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Research article

Tuning of a dead-time compensator focusing on industrial processes

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HIGHLIGHTS

- This paper presents new tuning rules of the robustness filter for DTCs.
- The technique is able to deal with stable, integrative and unstable process.
- Frequency domain analysis of robustness and noise attenuation characteristics.
- Tuning focusing on industrial processes.

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ABSTRACT

This paper proposes tuning rules for the Simplified Dead-Time Compensator (SDTC), which is intended to deal with stable, unstable and integrative dead-time processes. The main contribution is the proposal of new guidelines for the tuning of the robustness filter. The new set of rules allow for the use of lower order filters which are able to simultaneously account for closed-loop robustness and noise attenuation. Through illustrative examples, it is shown that the proposed approach provides enhanced disturbance rejection and noise attenuation in the control of industrial processes when compared with other recently published works. Furthermore, the internal temperature of an in-house thermal chamber is controlled to evaluate the applicability of the strategy on real processes.

1. Introduction

Dead-time appears in a wide range of industrial processes involving delayed transportation of energy, mass, information or other processes containing time-lag associated dynamics. Although classical controllers such as proportional–integral (PI) and proportional–integral–derivative (PID) may be used when dead-time is relatively small [1–3], their performance is usually degraded for long time-delay systems. Such misfortune can lead to closed-loop instability due to an unwanted extra decrease in the system phase [4]. One solution to this problem consists of using dead-time compensators (DTCs) [5].

The first DTC strategy was proposed in 1957, known as the Smith Predictor (SP) [6]. Although initially proposed as an improvement over classical PI or PID controllers, it presents limitations regarding robustness and disturbance rejection. In addition, it could not be used to control open loop unstable or integrative processes. Throughout the last decades many modifications have been proposed to overcome these drawbacks. Most of the solutions are intended for processes modeled by first order plus dead time (FOPDT) or second order plus dead time (SOPDT) systems, which are commonly found in industry [7–10]. A wide review of these solutions is found in [4].

Some of the most recent advances in DTCs are reviewed in this paragraph. In [11], a unified approach to deal with robustness was presented. In [12], a two-degree-of-freedom (2DOF) design method was proposed based on optimal control and desired disturbance rejection specifications. Several examples showed enhanced performance and robustness when compared to previous works. In [13], a generalized DTC was presented in order to optimize set-point tracking and disturbance rejection. The structure is based on both an undelayed output prediction and a 2DOF control structure. Although these recent works present good robustness and disturbance rejection, the problem of measurement noise (mainly in unstable processes) is not properly handled.

1.1. About the noise attenuation problem

Noise is commonly found in industrial processes and may cause regulatory performance degradation and increase undesired control signal variation. In [14] a design method for the Filtered SP

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Nomenclature

β	Robustness-tuning parameter
ω	Angular frequency
σ	Robustness-free parameters
τ_p	Unstable pole time constant
τ_u	Integrator pole time constant
d_n	Discrete time delay
F_1, F_2	FIR filters
G_n	Nominal process fast model
H_{un}	Transfer function from measurement noise to control signal
H_{yq}	Transfer function from the disturbance to the output signal
H_{yr}	Transfer function from the reference to the output signal
I_r	Robustness index
K_r	Reference filter
L_n	Nominal time delay
N	Measurement noise
n	Order of the delay-free process model
P	Real process
p_i	Poles of the process model
P_n	Nominal process model
Q	Input load disturbance
R	Reference
r_i	Poles of the desired characteristic polynomial
s_i	Coefficients of the desired characteristic polynomial
T_s	Sampling time
U	Control action
V	Robustness filter
$v_0 \dots v_n$	Robustness filter coefficients computed to attend the design requirements
Y	Process output

(FSP) robustness filter was proposed in order to improve noise attenuation. In [15] a simpler solution compared to [14] was presented with better robustness, disturbance rejection and noise attenuation. In addition, controller tuning rules were proposed for FOPDT processes. In [8] and [16] control impairment caused by measurement noise is mitigated by the addition of filters, which increases the order of the equivalent controller. In [17], the DTC from [15] was generalized for multiple delay systems, namely SDTC (Simplified DTC). Despite good results on noise attenuation, no further analysis was presented in order to improve disturbance rejection properties.

1.2. Contribution

This work introduces a new tuning method that simultaneously accounts for closed-loop robustness and noise attenuation for stable, unstable and integrative dead-time processes. It is shown that lower order filters are suitable to satisfy design specifications and provide enhanced performance when compared to more complex controllers from recent literature. In case stronger noise attenuation is required, the method allows to monotonically tune the robustness filter while maintaining desired performance characteristics. More specifically:

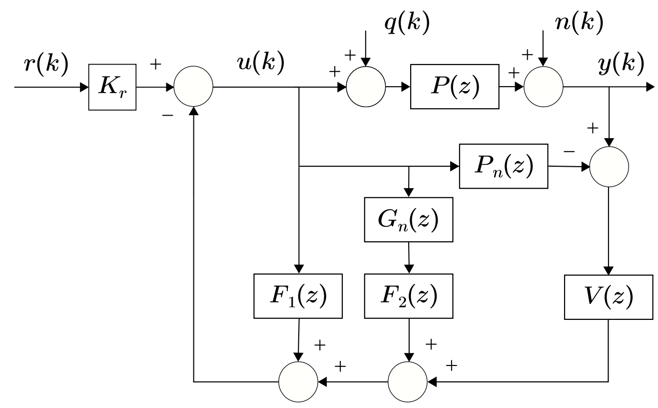

Fig. 1. SDTC conceptual structure.

- Three different robustness filters are presented. One to deal with FOPDT processes and two which can be tuned for SOPDT industrial processes.
- Each filter presents two adjustment parameters that allow disturbance rejection and noise attenuation to be individually tuned to meet a desired trade-off, while frequency domain analysis of such characteristics is presented.
- Such nice decomposition is achieved by using different poles in the robustness filter $V(z)$ instead of the traditional design of DTCs which employs multiple repeated poles.

2. Simplified dead-time compensator (SDTC)

This section presents a review of the SDTC from [17] for the case of single-delay SISO systems. The control structure is illustrated in Fig. 1, where $P_n(z) = G_n(z)z^{-d_n}$ is the nominal process model, $G_n(z)$ is the nominal process fast model, d_n is the nominal dead-time, $P(z)$ represents the real process, K_r is a constant, $F_1(z)$ and $F_2(z)$ are finite impulse response (FIR) filters and $V(z)$ is the robustness filter. In order to analyze controller properties the input–output relationships and the condition for robust stability are calculated for the nominal case ($P(z) = P_n(z)$)

$$H_{yr}(z) = \frac{Y(z)}{R(z)} = \frac{K_r P_n(z)}{1 + F_1(z) + G_n(z)F_2(z)}, \tag{1}$$

$$H_{yq}(z) = \frac{Y(z)}{Q(z)} = P_n(z)\left[1 - \frac{P_n(z)V(z)}{1 + F_1(z) + G_n(z)F_2(z)}\right], \tag{2}$$

$$H_{un}(z) = \frac{U(z)}{N(z)} = \frac{-V(z)}{1 + F_1(z) + G_n(z)F_2(z)}, \tag{3}$$

$$I_r(\omega) = \left|\frac{1 + F_1(z) + G_n(z)F_2(z)}{G_n(z)V(z)}\right|_{z=e^{j\omega T_s}} > \overline{\delta P}(e^{j\omega T_s}), \tag{4}$$

where $U(z)$, $Y(z)$, $R(z)$, $N(z)$ and $Q(z)$ are the Z-transform of the following signals: control action, process output, reference, measurement noise, and input load disturbance, respectively; $H_{yr}(z)$, $H_{yq}(z)$, and $H_{un}(z)$ are the input–output transfer functions of the closed loop in Fig. 1; $I_r(\omega)$ is defined as robustness index, T_s is the sampling time (with $0 < \omega < \pi/T_s$) and $\overline{\delta P}(e^{j\omega T_s})$ is the upper bound of the multiplicative uncertainty norm.

It is worth to note from (1) that K_r, $F_1(z)$ and $F_2(z)$ can be tuned in order to obtain a desired set-point tracking. From (2), (3), and (4), it can be seen that filter $V(z)$ can be used to cancel the effect of slow or unstable poles in the disturbance rejection $H_{yq}(z)$, to attenuate the effect of measurement noise, and/or to obtain a desired robustness index $I_r(\omega)$.

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2.1. Tuning of K_r, $F_1(z)$ and $F_2(z)$

The tuning of the primary controller, which is defined by K_r, $F_1(z)$, and $F_2(z)$ is realized in order to obtain a desired set-point tracking for the nominal case. For this, consider $F_1(z)$ and $F_2(z)$ as FIR filters

$$F_1(z) = f_{1_1}z^{-1} + f_{1_2}z^{-2} + \cdots + f_{1_{n-1}}z^{-n+1}, \tag{5}$$

$$F_2(z) = f_{2_0} + f_{2_1}z^{-1} + f_{2_2}z^{-2} + \cdots + f_{2_{n-1}}z^{-n+1}, \tag{6}$$

where n is the order of the delay-free process model $G_n(z)$. The coefficients of $F_1(z)$ and $F_2(z)$ are calculated using pole placement by comparing the denominator of (1) to a desired closed-loop reference model. In order to find the coefficients of $F_1(z)$ and $F_2(z)$, one must solve an equation of the type $\Phi x = y$, with

$$\Phi = \underbrace{\begin{bmatrix} 1 & 0 & \dots & 0 \\ a_1 & 1 & & \vdots \\ \vdots & a_1 & & 0 \\ a_n & \vdots & & 1 \\ 0 & a_n & & a_1 \\ 0 & 0 & & a_n \end{bmatrix}}_{n-1}\underbrace{\begin{bmatrix} b_1 & \dots & 0 \\ b_2 & & \vdots \\ \vdots & & 0 \\ b_n & & b_1 \\ 0 & & \vdots \\ 0 & & b_n \end{bmatrix}}_{n}, \quad x = \begin{bmatrix} f_{1_1} \\ \vdots \\ f_{1_{n-1}} \\ f_{2_0} \\ \vdots \\ f_{2_{n-1}} \end{bmatrix}, \text{ and}$$

$$y = \begin{bmatrix} s_1 - a_1 \\ \vdots \\ s_n - a_n \\ s_{n+1} \\ \vdots \\ s_{2n-1} \end{bmatrix}, \tag{7}$$

where Φ is a non-singular $2n-1$ square matrix, $a_1 \dots a_n$ and $b_1 \dots b_n$ are the coefficients of

$$G_n(z) = \frac{b_1 z^{-1} + b_2 z^{-2} \dots b_n z^{-n}}{1 + a_1 z^{-1} + a_2 z^{-2} \dots a_n z^{-n}}, \tag{8}$$

and $s_1 \dots s_{2n-1}$ are the coefficients of the desired characteristic polynomial

$$\begin{aligned} &1 + s_1 z^{-1} + s_2 z^{-2} \dots s_{2n-1} z^{-2n+1} \\ &\quad = (1 - r_1 z^{-1})(1 - r_2 z^{-1}) \dots (1 - r_{2n-1} z^{-1}). \end{aligned} \tag{9}$$

Therefore, closed-loop poles $r_1 \dots r_{2n-1}$, with $0 \le r_i < 1$, are chosen in order to tune set-tracking point response. For example, if a faster set-point is desired, than smaller values of r_i can be chosen, and *vice-versa*.

Note that in the case of FOPDT systems $F_1(z) = 0$ and $F_2(z) = f_{2_0}$, thus the control structure reduces to the one presented in [15]. K_r is a gain calculated to yield zero steady-state error, then it follows that

$$K_r = \frac{1 + F_1(1) + G_n(1)F_2(1)}{P_n(1)}. \tag{10}$$

2.2. Tuning of the robustness filter $V(z)$

The SDTC robustness filter is defined as

$$V(z) = \frac{v_0 + v_1 z^{-1} + \cdots + v_n z^{-n}}{(1 - \beta z^{-1})^{n+1}}, \tag{11}$$

where $v_0 \dots v_n$ are the filter coefficients computed to attend the design requirements and β is a user tuning parameter. The first design requirement is to guarantee rejection of input step-like disturbances in order to assure reference tracking at steady-state. Therefore (2) must equal zero for $z = 1$, leading to

$$V(1) = \frac{1 + F_1(1) + G_n(1)F_2(1)}{P_n(1)} = K_r. \tag{12}$$

Secondly, the filter is tuned to eliminate slow or unstable modes of the plant model $P_n(z)$ which could appear in the disturbance rejection response (2). Consider that p_i are the poles of the process model to be canceled, then the following equations must be satisfied

$$\left[1 - \frac{P_n(z)V(z)}{1 + F_1(z) + G_n(z)F_2(z)}\right]_{z=p_i \neq 1} = 0, \tag{13}$$

$$\frac{d}{dz}\left[1 - \frac{P_n(z)V(z)}{1 + F_1(z) + G_n(z)F_2(z)}\right]_{z=p_i=1} = 0, \tag{14}$$

$i = 1, \dots, n$

where n is the number of undesired poles, generating a set of $n+1$ equations derived from (12), (13), and (14) to calculate robustness filter coefficients $v_0 \dots v_n$. In case it is desired to reject higher order disturbances and/or to follow higher order references (ramps, parabolas, etc.), higher order filters and controllers must be applied [18].

3. Proposed tuning rules for the robustness filter

In order to analyze the tuning of $V(z)$, consider the following four equations derived from (1)–(4)

$$H_{yr}(\omega) = \mid K_r M(z) \mid_{z=e^{j\omega T_s}}, \tag{15}$$

$$H_{yq}(\omega) = \mid G_n(z)\left[1 - M(z)V(z)\right] \mid_{z=e^{j\omega T_s}}, \tag{16}$$

$$H_{un}(\omega) = \left|\frac{V(z)M(z)}{G_n(z)}\right|_{z=e^{j\omega T_s}}, \tag{17}$$

$$I_r(\omega) = \frac{1}{\mid M(e^{j\omega T_s})V(e^{j\omega T_s}) \mid} > \overline{\delta P}(e^{j\omega T_s}), \tag{18}$$

where

$$\begin{aligned} M(z) &= \frac{N_g(z)}{D_g(z)(1 + F_1(z)) + N_g(z)F_2(z)} z^{-d_n} \\ &= \frac{N_g(z)}{(1 - r_1 z^{-1})(1 - r_2 z^{-1}) \dots (1 - r_{2n-1} z^{-1})} z^{-d_n} \end{aligned}$$

with $G_n(z) = N_g(z)/D_g(z)$. Note that the zeros of $M(z)$ are equal to the zeros of the process model while the poles of $M(z)$ are the user defined closed-loop poles for set-point tracking response, thus it can be observed that in industrial processes $M(z)$ has low pass characteristics.

3.1. Analysis of the robustness filter effect

3.1.1. Disturbance rejection

One can see from (16) that it is highly desired that $H_{yq}(\omega)$ approaches to zero for the frequency range $0 < \omega < \pi/T_s$. Unfortunately, it is easy to check that such objective cannot be met at high frequencies ($\omega \to \pi/T_s$) as $M(z)V(z)$ from (16) has low pass characteristics. An alternative to deal with this problem is to raise the robustness filter $V(z)$ gain at high frequencies by reducing its number of poles.

3.1.2. Noise attenuation

For industrial applications, it is important that the control signal be the least affected by noise measurement as possible. Noise amplification can be responsible for undesired nonlinearities in the control loop, such as saturation. Measurement noise tends to occur at high frequencies. Thus, in order to avoid impaired performance due to such phenomenon, robustness filter $V(z)$ in (17) must present low gain for $\omega \rightarrow \pi/T_s$, indicating the need for higher order $V(z)$ filters. This condition elucidate the trade-off between input disturbance rejection and noise attenuation when tuning the SDTC.

3.1.3. Robust stability condition

In general the robust stability condition, given by (18), tends to be violated at medium frequencies [4,7]. Low and medium frequency specifications can be attended by low order filters, therefore the order of the robustness filter $V(z)$ is not determinant to achieve desired robustness.

3.1.4. Choice of the filter $V(z)$ poles

Traditionally, the robustness filter is tuned using a single constant parameter in the filter denominator which defines multiple repeated stable poles. In some cases this parameter is tuned to reach a desired robustness and disturbance rejection [19,12], while in other cases the noise attenuation is prioritized by increasing the filter order [7,14]. In this paper, a more flexible solution is proposed by using different poles in the robustness filter $V(z)$ to meet a desired trade-off between disturbance rejection and noise attenuation

$$V(z) = \frac{v_0 + v_1 z^{-1} + \cdots + v_n z^{-n}}{(1-\beta_1 z^{-1})(1-\beta_2 z^{-1})\ldots(1-\beta_m z^{-1})}, \quad (19)$$

where $m = n + 1$. Note that, if $\beta_1 = \beta_2 = \cdots = \beta_m = \beta$ the filter reduces to the one in (11). Next section presents tuning rules of β_i, $i = 1 \ldots m$, for different study cases.

3.2. Study cases

This work investigates the control of processes modeled by following three transfer functions

$$P_1(s) = \frac{k_n\, e^{-L_n s}}{(\tau_p s - 1)(\tau_u s + 1)}, \quad (20)$$

$$P_2(s) = \frac{k_n\, e^{-L_n s}}{s(\tau_u s + 1)}, \quad (21)$$

$$P_3(s) = \frac{k_n\, e^{-L_n s}}{(\tau_p s - 1)}, \quad (22)$$

where $P_1(s)$ and $P_2(s)$ are second-order plus dead-time (SOPDT) unstable and integrative models, respectively, and $P_3(s)$ is an unstable first-order plus dead-time (FOPDT) model, where $\tau_p > 0$ and $\tau_u > 0$. Such models can represent a wide variety of industrial processes. In [7] it was used to model the concentration of an open loop unstable chemical reactor. The temperature control of an aluminum thin plate is presented in [8]. Field tests of a damping controller designed to mitigate electromechanical oscillations on an 18-MVA diesel generating unit are presented in [9].

3.2.1. Robustness filter for FOPDT processes

The robustness filter

$$V_1(z) = \frac{v_0 + v_1 z^{-1}}{(1-\beta_1 z^{-1})(1-\beta_2 z^{-1})} \quad (23)$$

is proposed for the case of FOPDT processes (22), where the tuning parameters are chosen as $0 \leq \beta_1 < \beta_2$ and $0 < \beta_2 < 1$. Parameter β_1 is tuned considering a desired noise attenuation response, that is, if noise attenuation is not a priority then β_1 can be chosen close to zero, otherwise, close to β_2. Parameter β_2, on the other hand, is chosen to obtain desired robustness characteristics. That is, as β_2 gets closer to 1, the system overall robustness against uncertainties will increase. On the other hand, slower disturbance rejection will occur, and *vice-versa*.

3.2.2. Robustness filter for SOPDT processes

Following two filters

$$V_2(z) = \frac{v_0 + v_1 z^{-1} + v_2 z^{-2}}{(1-\beta_1 z^{-1})(1-\beta_2 z^{-1})}, \quad (24)$$

and

$$V_3(z) = \frac{v_0 + v_1 z^{-1} + v_2 z^{-2}}{(1-\beta_1 z^{-1})(1-e^{-\sigma+\Omega i} z^{-1})(1-e^{-\sigma-\Omega i} z^{-1})} \quad (25)$$

are proposed for the case of SOPDT processes, where σ and Ω are free parameters.

The tuning of $V_2(z)$ follows the same procedure as $V_1(z)$, that is, initially β_2 is tuned in order to obtain desired robustness characteristics, then β_1 is set between $0 \leq \beta_1 < \beta_2$.

Another option to deal with measurement noise attenuation is to use filter $V_3(z)$. As shown in [20], complex poles can improve the relationship between noise attenuation and robustness. In addition, it was shown that the ratio Ω/σ can define the noise attenuation characteristic where $atan(\Omega/\sigma) \leq \pi/3$ is desired [20]. Filter $V_3(z)$ is tuned as follows: (i) define a desired ratio $D_r = \Omega/\sigma$, (ii) tune σ to achieve a desired robustness, (iii) set β_1 between $0 \leq \beta_1 < 1$ close to one for improved noise attenuation. In order to illustrate the tuning, consider the plant studied in [11],

$$G(s) = \frac{0.1}{s(2s+1)^5}, \quad (26)$$

which can be approximated by a second order integrating plant described by the process model (21)

$$P(s) = \frac{0.1 e^{-5s}}{s(5s+1)}. \quad (27)$$

Using a sampling time of $T_s = 0.2$ s, the zero-order-hold method yields the discretized plant

$$P(z) = \frac{0.00039472(z+0.9868)}{(z-1)(z-0.9608)} z^{-25}. \quad (28)$$

Consider Dr relation in robustness filter (25) is kept fixed at $tan(\pi/3)$, then noise attenuation pole β_1 varies in the range between $0 \leq \beta_1 < 1$. Fig. 2 shows the relation between $H_{un}(\omega)$ (17) and β_1. From Fig. 2 it is possible to notice that the value of $H_{un}(w)|_{w\rightarrow\pi/T_s}$ gets lower as β_1 increases, thus obtaining a desired measurement noise gain in the control signal at high frequencies.

4. Simulation results

In order to evaluate the performance of the proposed tuning rules, following four examples from recent literature were used. All simulations were compared to recently published papers that propose tuning for dead-time processes. In order to clearly separate the effects of the input disturbance and of the noise measurement in the output response, the noise is only added in the last seconds of simulation, that is, when the system reaches steady-state, leading to a better analysis.

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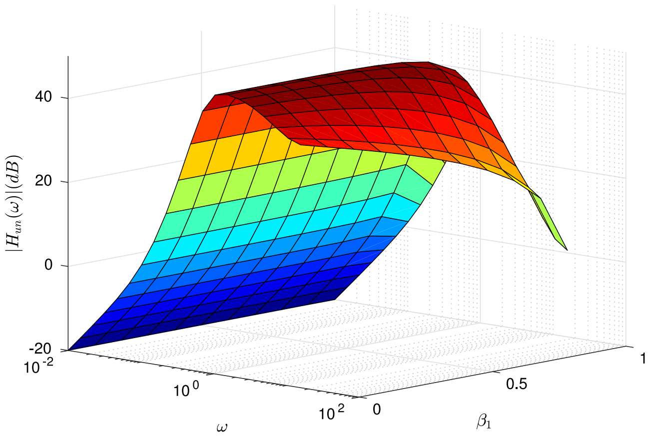

Fig. 2. Relation between $|H_{un}(w)|$ and β_1 with $Dr = tan(\pi/3)$ for (28).

4.1. Example 1

Consider the illustrative process (26)–(28). Two SDTC controllers are tuned for this example. In order to achieve similar set-point response with compared controllers from [12] and [21], primary controller was tuned with $F_1(z) = -0.436z^{-1}$, $F_2(z) = 105.9 - 101.3z^{-1}$ and $K_r = 4.5906$ for both SDTC.

Attenuation of high frequency modes along with fast disturbance rejection are desired for this example. As aforementioned, complex poles exhibit good balance between noise attenuation and robustness, thus initially leading to the adoption of (25) as the robustness filter to the SDTC$_1$. By following specified tuning rules from Section 3.2.2, ratio $D_r = \tan(\pi/3)$ was defined, then $\sigma = 0.0842$ was chosen. Lastly, $\beta_1 = 0.87 \leq 1$ was set, leading to

$$V(z) = \frac{16.03 - 31.06z^{-1} + 15.05z^{-2}}{(1 - 0.87z^{-1})(1 - 1.82z^{-1} + 0.845z^{-2})}. \quad (29)$$

A second and more robust proposal is made for the SDTC$_2$ by choosing $\beta_1 = 0.97$ and $\beta_2 = 0.91$ for (24), obtaining

$$V(z) = \frac{22.76 - 44.31z^{-1} + 21.56z^{-2}}{(1 - 0.97z^{-1})(1 - 0.91z^{-1})}. \quad (30)$$

Fig. 3 shows time responses to a unit step reference. At $t = 50$ s a negative unity step disturbance is applied at the process input. Furthermore, white noise with zero mean and a variance of 0.001 is added to the measured output in the last 10 s of simulation. Notice that while possessing faster regulation response than controllers proposed by [12] and [21], the SDTC maintained similar noise attenuation.

Suppose now that due to unmodeled dynamics, both the gain and time constant of (27) are 20% higher than the nominal case. Fig. 4 shows the results for this situation. Similarly to the nominal case, SDTC with uncertainty exhibited fast regulation response with only small oscillations.

A second uncertainty case is then considered, with gain 20% higher and time constant 20% lower than the nominal model. Results for this case are presented in 5. In this situation, only the SDTC$_2$ and the controller from [12] were able to remain stable, with slightly better response from the proposed controller, which presented faster disturbance rejection.

4.2. Example 2

Consider the unstable SOPDT process recently studied in [13]

$$P(s) = \frac{2}{(10s - 1)(2s + 1)} e^{-5s}. \quad (31)$$

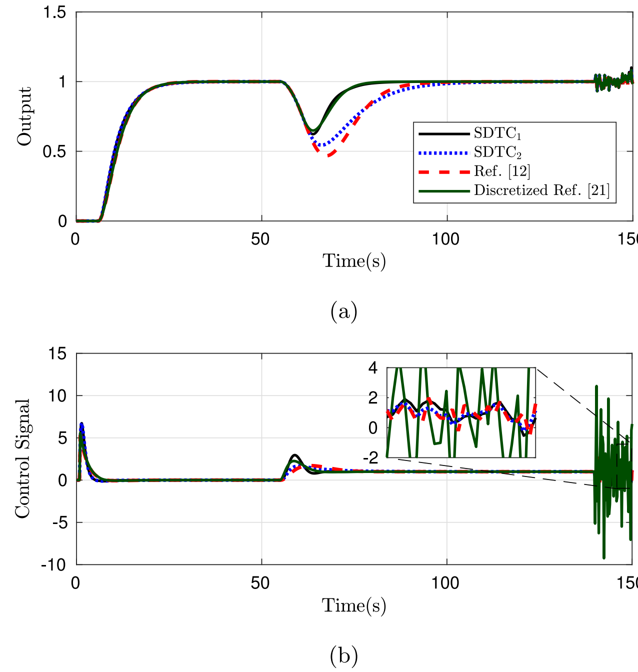

Fig. 3. Nominal system responses for example 1. (a) Output signals. (b) Control signals.

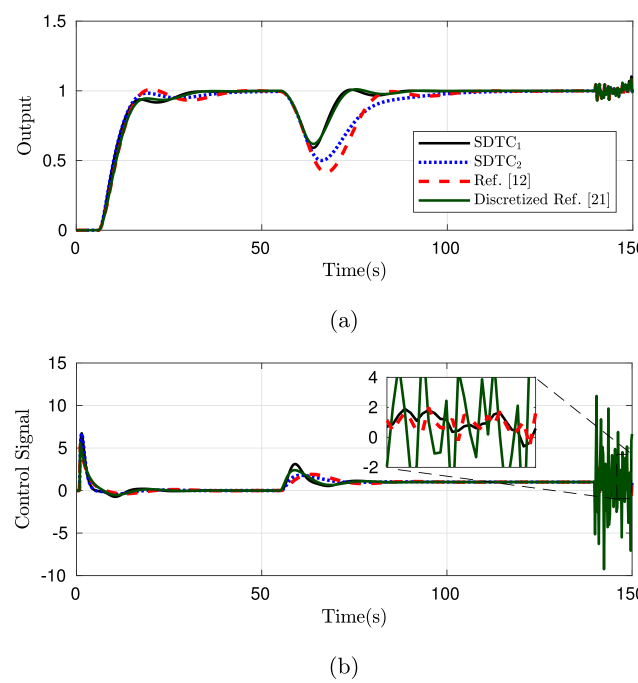

Fig. 4. Perturbed system responses for example 1. (a) Output signals. (b) Control signals.

The discrete-time model $P_n(z)$ with long dead-time is obtained using a sampling time of $T_s = 0.1$ s is given by

$$P_n(z) = \frac{0.00049342(z + 0.9868)}{(z - 1.01)(z - 0.9512)} z^{-50}. \quad (32)$$

For this case, two SDTC controllers were designed. In order to obtain fast set-point tracking, the primary controller of both are tuned with $F_1(z) = -0.8904z^{-1}$, $F_2(z) = 3.433 - 3.268z^{-1}$, and $K_r = 0.1102$.

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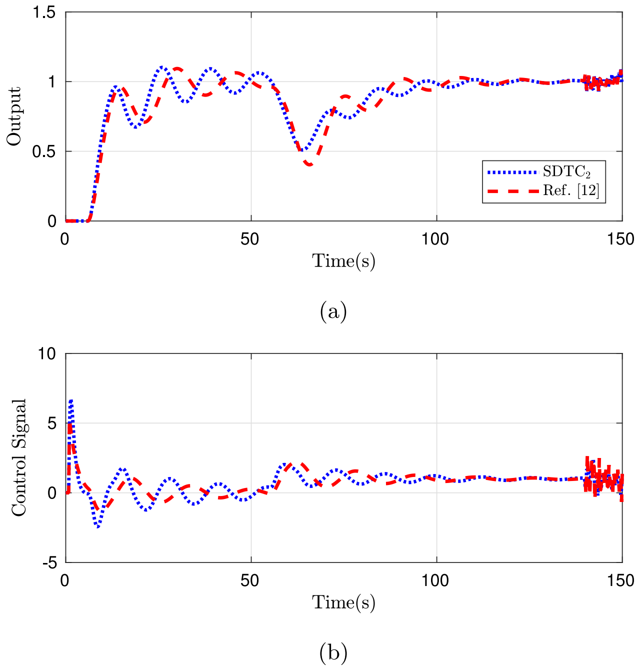

Fig. 5. Perturbed system responses for example 1 with gain 20% higher and time constant 20% lower than the nominal model. (a) Output signals. (b) Control signals.

In addition, both controllers employed (25) as the robustness filter model with $\sigma = 0.45$, $\Omega = 1.15$. Fast disturbance rejection was prioritized for the SDTC$_1$, thus $\beta_1 = 0$, leading to

$$V(z) = \frac{296.3 - 576.1z^{-1} + 279.9z^{-2}}{1 - 0.522z^{-1} + 0.4057z^{-2}}. \tag{33}$$

In order to improve noise attenuation characteristics while keeping faster disturbance rejection than the controller from [13], β_1 was increased for the SDTC$_2$, obtaining the following filter

$$V(z) = \frac{34.06 - 66.26z^{-1} + 32.21z^{-2}}{(1 - 0.9z^{-1})(1 - 0.522z^{-1} + 0.4057z^{-2})}. \tag{34}$$

Fig. 6 shows the relation $|H_{un}(w)|$. It is possible to see that the increase in β_1 for the SDTC$_2$ is an effective design procedure that improves the controller capacity to deal with noise (which occurs at high frequencies).

Two control tests were executed in order to evaluate the SDTC performance. A unity step-change was applied to the system at time $t = 0$ s and a negative constant load disturbance of magnitude 0.2 entered the control signal at time $t = 60$ s. In addition, measurement white noise with zero mean and a variance of 5×10^{-5} was added to the output in the last five seconds of simulation.

Fig. 7 shows the results for the nominal case. As it can be seen, both SDTC controllers exhibit faster disturbance rejection than the controller from [13]. Note that, as expected, the SDTC$_2$ achieved the best noise attenuation among all three controllers, making it the most appropriated solution for practical industrial applications.

As in [13], consider now that the process time delay and proportional gain are actually 5% larger while the stable pole is 5% smaller than the obtained model. Integral of the square error (ISE) for this situation is shown in Table 1, once more demonstrating the improvement yielded by the proposed strategy.

4.3. Example 3

The following process from [12,22] is studied in this example

$$P(s) = \frac{e^{-4s}}{s(s+1)}. \tag{35}$$

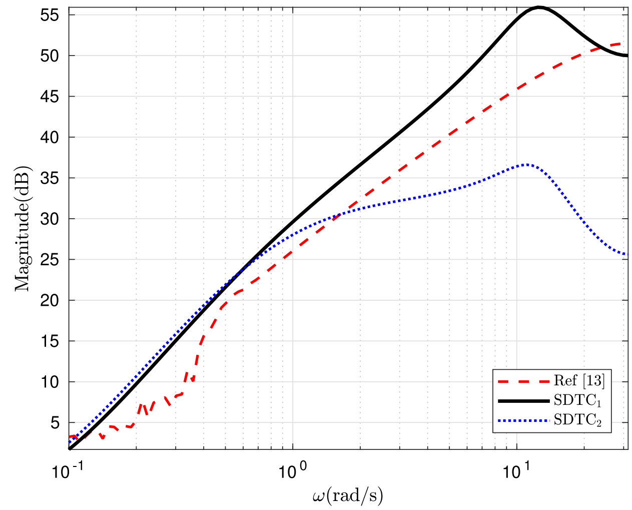

Fig. 6. Noise sensitivity $|H_{un}(w)|$ for example 2.

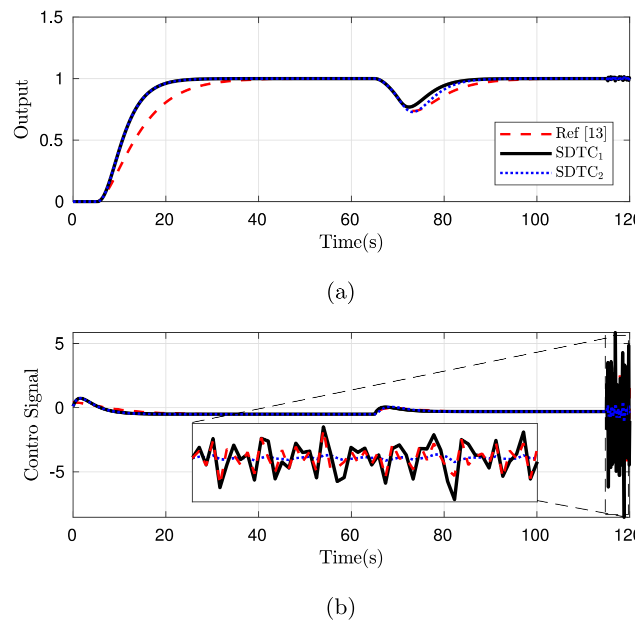

Fig. 7. Nominal system responses for example 2. (a) Output signals. (b) Control signals.

Using a sampling time $T_s = 0.2$ s, the discrete time model of the process is given by

$$P_n(z) = \frac{0.018731(z + 0.9355)}{(z-1)(z - 0.8187)}z^{-20}. \tag{36}$$

For comparison purposes, this case includes the traditional SDTC with repeated filter poles, namely SDTC$_2$. The proposed tuning rules are applied in the design of the SDTC$_1$. The primary controllers and robustness filters for both SDTC$_1$ and SDTC$_2$ were designed to yield reference tracking and disturbance rejection performances similar to that presented in [12], thus $F_1(z) = -0.02328z^{-1}$, $F_2(z) = 7.582 - 6.616z^{-1}$, and $K_r(z) = 0.9654$ for both controllers. Disturbance rejection filters were tuned according to (24) and (11), with $\beta_1 = 0.87$ and $\beta_2 = 0.965$ for the SDTC$_1$, and $\beta = 0.91$ for the SDTC$_2$, leading to

$$V(z) = \frac{1.516 - 2.733z^{-1} + 1.221z^{-2}}{(1 - 0.87z^{-1})(1 - 0.965z^{-1})}, \tag{37}$$

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Table 1
ISE for examples and experiment.

	Example 1				Example 2		
	$SDTC_1$	$SDTC_2$	Ref. [12]	Ref. [21]	$SDTC_1$	$SDTC_2$	Ref. [13]
Nominal	10.1552	11.7367	12.8919	10.6036	9.8132	9.6574	11.7023
Perturbed 1	10.0866	11.6830	12.9917	10.5032	10.0387	9.7847	11.7279
Perturbed 2	–	11.3755	12.3504	–	–	–	–

	Example 3			Example 4		Experiment	
	$SDTC_1$	$SDTC_2$	Ref. [12]	SDTC	Ref. [12]	SDTC	Ref. [13]
Nominal	7.2601	7.6869	7.4178	2078.6	2100.2	–	–
Perturbed	8.8380	9.7113	8.8668	2273.8	2288.6	130.7141	141.1987

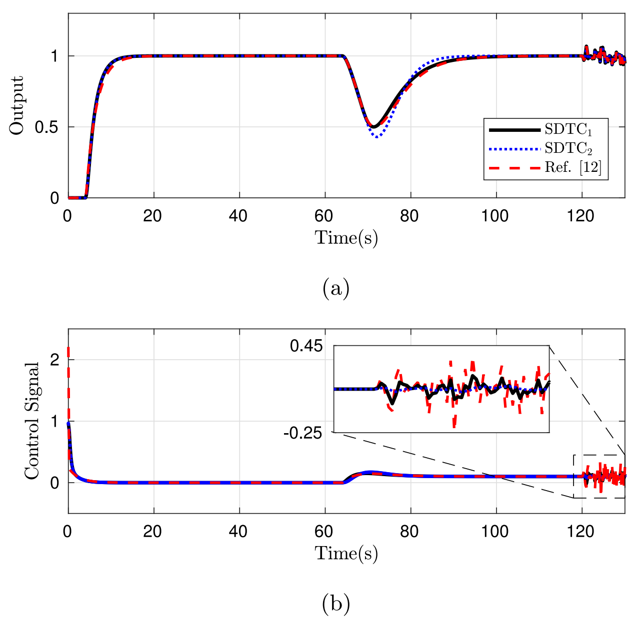

Fig. 8. Nominal system responses for example 3. (a) Output signals. (b) Control signals.

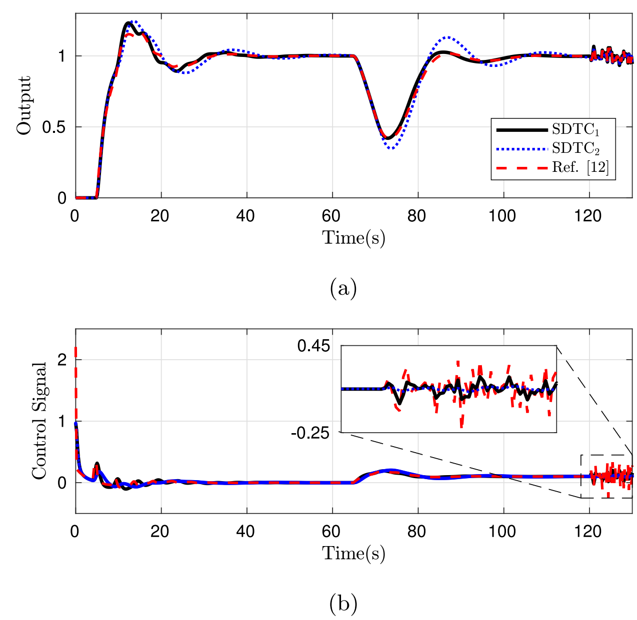

Fig. 9. Perturbed system responses for example 3. (a) Output signals. (b) Control signals.

and

$$V(z) = \frac{0.2283 - 0.4113z^{-1} + 0.1838z^{-2}}{(1 - 0.91z^{-1})^3}, \quad (38)$$

for $SDTC_1$ and $SDTC_2$, respectively.

Control results for the $SDTC_1$, the $SDTC_2$ and the controller proposed by [12] are shown in Fig. 8. A unit step reference was introduced at time $t = 0$ s, while a step-like disturbance of -0.1 was added to the control signal at time $t = 65$ s. For analysis purposes, measurement white noise with zero mean and a variance of 0.001 was also added from time $t = 120$ s to the end of the experiment. Furthermore, Fig. 9 shows the results of a second experiment performed in order to evaluate the system robustness in the presence of a 20% error in the process delay model.

From Figs. 8 and 9 it is possible to notice that the $SDTC_1$ and the controller proposed by [12] have similar output signals, with slightly better disturbance rejection achieved by the $SDTC_1$. In addition, $SDTC_1$ was able to keep good noise attenuation with faster response than the traditional $SDTC_2$.

4.4. Example 4

Consider the following first-order unstable process with time-delay of the chemical reactor concentration studied in [12,15],

$$P(s) = \frac{3.433e^{-20s}}{101.1s - 1}. \quad (39)$$

Using a sampling time $T_s = 0.5$ s, the discrete model of the process is given by

$$P_n(z) = \frac{0.016689}{z - 1.00486}z^{-40}. \quad (40)$$

In order to obtain similar set-point tracking response with that from [12], the primary controller is tuned with $F_1(z) = 0$, $F_2(z) = 1.742$, and $K_r(z) = 1.451$.

In order to achieve fast disturbance rejection robustness filter (23) with $\beta_1 = 0$ and $\beta_2 = 0.986$ was chosen, yielding

$$V(z) = \frac{4.016 - 3.996z^{-1}}{1 - 0.986z^{-1}}. \quad (41)$$

A step reference is applied to the system at time $t = 0$ s while a negative input disturbance of magnitude 1 is applied at time $t = 600$ s. Additionally, white noise with zero mean and a variance of 0.1 is added to the measured output in the last 200 s of simulation. Results for this case are shown in Fig. 10. Consider now the process delay is actually 30% larger than the modeled one. Fig. 11 shows the results for this situation.

Results show that the SDTC was able to achieve faster disturbance rejection for both nominal and perturbed cases. Furthermore, noise attenuation is superior to the controller from [12]. Note that such results are obtained by using simple gains in the primary controller, and a monotonically tuned robustness filter.

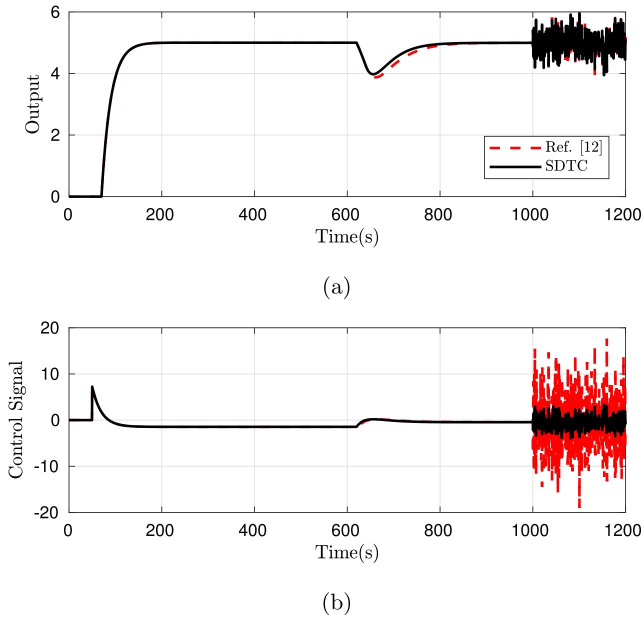

Fig. 10. Nominal system responses for example 4. (a) Output signals. (b) Control signals.

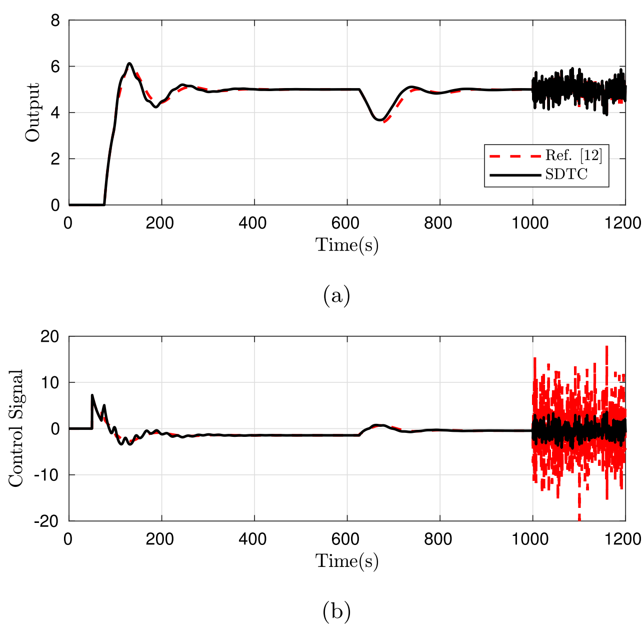

Fig. 11. Perturbed system responses for example 4. (a) Output signals. (b) Control signals.

5. Experimental tests

The proposed strategy was applied for the temperature control of an in-house thermal chamber, which is shown in Fig. 12. The temperature inside the chamber is controlled by an electrical resistor which provides heat and is situated in an air reservoir right below the acrylic dome. The reservoir is separated only by two openings which allow air to circulate. Additionally, a fan with constant rotational speed provides the internal air flow. This set of actuators is a source of delay and nonlinearities in the system. The control input is limited by the resistor maximum power, which varies in a scale from 0 to 100%, thus the saturation model is included in the control loop, as shown in the control diagram in

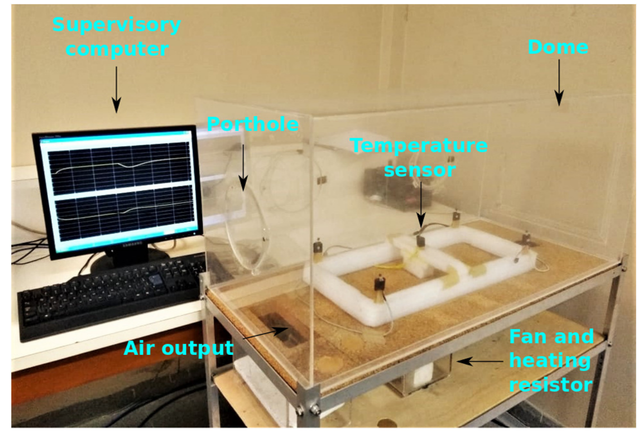

Fig. 12. In-house thermal chamber.

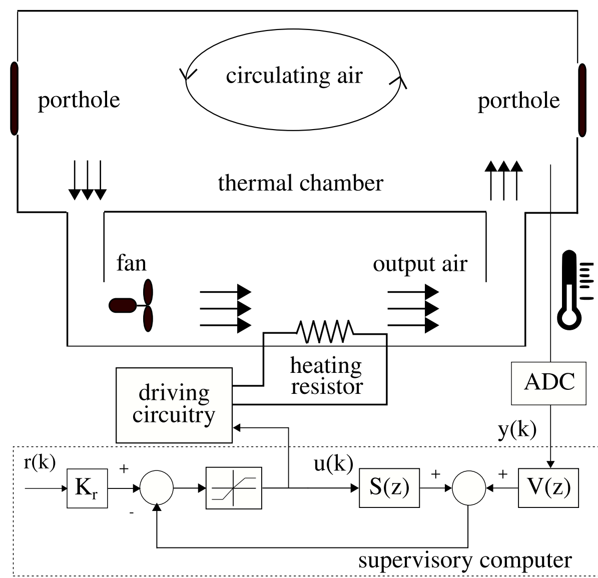

Fig. 13. Thermal chamber control diagram.

Fig. 13, where subsystem $S(z) = F_1(z) + G_n(z)(F_2(z) - V(z)z^{-d_n})$ is defined to obtain an internally stable implementation of the predictor for any process model [17]. The power delivered to the heating resistor is controlled by the duty cycle of a switching power supply. Furthermore, there are two portholes which can be manually opened in order to disturb the internal temperature by interaction with the external environment. This system can represent a wide variety of industrial and commercial applications, such as thermal control of neonatal incubators and industrial furnaces.

The SDTC is implemented on a supervisory computer. The control signal is sent via Universal Serial Bus (USB) cable to a driving circuit through a Nidaq-USB6009 data acquisition card manufactured by National Instruments. In order to close the control loop, a temperature sensor provides the actual temperature inside the chamber to the acquisition card through an analog digital converter (ADC).

An open-loop identification step test was performed by applying maximum power to the electrical resistor. The temperature response can be view in Fig. 14. Practical applications with slow time-constant can be approximated by integrative models [5]. Besides containing less identification parameters, using an integrative model allows to reduce the amount of time required for the identification test, since it is not necessary to reach steady-state

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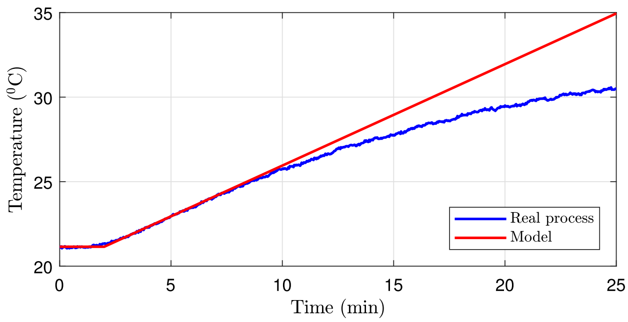

Fig. 14. Temperature response for process identification.

regime. Thus, by using the two-parameter method from [23] the plant was approximated by

$$P(s) = \frac{0.6}{s}e^{-2s}, \tag{42}$$

which was discretized by using the zero-order-hold method with $T_s = 0.2$ min, obtaining

$$P(z) = \frac{0.12}{z-1}z^{-10}. \tag{43}$$

The SDTC was tuned to produce fast set-point tracking response (1) with a time constant of two minutes. Thus, the primary controller was tuned with $F_1(z) = 0$, $F_2(z) = f_{2_0} = 0.8333$, and $K_r = 0.8333$. To provide good disturbance rejection and appropriate noise attenuation, the disturbance filter is given by (23)

$$V(z) = \frac{0.2042 - 0.2z^{-1}}{(1 - 0.95z^{-1})(1 - 0.9z^{-1})}. \tag{44}$$

Fig. 15 shows experimental results for a step change on the set-point from 20.7 °C to 26 °C. In order to assess controller robustness, portholes remained opened from $t = 30$ min to $t = 40$ min. For comparison purposes, the control method given in [13] is also used for implementation with $\lambda = 0.9$, $\lambda_f = 0.96$, $\lambda_s = 0.925$, $m = 1$, $n_h = 0$, $n_d = 2$, $n_f = 2$, $\beta_1 = 2/(1 - \lambda_f)$, and $\beta_2 = 1 - \beta_1$.

Note that both controllers were able to follow the reference without overshoot, and present similar response over the time while the portholes remain open from $t = 30$ min to $t = 40$ min. However, when the portholes were closed at $t = 40$ min, it is possible to note that, differently from the controller from [13], the SDTC was capable to reach the set-point once again twenty minutes prior to the compared controller, which kept oscillating for a longer period.

6. Conclusion

A new set of tuning rules for a simplified dead-time compensator focusing on industrial process has been proposed in this paper. The set of rules for the poles of the robustness filter has successfully demonstrated its advantages for both robust tuning and measurement noise attenuation. Not merely the proposed tuning rules achieved superior results compared to its classical counterpart, it has also shown to be simpler than recent dead-time process control strategies in the literature [13,12].

In general, simplicity is pivotal for controller design implementation and understanding of the tuning rules, which are characteristics clearly achieved by the proposed controller. The variety of simulation examples from different applications [11,12,22,24,13] validates the SDTC versatility, being able to control stable, unstable, and integrative processes even in the presence of modeling uncertainties. The experimental results presented satisfactory performance on the control of a thermal chamber system subjected to modeling mismatch, external disturbance, and measurement noise.

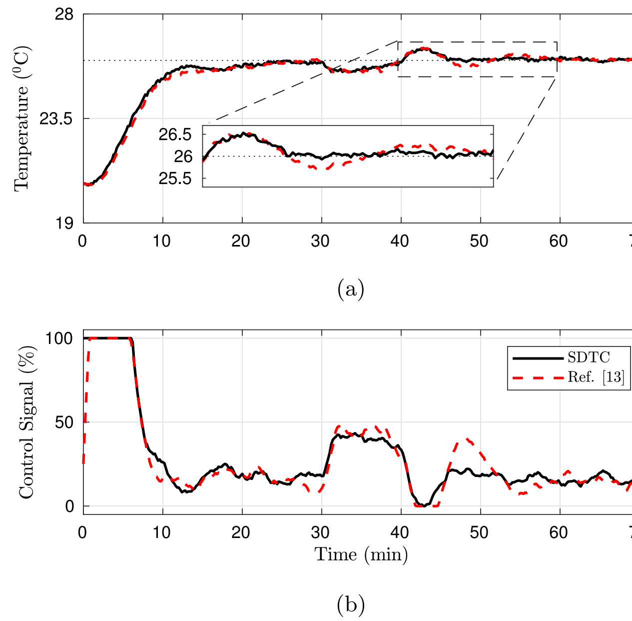

Fig. 15. Experimental results. (a) Output signals. (b) Control signals.

Acknowledgments

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