead-time compensators (DTCs). The proposed FSP structure does not use any extra tuning parameter due to the anti-windup characteristic. In addition stability analysis is presented based on describing function method to show robustness properties of the controller. Simulation results are used to compare the obtained solution with other anti-windup DTCs and a constrained model-based predictive controller (MPC). Experimental results on a neonatal intensive care unit are presented in order to shown the usefulness of the proposed controller.

**Keywords**— Dead-time compensator, actuator saturation, anti-windup, time delay systems.

## 1 Introduction

Dead-time compensators have been widely studied for about the past 25 years mainly due to the ability to improve the performance of classical PI and/or PID controllers when the process presents time delay between the input and output. The first DTC compensator was proposed in Smith (1957), also known in literature as the Smith predictor (SP), although its application is restricted to open-loop stable plants only, while the disturbance rejection response is dominated by the slow poles of the plant (Normey-Rico and Camacho, 2007). Since then several extensions have been proposed to improve robustness, disturbance rejection, and measurement noise attenuation. Some works intended to improve the SP robustness and disturbance rejection that includes stable and/or integrative dead time processes can be found in Astrom et al. (1994), Mataušek and Micić (1996), Mataušek and Micić (1999), Rao et al. (2007), Kaya (2003), Rao and Chidambaram (2008), Normey-Rico and Camacho (2008), Kirtania and Choudhury (2012). Nevertheless, the study of the effect of the measurement noise is less common. In García et al. (2006), Albertos and García (2009), García and Albertos (2008) is shown the noise effect in DTC structures using simulations. In Santos et al. (2010) an analysis and improvement of noise attenuation for stable, integrative and unstable dead-time processes using the filtered SP (FSP) were presented. However, the aforementioned works are not concerned with the actuator saturation, which is common in some practical applications and can cause windup problems due to the integral action of the primary controller. An applicable solution of the modified Smith predictor (Mataušek and Micić, 1996; Mataušek and Micić, 1999), with anti-windup was proposed in Mataušek and Ribić (2012), although an optimization procedure is necessary to define some desired robustness and noise sensitivity constraints. In Huba (2013) is presented a predictive disturbance observer based filtered PI control for first order plus dead time (FOPDT) processes and in Huba (2015) is analyzed the tuning for integrative plants with dead time based on robustness and performance criteria. Another alternative to deal with constraints lies in the use of model-based predictive controllers (MPCs) (Camacho and Bordons, 2004; Normey-Rico and Camacho, 2007), however, it is necessary to solve a constrained quadratic problem at each sampling time.

In a recent paper (Torrico et al., 2013), simple tuning rules were proposed for the FSP applied to the control of stable, integrative, and unstable first-order plus dead-time processes. The primary controller is free from integral action, differently from the traditional FSP, and ensures good trade-off among disturbance rejection, robustness, and noise attenuation. The results were better than those proposed by Santos et al. (2010). However, the anti-windup implementation has not been studied yet. In Huba and Tapak (2011) it was proposed an equivalent control structure to that of Torrico et al. (2013) with anti-windup action, however, the tuning is limited only for open-loop stable systems.

Within this context, this paper proposes an anti-windup structure for the FSP presented in Torrico et al. (2013). Simulation results are used to establish a fair comparison with other anti-windup DTC presented in Huba (2013), Zhang and Jiang (2008) and also a constrained MPC. Furthermore, in order to test the applicability of the proposed controller, an experiment was performed to control the temperature in a neonatal intensive care unit. The rest of the paper is organized as follows. Section 2 presents a review of the FSP. Section 3 presents the proposed anti-windup FSP structure. Section 4 presents simulation results. Section 5 presents experimental results. Finally, in Section 6 the conclusions of the paper are presented.

## 2 Review of the Filtered Smith Predictor (FSP)

The FSP control structure is depicted in Fig. 1, where $P_n(s) = G_n(s)e^{-L_n s}$ is the nominal process, $G_n(s)$ is the dead-time free model, $L_n$ is the nominal dead-time, and $P(s)$ represents the real process. The input-output transfer functions when $P_n(s) = P(s)$ are:

$$H_{yr}(s) = \frac{Y(s)}{R(s)} = \frac{P_n(s)F(s)C(s)}{1 + G_n(s)C(s)} \quad (1)$$

$$H_{yq}(s) = \frac{Y(s)}{Q(s)} = P_n(s)\left[1 - \frac{P_n(s)C(s)V(s)}{1 + G_n(s)C(s)}\right] \quad (2)$$

$$H_{un}(s) = \frac{-V(s)C(s)}{1 + G_n(s)C(s)} \quad (3)$$

where $U(s)$, $Y(s)$, $R(s)$, $N(s)$ and $Q(s)$ are the Laplace transform of the following signals: control action, process output, reference, measurement noise, and input load disturbance, respectively.

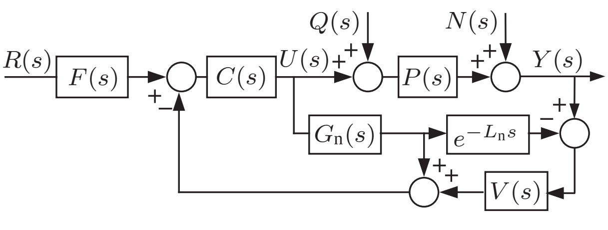


Figure 1: FSP conceptual structure.

In addition, the following condition is necessary for robust stability Normey-Rico and Camacho (2007):

$$I_{\rm r}(j\omega) = \frac{1 + G_{\rm n}(j\omega)C(j\omega)}{|\, G_{\rm n}(j\omega)C(j\omega)V(j\omega)\, |} > \overline{\delta P}(j\omega), \;\; \omega > 0, \quad (4)$$

where $\overline{\delta P}(j\omega)$ is the norm-bounded multiplicative uncertainty and $I_r(j\omega)$ is defined as robustness index.

It is worth to notice from Eq.(1) to (4) that $F(s)$ and $C(s)$ can be tuned in order to obtain a desired set-point tracking, while the filter $V(s)$ can be used to cancel the effect of slow or unstable poles in the disturbance rejection $H_{yq}(s)$ and to obtain a desired tradeoff between robustness and disturbance rejection.

In order to simplify the controller analysis, the FSP is represented in a two-degree of freedom (2DOF) form as shown in Fig. 2, where:

$$C_{eq}(s) = \frac{V(s)C(s)}{1 + G_n(s)C(s)\left(1 - V(s)e^{-L_n s}\right)} \quad (5)$$

$$F_{eq}(s) = \frac{F(s)}{V(s)}. \quad (6)$$

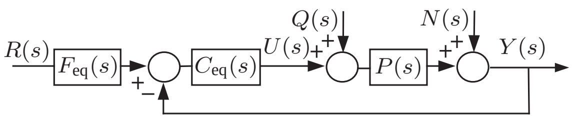


Figure 2: 2DOF structure.

Note that $C_{eq}(s)$ must have at least one pole at $s = 0$ in order to reject step-like disturbances, and the condition $F_{eq}(0) = 1$ to ensure the step set-point tracking.

For a first-order plus dead-time model defined as:

$$P_n = \frac{k\; e^{-L_n s}}{s - a_1},$$

the tuning of the simplified FSP (Normey-Rico and Camacho, 2008) can be summarized as follows. Define $C(s) = k_c$ as a simple gain, where $k_c$ is tuned in order to reach the desired reference tracking response. Then set $F(s) = k_r$, where $k_r$ can be tuned in order to achieve null steady-state error for step set-point, i.e:

$$k_r = \lim_{s \to 0} \frac{1 + k_c G_n(s)}{k_c G_n(s)}.$$

Additionally, consider:

$$V(s) = \frac{b_1 s + b_2}{(\alpha s + 1)^2}, \quad (7)$$

where $\alpha$ is used to establish an appropriate tradeoff between disturbance rejection speed and robustness. Parameters $b_2$ and $b_1$ are used to place a pole at $s = 0$ in $C_{eq}(s)$ and to cancel the pole $s = a_1$ in $H_{yq}(s)$ (equivalent to the cancellation of the zero $s = a_1$ in $C_{eq}(s)$) which can cause slow or unstable disturbance rejection response. This implies, from (2) and (5), for stable process ($a_1 < 0$) (Torrico et al., 2013):

$$\begin{cases} 1 + C(s)S(s)|_{s=0} = 0, \\ 1 + C(s)S(s)|_{s=a_1} = 0, \end{cases} \tag{8}$$

where $S(s) = [1 - V(s)e^{-L_n s}]G_n(s)$. Analogously for an integrative process ($a_1 = 0$), it gives:

$$\begin{cases} 1 + C(s)S(s)|_{s=0} = 0, \\ \frac{d}{ds}\left(1 + C(s)S(s)\right)\big|_{s=0} = 0. \end{cases} \tag{9}$$

Note that a linear system with two equations and two variables $b_1$ and $b_2$ can be obtained from Eqs. (8) or (9), whose solution leads to:

$$b_1 = \frac{(\alpha a_1 + 1)^2}{a_1 e^{-L_n a_1}} - \frac{b_2}{a_1},\ b_2 = k_r$$

and

$$b_1 = \frac{1}{k_c} + L_n + 2\alpha,\ b_2 = k_r,$$

respectively.

It is worth to mention that if it is desired to reject higher order disturbances and/or to follow higher order references (ramps, parabolas, etc.) then higher order filters and controllers must be applied (Torrico and Normey-Rico, 2005).

## 3 Proposed anti-windup FSP

This section presents the proposed anti-windup control FSP structure and stability analysis by applying the describing function method.

### *3.1 Control Structure*

The proposed anti-windup FSP is illustrated in Fig. 3. Such structure is based on a well established anti-windup compensator (Zaccarian and Teel, 2011) and (Galeani et al., 2009), where $C_{AW}(s)$ is the anti-windup compensator. The controller parameters $k_c$, $k_r$, and $V(s)$ can be designed as in Section 2 in order to obtain stable closed-loop response for the system with no saturation. In addition, it can be seen that the compensator includes the input saturation model which is defined as:

$$\tilde{u}(t) = \begin{cases} u_{\mathrm{u}} & \text{if } u(t) > u_{\mathrm{u}} \\ u(t) & \text{if } u_{\mathrm{l}} \le u(t) \le u_{\mathrm{u}} \\ u_{\mathrm{l}} & \text{if } u(t) < u_{\mathrm{l}} \end{cases} \tag{10}$$

where $u_{\mathrm{l}}$ and $u_{\mathrm{u}}$ are the lower and upper limits of $\tilde{u}(t)$, respectively.

Note that, for a step-like references, $e(t)$ goes to zero at steady state if saturation is not considered because $k_c S(0) = -1$. Nevertheless, under input saturation, $e(t)$ is almost constant or with slower dynamics, thus, if it is not used an anti-windup compensator ($C_{AW}(s) = 0$) then $u(t)$ can grow up, partially due to integral action, until the signal of $e(t)$ changes. This phenomena is known as windup and can cause undesired overshoot, sustained oscillations or even lead to instability (Turner and Bates, 2007; Kothare et al., 1994). This problem can be mitigated using the anti-windup compensator $C_{AW}(s)$ which can be tuned in order to reduce the control growing rate.

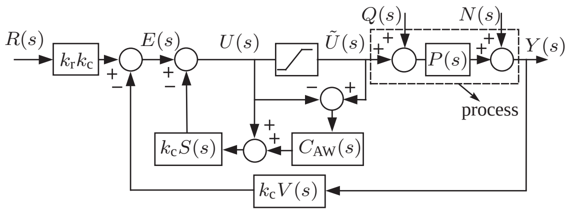


Figure 3: Proposed anti-windup FSP.

From Fig. 3 it can be seen that under saturation the control signal is given by:

$$U(s) = E(s) - k_c S(s)[U(s) + C_{AW}(s)\ \delta U(s)]. \tag{11}$$

where $\delta U(s) = \tilde{U}(s) - U(s)$.

Notice that $C_{AW}(s)\ \delta U(s)$ in Eq. (11) is different to zero under saturation. $C_{AW}(s)$ is designed in order to reduce the difference between the control signal $u(t)$ and the saturated signal $\tilde{u}(t)$ (Zaccarian et al., 2005).

In this work, in order to maintain the tuning simplicity of the original FSP controller, the anti-windup compensator is fixed as $C_{AW}(s) = 1$. Thus, Eq. (11) can be written as:

$$U(s) = E(s) - k_c S(s)\tilde{U}(s), \tag{12}$$

Eq. (12) states that $U(s)$ depends on $S(s)$. Therefore, $V(s)$ can be tuned reduce $\delta U(s)$, and improve anti-windup properties of the proposed control scheme.

It is important to notice that this anti-windup control structure cannot be used in traditional FSP. This is because of in the FSP design (Normey-Rico and Camacho, 2007) a PI controller is used instead of the static gain $k_c$. From Eq. (12) can be seen that integral action will be associated with the saturated control increasing the difference between $u(t)$ and $\tilde{u}(t)$.

### *3.2 Closed-loop stability analysis*

This section presents the stability analysis for the case of null external disturbances ($Q(s) = 0$ and $N(s) = 0$) using the describing function method (DFM) (Khalil, 2002). The DFM was originally proposed in order to find limit cycles for strictly proper and Hurwitz models (Glattfelder and Schaufelberger, 2003). Time delay between the input an output also can be accepted. Although the DFM does not proves absolute stability, because is based on approximations, it is widely used in practical control problems. Some cases where the DFM is not accurate are described in Slotine and Li (1991).

In Zhang and Jiang (2008) is stated that the DFM can also be applied in the case of dead-time compensators for integrative processes. However, it is important to assure that $M(s)$ has low pass characteristics in order to attenuate high frequency harmonics and improve the accuracy of the method. Observe that in this work $M(s)$ attenuates high frequencies because of $\lim_{\omega \to \infty} |M(j\omega)| = 0$. The accuracy of the DFM will be verified in next section by simulation examples.

The DFM consists of approximating the input-output relationship of the static nonlinear time invariant element by:

$$\phi = \frac{X_2 \angle \theta}{X_1}, \tag{13}$$

where $X_2 \angle \theta$ is the Fourier series first harmonic of the output when a sinusoidal input $X_1 = A_1 \sin(\omega t)$ is applied to the input of the nonlinear element. The describing function of the saturation non-linearity is given by Khalil (2002):

$$\phi = \frac{2}{\pi} \left[ \sin^{-1}\left(\frac{A_s}{X_1}\right) + \frac{A_s}{X_1}\sqrt{1 - \left(\frac{A_s}{X_1}\right)^2} \right],$$

where $A_s$ is the saturation amplitude.

The proposed control structure in Fig. 3 can be represented in a simplified form as illustrated in Fig. 4. It can be assumed, without loss of generality, that $R(s) = 0$. Observe that if the saturation is approximated by the describing function then the characteristic equation of the system is given by:

$$1 + \phi M(s) = 0, \tag{14}$$

where $M(s) = k_c(P(s)V(s) + S(s))$. Eq. 14 can be written as

$$M(s) = -\frac{1}{\phi}. \tag{15}$$

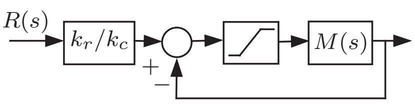


Figure 4: Equivalent closed loop representation.

Note that if $M(s)$ has no poles in the open right-half-plane, the Nyquist stability criterion can be extended as follows. The closed-loop system is stable if the Nyquist plot of $M(s)$ does not encircle or intersects the locus of $-\frac{1}{\phi}$. As shown in Ionescu et al. (2008), the locus of $-\frac{1}{\phi}$ is a half-line that varies from $-1$ to $-\infty$ along the real axis. In addition, if the Nyquist plot of $M(s)$ does not encircle the point $-1$ and $P(s)$ has low pass characteristics, then $-\frac{1}{\phi}$ will not intersect the Nyquist plot of $M(s)$. In this case, linear methods can be used for stability and robustness analysis (Ionescu et al., 2008).

## 4 Simulation Results

This section presents two simulation case studies using the integrative plants presented in Huba (2015) and Zhang and Jiang (2008). The considered controllers were evaluated under input saturation, dead-time uncertainties, input disturbances, and step reference variations.

### *4.1 Example 1*

This example presents comparative simulation results obtained with the following three controllers: an input constrained MPC (Camacho and Bordons, 2004), the controller reported in Zhang and Jiang (2008), and the proposed FSP. For this purpose, the following process model presented in Zhang and Jiang (2008) is considered:

$$P(s) = \frac{e^{-5s}}{s}.$$

The input limits are $u_l = -1$ and $u_u = 1$. Ther parameters of the Zhang and Jiang (2008) controller are defined in the paper. The MPC uses the following model to compute the predictions:

$$(1-q^{-1})y(t) = 0.1u(t-1-d) + \frac{(1-\beta q^{-1})^2}{(1-q^{-1})} e_n(t), \tag{16}$$

where $q^{-1}$ is the backward shift operator, $\beta = e^{-T/2.4}$, $d = L_n/T$, $T = 0.2$ s is the sampling time, and $e_n(t)$ is a white noise. The MPC tuning parameters are: the limits of the prediction windows $N_1 = d + 1$, $N_2 = d + 100$, the control horizon $N_u = 70$, and the control weights defined as $\lambda_1 = 0$ and $\lambda_i = 250$, $i = 2, \ldots, N_u$. The MPC was tuned in order to present a step response quite similar to Zhang and Jiang (2008) controller in the nominal case without input saturation.

For the FSP controller two different tunings are considered. The first one, named $\text{FSP}_1$, aims a step response close to the one observed for the MPC. Thus, the $\text{FSP}_1$ controller is given by:

$$k_r = 1.0,\ k_c = 0.4167, \text{ and } V(s) = \frac{12.2s + 1}{(2.4s + 1)^2}.$$

On the other hand, the second one ($\text{FSP}_2$) was tuned aiming an improved disturbance rejection under input saturation, leading to the following parameters:

$$k_r = 1.0,\ k_c = 0.2, \text{ and } V(s) = \frac{12.8s + 1}{(1.4s + 1)^2}.$$

In addition, in order to better assess the effectiveness of the anti-windup scheme, it was implemented the $FSP_1$ without anti-windup action, named $FSP_3$.

Fig. 5 illustrates the plot of $-1/\phi$ and the Nyquist plot of $M(s)$ using Zhang and Jiang (2008), and the proposed FSP controllers for the model delay $L_n = 5$ and the process delay $L = 6$. In addition, the minimum distance between the critical point $-1$ and the Nyquist plot of the controllers has been measured, which results in $R_{\text{Zhang and Jiang}} = 0.18$, $R_{FSP_1} = 0.38$, and $R_{FSP_2} = 0.22$.

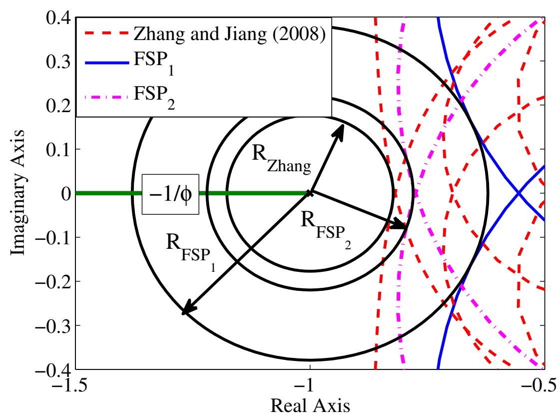


Figure 5: Plot of $-1/\phi$ and Nyquist of Zhang and Jiang (2008) and FSP for $L_n = 5$ and $L = 6$.

It is important to notice that the minimum distance must be maximized in order to increase the controller robustness. Therefore, by looking at the respective radius presented in Fig. 5, the proposed anti-windup FSP controllers exhibits a larger discus, which means an increased robustness when compared to the Zhang and Jiang (2008) controller. The MPC controller analysis was not included because the control action is computed using constrained quadratic programming algorithms.

Figs. 6 and 7 show the simulation results for a step reference. An input disturbance pulse with amplitude of $-1.5$ was applied from $t = 40$ s to $t = 50$ s. A step input disturbances with amplitude of $-0.5$ was applied at $t = 100$ s.

Fig. 6 shows the simulation results without uncertainties. As can be observed all the anti-windup controllers follow the reference in a similar way. As expected, the $FSP_3$ response has an overshoot which is close to 20%.

On the other hand, in the case of both input pulse disturbance and input saturation, the proposed $FSP_2$ controller is the only one which does not present undesired peaks. For the step input disturbance the control action is not saturated and the performance of all controllers are nearly the same. It is worth to mention that the predictor of the FSP can be interpreted as an observer. Then, a smaller time constant of $V(s)$ speeds up the prediction. For the proposed $FSP_2$ it can be observed that the time constant of $V(s)$ is smaller than the $FSP_1$, which means lower robustness, however, this fact can be compensated using lower values of $k_c$.

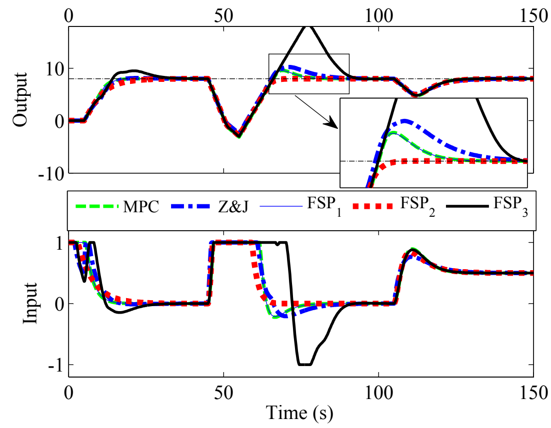


Figure 6: Simulation results (no uncertainties), Z&J is Zhang and Jiang (2008).

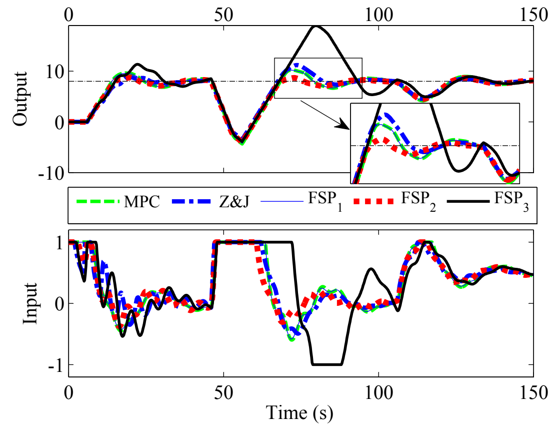


Figure 7: Simulation results (10% dead-time uncertainty), Z&J is Zhang and Jiang (2008).

Fig. 7 shows simulation results using +20% dead-time uncertainty. It can be seen that the proposed $FSP_2$ is still the best. It is important to highlight that the proposed FSP achieves similar or better performance than a MPC, which is a more complex controller.

In order to show the effectiveness of the DFM, the dead-time uncertainty was fixed at +20% and the gain uncertainty was increased until the Nyquist plot is in the neighborhood of $-1$ considering two cases. In case 1 the gain uncertainty was increased so that the distance between the critical point $-1$ and the Nyquist plot is close to $R_{FSP} \simeq 0.04$. In case 2 the gain uncertainty was increased until the Nyquist plot reaches $-1/\phi$. Figs. 8 and 9 show the output response and Nyquist plot considering the two cases for $FSP_1$ and $FSP_2$ controllers, respectively. Both figures show the DFM reliability on determining the system stability. As expected, in case 1, the output converges to the reference and in case 2, the output presents sustained oscillations.

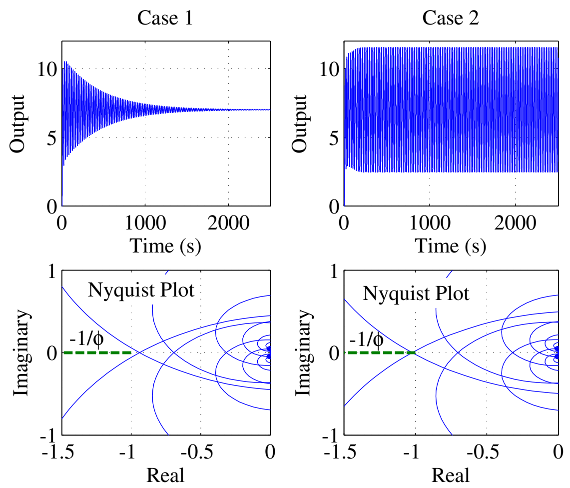


Figure 8: Output response and Nyquist plot for $FSP_1$.

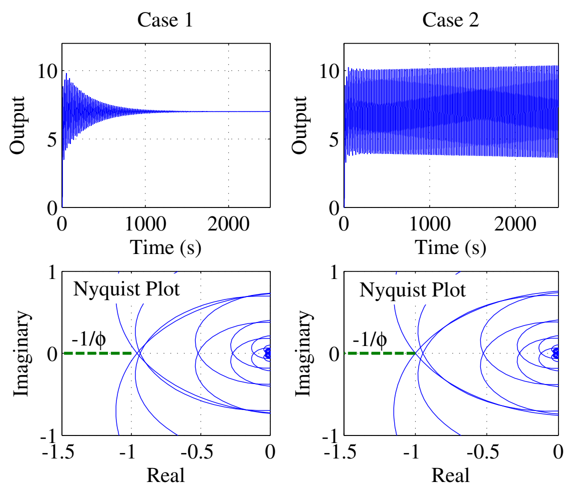


Figure 9: Output response and Nyquist plot for $FSP_2$.

### *4.2 Example 2*

This example compares the proposed FSP with the controller proposed in Huba (2015). In order to maintain the original controller design, the plant model and controller of the paper are used. The plant model is:

$$P(s) = \frac{e^{-Ls}}{s}, \quad L \in [0.91, 1],$$

the Huba controller parameters are $T_n = 0.1696, K_p = 0.3322$, and $n = 2$. The control signal is limited by $u_l = -2$ and $u_u = 2$. The FSP was tuned using the nominal model:

$$P_n(s) = \frac{e^{-0.955s}}{s},$$

leading to the tuning parameters:

$$k_r = 1, \; k_c = \frac{1}{2.4}, \; \text{and} \; V(s) = \frac{12.2s + 1}{(2.4s + 1)^2}.$$

Simulation results are shown in Fig. 10 for $L = 1$. A sequence of two step references were applied at $t = 0$ s and $t = 10$ s. In addition, input disturbances were applied, first between 24 s and 41 s with amplitude of $-1.5$, followed by another one from 41 s to 43 s with amplitude of $-3$. The FSP controller was tuned to obtain disturbance rejection response slightly better than that of the Huba (2015) controller in the nominal case. Note that the proposed FSP controller exhibits better disturbance rejection for the second disturbance.

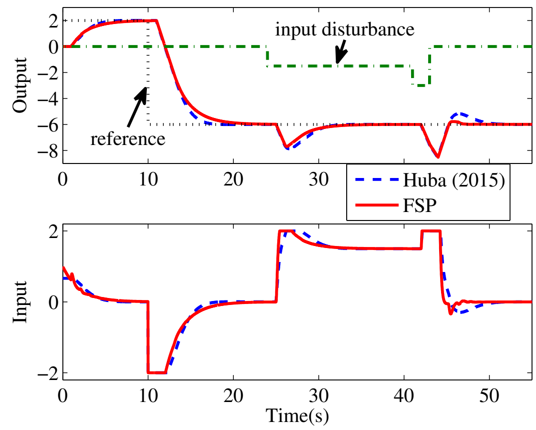


Figure 10: Simulation results: Proposed FSP x Huba.

## 5 Experimental Results

To show the usefulness of the proposed anti-windup FSP, the temperature control of a neonatal intensive care unit (NICU), depicted in Fig. 5, is presented. The plant model was obtained using a step-test identification procedure (Normey-Rico and Camacho, 2007) and is given by:

$$P(s) = \frac{0.169e^{-7.8s}}{60s + 1},$$

where the time is measured in minutes and the control is within the range from 0 to 100 %.

The control parameters were set as $k_c = 76$ and $k_r = 1.078$. The filter $V(s)$ with $b_1 = 10.66$, $b_2 = 1.078$ and $\alpha = 3$ was used to increase the system robustness with a properly measurement noise attenuation. It is important to notice that with this controller the nominal desired closed

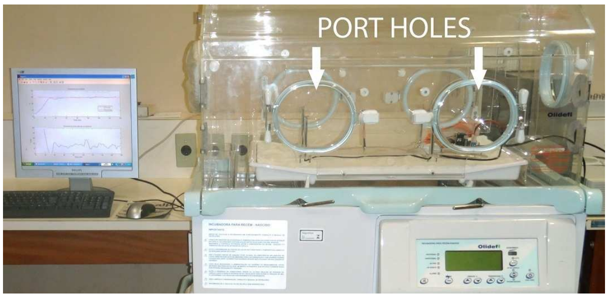


Figure 11: Picture of the neonatal intensive care unit.

loop transfer function is:

$$H_{yr}(s) = \frac{e^{-7.8s}}{4.3s+1}. \quad (17)$$

Thus, the closed-loop time constant is nearly 14 times smaller than the open-loop one. With a conventional PID controller it is not possible to obtain the same improvement as the one obtained with FSP.

Experimental results using the proposed controller are shown in Fig. 12. The temperature set-point is $30^oC$. Observe that, as expected, the settling time is close to 30 min with small oscillation, showing an undershoot of $0.5^oC$ due to unmodelled dynamics.

Besides, the plant input became saturated during the first 20 min and the controller did not show windup issues.

According to the nominal desired closed loop transfer function, the expected settling time free from input saturation is 20.7 min (5% criteria). However, due to the input saturation, the observed response in Fig. 12 has a settling time of approximately 30 min.

In order to assess the controller robustness, the front port holes of the NICU were opened between $t = 100$ min and $t = 105$ min. In this case, an undershoot of $0.3^oC$ occurred and the set-point was achieved once again within 12 min.

## 6 Conclusion

An anti-windup design for the FSP applied to control stable and integrative plants has been presented. The proposed controller includes an input saturation model in its structure and maintains the tuning simplicity of a conventional FSP. In a case of dead-time integrative plants and when input saturation occurs, it was shown that disturbance rejection response of the proposed FSP can be improved if compared to another anti-windup DTC schemes previously proposed in the literature.

The developed experiment effectively assures that the proposed controller does not present windup issues, while keeps the good performance of a conventional FSP. Due to its inherent simplicity, the proposed scheme is supposed to present great potential if implemented in commercial applications.

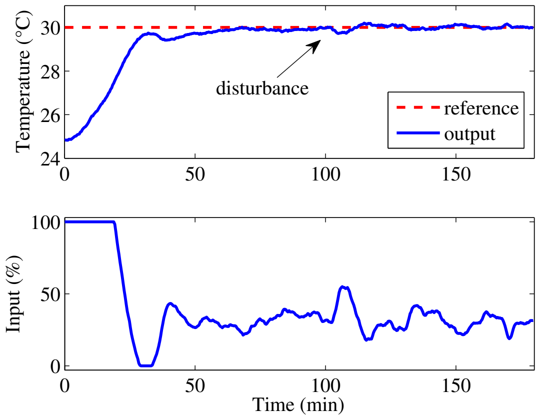


Figure 12: Experimental results: Temperature control of a NICU.

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