Performance Degradation Driven PID Controller Design

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Abstract: This paper is concerned with the design of the closed-loop control system, in order to take into account the system performance to load-disturbance and to set-point changes and its robustness to variation of the controlled process characteristics. The aim is to achieve a good balance between the multiple trade-offs. The proposed approach is complementary to the work presented by Arrieta and Vilanova (2011, 2012). Here, it is provided a PID design that allowing some degradation in the system's combined performance, achieves an increase in the robustness.

Keywords: PID control, Process control, robustness, performance

1. INTRODUCTION

Since their introduction in 1940 (Babb, 1990; Bennett, 2000) commercial *Proportional - Integrative - Derivative* (PID) controllers have been with no doubt the most extensive option that can be found on industrial control applications (Åström and Hägglund, 2001). Their success is mainly due to its simple structure and to the physical meaning of the corresponding three parameters (therefore making manual tuning possible). This fact makes PID control easier to understand by the control engineers than other most advanced control techniques. In addition, the PID controller provides satisfactory performance in a wide range of practical situations.

With regard to the design and tuning of PID controllers, there are many methods that can be found in the literature over the last sixty years. Special attention is made of the *IFAC workshop PID'00 - Past, Present and Future of PID Control*, held in Terrassa, Spain, in April 2000, where a glimpse of the state-of-the-art on PID control was provided. Moreover, because of the widespread use of PID controllers, it is interesting to have simple but efficient methods for tuning the controller.

In fact, since the initial work of Ziegler and Nichols (1942), an intensive research has been done, developing autotuning methods to determine the PID controller parameters (Skogestad, 2003; Åström and Hägglund, 2004; Kristiansson and Lennartson, 2006). It can be seen that most of them are concerned with feedback controllers which are tuned either with a view to the rejection of disturbances (Cohen and Coon, 1953; López et al., 1967) or for a well-damped fast response to a step change in the controller set-point (Rovira et al., 1969; Martin et al., 1975; Rivera et al., 1986).

Moreover, in some cases the methods considered only the system performance (Ho et al., 1999), or its robustness (Åström and Hägglund, 1984; Ho et al., 1995; Fung et al., 1998). However, the most interesting cases are the ones that combine performance and robustness, because they face with all system's requirements Ho et al. (1999); Ingimundarson et al. (2004); Yaniv and Nagurka (2004); Vilanova (2008).

Taking into account that in industrial process control applications, it is required a good load-disturbance rejection (usually known as *regulatory-control*), as well as, a good transient response to set-point changes (known as *servo-control* operation), the controller design should consider both possibilities of operation.

Despite the above, the servo and regulation demands cannot be optimally satisfied simultaneously with a One-Degree-of-Freedom (1-DoF) controller, because the resulting dynamic for each operation mode is different and it is possible to choose just one for an optimal solution.

Considering the previous statement, most of the existing studies have focused only in fulfilling one of the two requirements, providing tuning methods that are optimal to servo-control or to regulation-control. However, it is well known that if we optimize the closed-loop transfer function for a step-response specification, the performance with respect to load-disturbance attenuation can be very poor and vice-versa (Arrieta and Vilanova, 2010). Therefore it is desirable to get a compromise design, between servo/regulation when using 1-DoF controller.

The proposed method considers 1-DoF PID controllers as an alternative when *explicit* Two-Degree-of-Freedom (2-DoF) PID controllers are not available. Therefore, it could be stated that the proposed tuning can be used when both operation modes may happen and it could be seen as an *implicit* 2-DoF approach (because the design takes into account both objectives, servo and regulation modes) (Arrieta et al., 2010).

Moreover, it is important that every control system pro-

vides a certain degree of robustness, in order to preserve the closed-loop dynamics, to possible variations in the process. Therefore, the robustness issue should be included within the multiple *trade-offs* presented in the control design and it must be solved on a balanced way.
The previous cited methods study the performance and robustness jointly in the control design. However, no one treats specifically the performance/robustness *trade-off* problem, nor consider in the formulation the servo/regulation *trade-off* or the interacting between all of these variables. In this sense, an initial stage has been performed by Arrieta and Vilanova (2011, 2012), providing a simple PID tuning that guarantees a certain level or value for the robustness characteristic taking into account at the same time the balance between the servo and regulation combined performance.
The approach presented in this paper is different but complementary to the work exposed in Arrieta and Vilanova (2011, 2012). We provide a PID design based on the optimality degree of the system's performance. The tuning looks for a robustness increase, choosing an allowed degradation value in the combined performance. Therefore, it can be stated as the main contribution presented in this paper.
The paper is organized as follows. Section 2 introduces the control system configuration, the general framework, as well as some related concepts and methods. In Section 3 it is defined the performance optimality index, whereas in Section 4 it is presented the proposed PID tuning. Some results are provided in Section 5 and the paper ends in Section 6 with some conclusions.

2. MATERIALS AND METHODS

2.1 Control system configuration

We consider the feedback control system shown in Fig. 1, where $P(s)$ is the controlled process, $C(s)$ is the controller, $r(s)$ is the set-point, $u(s)$ is the controller output signal, $d(s)$ is the load-disturbance and $y(s)$ is the system output. The output of the ISA-PID controller (Åström and

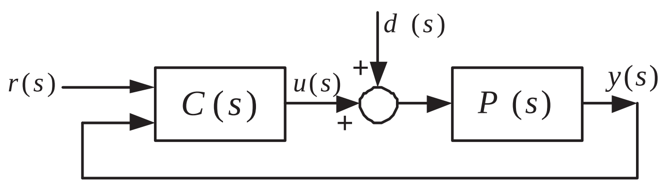

Figure 1. Closed-loop control system.

Hägglund, 2006) is given by

$$u(s) = K_p\left(1+\frac{1}{T_i s}\right)e(s) - K_p\left(\frac{T_d s}{1+(T_d/N)s}\right)y(s) \quad (1)$$

where $e(s) = r(s) - y(s)$ is the control error, K_p is the controller static gain, T_i the integral time constant, T_d the derivative time constant and the derivative filter constant N is taken $N = 10$ as it is usual practice in industrial controllers.
Also, the process $P(s)$ is assumed to be modelled by a First-Order-Plus-Dead-Time (FOPDT) transfer function of the form

$$P(s) = \frac{K}{1+Ts}\mathrm{e}^{-Ls} \quad (2)$$

where K is the process gain, T is the time constant and L is the dead-time. This model is commonly used in process control because is simple and describes the dynamics of many industrial processes approximately (Åström and Hägglund, 2006).
The availability of FOPDT models in the process industry is a well known fact. The generation of such model just needs for a very simple step-test experiment to be applied to the process. From this point of view, to maintain the need for plant experimentation to a minimum is a key point when considering industrial application of a technique.

2.2 Performance

One way to evaluate the performance of control systems is by calculating a cost function based on the error, i.e. the difference between the desired value (set-point) and the actual value of the controlled variable (system's output). Of course, as larger and longer in time is the error, the system's performance will be worse.
In this sense, a common reference for the evaluation of the controller performance, is a functional based on the integral of the error like: Integral-Square-Error (ISE), or Integral-Absolute-Error (IAE).
Some approaches had used the ISE criterion, because its definition allows an analytical calculation for the index (Zhuang and Atherton, 1993). However, nowadays can be found in the literature that IAE is the most useful and suitable index to quantify the performance of the system (Chen and Seborg, 2002; Skogestad, 2003; Åström and Hägglund, 2006; Kristiansson and Lennartson, 2006; Tan et al., 2006). It can be used explicitly in the design stage or just as an evaluation measure.
The formulation of the criterion is stated as

$$IAE \doteq \int_0^\infty |e(t)|\,dt = \int_0^\infty |r(t) - y(t)|\,dt \quad (3)$$

where the index can be measure for changes in the set-point or in the load-disturbance.

2.3 Robustness

Robustness is an important attribute for control systems, because the design procedures are usually based on the use of low-order linear models identified at the closed-loop operation point. Due to the non-linearity found in most of the industrial process, it is necessary to consider the expected changes in the process characteristics assuming certain relative stability margins, or robustness requirements, for the control system.
As an indication of the system *robustness* (relative stability) the Sensitivity Function peak value will be used. The control system Maximum Sensitivity is defined as

$$M_s \doteq \max_\omega |S(j\omega)| = \max_\omega \frac{1}{|1 + C(j\omega)P(j\omega)|} \quad (4)$$

and recommended values for M_s are typically within the range 1.4 - 2.0 (Åström and Hägglund, 2006). The use of the maximum sensitivity as a robustness measure, has the advantage that lower bounds to the Gain, A_m, and Phase, ϕ_m, margins (Åström and Hägglund, 2006) can be assured according to

$$A_m > \frac{M_s}{M_s - 1} \quad ; \quad \phi_m > 2\sin^{-1}\left(\frac{1}{2M_s}\right)$$

Therefore, to assure $M_s = 2.0$ provides what is commonly considered minimum robustness requirement (that translates to $A_m > 2$ and $\phi_m > 29^o$, for $M_s = 1.4$ we have $A_m > 3.5$ and $\phi_m > 41^o$).
In many cases, robustness is specified as a target value of M_s, however the accomplishment of the resulting value is never checked.

2.4 Simple PID Tuning Rules for Arbitrary M_s-Based Robustness Achievement

In Arrieta and Vilanova (2011, 2012), a joint criteria that faces with the *trade-off* between the performance for servo and regulation operation and also that takes into account the accomplishment of a robustness level is presented.
A cost objective function is formulated, where J_x^z represents criteria (3) taking into account the operation mode x, for a tuning mode z. The index is stated in order to get as much closer as possible, the resulting point (J_r^{rd}, J_d^{rd}), to the "ideal" one, (J_r^o, J_d^o). Therefore,

$$J_{rd} = \sqrt{\left(J_r^{rd} - J_r^o\right)^2 + \left(J_d^{rd} - J_d^o\right)^2} \tag{5}$$

where J_r^o and J_d^o are the optimal values for servo and regulation control respectively, and J_r^{rd}, J_d^{rd} are the performance indexes for the *intermediate* tuning considering both operation modes.
The index (5) is minimized with the aim to achieve a balanced performance for both operation modes of the control system. Also, using (4) as a robustness measure, the optimization is subject to a constraint of the form

$$|M_s - M_s^d| = 0 \tag{6}$$

where M_s and M_s^d are the Maximum Sensitivity and the desired Maximum Sensitivity functions respectively. This constraint tries to guarantee the selected robustness value for the control system. See Arrieta and Vilanova (2011), for more details.
Results are expressed just in terms of the FOPDT process model parameters (2), in a tuning methodology for PID parameters, with the corresponding desired level robustness as

$$K_pK = a_1\tau^{b_1} + c_1$$
$$\frac{T_i}{T} = a_2\tau^{b_2} + c_2 \tag{7}$$
$$\frac{T_d}{T} = a_3\tau^{b_3} + c_3$$

where the constants a_i, b_i and c_i are given in Table 1, according to the desired robustness level for the control system and $\tau = L/T$ is the normalized dead-time.

With the aim to give more completeness to the previous tuning method, an extension of the approach was proposed, allowing to determine the PID controller for any arbitrary value M_s^d in the range $[1.4, 2.0]$. Thus, tuning expressions (7) can be rewritten as

Table 1. PID settings for servo/regulation tuning with robustness consideration

constant	M_s^d free	$M_s^d = 2.0$	$M_s^d = 1.8$	$M_s^d = 1.6$	$M_s^d = 1.4$
a_1	1.1410	0.7699	0.6825	0.5678	0.4306
b_1	-0.9664	-1.0270	-1.0240	-1.0250	-1.0190
c_1	0.1468	0.3490	0.3026	0.2601	0.1926
a_2	1.0860	0.7402	0.7821	0.8323	0.7894
b_2	0.4896	0.7309	0.6490	0.5382	0.4286
c_2	0.2775	0.5307	0.4511	0.3507	0.2557
a_3	0.3726	0.2750	0.2938	0.3111	0.3599
b_3	0.7098	0.9478	0.7956	0.8894	0.9592
c_3	-0.0409	0.0034	-0.0188	-0.0118	-0.0127

$$K_pK = a_1(M_s^d)\tau^{b_1(M_s^d)} + c_1(M_s^d)$$
$$\frac{T_i}{T} = a_2(M_s^d)\tau^{b_2(M_s^d)} + c_2(M_s^d) \tag{8}$$
$$\frac{T_d}{T} = a_3(M_s^d)\tau^{b_3(M_s^d)} + c_3(M_s^d)$$

where the constants are expressed as functions of M_s^d. Therefore, from Table 1 each constant a_i, b_i and c_i was generated from a generic second order M_s^d dependent polynomial as

$$\begin{aligned}
a_1 &= -0.3112(M_s^d)^2 + 1.6250(M_s^d) - 1.2340\\
b_1 &= 0.0188(M_s^d)^2 - 0.0753(M_s^d) - 0.9509\\
c_1 &= -0.1319(M_s^d)^2 + 0.7042(M_s^d) - 0.5334\\
a_2 &= -0.5300(M_s^d)^2 + 1.7030(M_s^d) - 0.5511\\
b_2 &= -0.1731(M_s^d)^2 + 1.0970(M_s^d) - 0.7700\\
c_2 &= -0.0963(M_s^d)^2 + 0.7899(M_s^d) - 0.6629\\
a_3 &= 0.1875(M_s^d)^2 - 0.7735(M_s^d) + 1.0740\\
b_3 &= 0.3870(M_s^d)^2 - 4.7810(M_s^d) + 4.9470\\
c_3 &= 0.1331(M_s^d)^2 - 0.4733(M_s^d) + 0.4032
\end{aligned} \tag{9}$$

It is important to note that the tuning just depend of the system's model information and the design parameter M_s^d. Moreover, it is worth to note that each one of the parameters (7) and (8), are generated according to a relation of the form $p_i = a_i\tau^{b_i} + c_i$.

3. PERFORMANCE OPTIMALITY INDEX

The analysis exposed here shows the interaction between performance and robustness in control systems. It is possible to say that, an increase of robustness implies an optimality loss in the performance (i.e. a degradation), with respect to the one that can be achieved without any robustness constraint.
It is possible to define the degree of optimality of the constrained case, with respect to the unconstrained one (that is the optimum and corresponds to the M_s^d-free case in Table 1).
In order to quantify the degree of optimality, the following index is proposed

$$I_{Perf} \doteq \frac{J_{rd}^o}{J_{rd}^{rdM_s}} \tag{10}$$

where J_{rd}^o is the optimal index value (5), using the tuning (7) for no constraint of M_s (first column of Table 1), that means the best one that can be achieved. Then, $J_{rd}^{rdM_s}$ is the value of index (5) for the cases where the tuning has

a robustness constraint.
Note that (10) is normalized in the $[0, 1]$ range, where $I_{Perf} = 1$ means a perfect optimality and, as much as the robustness is increased, the index $J_{rd}^{rdM_s}$ will increase and, consequently, $I_{Perf} < 1$, meaning an optimality reduction. The degree of optimality that each control system achieves, when a desirable value of M_s is stated, can be evaluated taking advantage of the generic tuning rule (8). For each value of $M_s^d \in [1.4 - 2.0]$, the optimality degree (10) can be obtained.
For each τ, we take advantage of the possibilities of the tuning (8) and (9), to get the PID parameters for any value of $M_s^d \in [1.4 - 2.0]$ and then, compute the degree of optimality using (10). Fig.2 shows the I_{Perf} variation, as a function of M_s^d, for some values of the normalized dead-time, τ. Note that, as an example, the horizontal line indicates when the degree of optimality is 55%. With the intersection points of this line and the curves corresponding to the I_{Perf} variation for each τ, it is possible to determine a set of desired robustness that is related with this degree of optimality ($I_{Perf} = 0.55$).

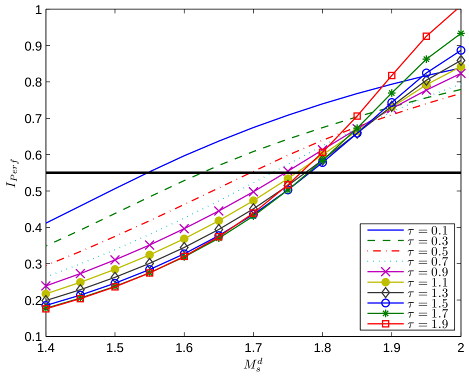

Figure 2. Variation of the index I_{Perf}.

4. PID TUNINGS WITH PERFORMANCE OPTIMALITY DEGREE

As it has been shown above, there is a relation (*trade-off*) between the degree of optimality and the increase in the system's robustness. It is possible therefore to find the corresponding M_s^d value for any specific optimality, as a point (M_s^d, I_{Perf}).
Following the above idea for all plants in the range $\tau \in [0.1, 2.0]$, fixing a certain degree of optimality we can look for the corresponding set of M_s^d values. So, using the robustness profile in tuning (8) and (9), the controller's parameters $[K_p, T_i, T_d]$, can be obtained.
Here, with the aim to facilitate the understanding of the general idea and taking into account that, it could be easier to specify a certain degradation, than a degree of optimality (i.e. an optimality loss), we redefine (10) as,

$$Deg \doteq 1 - I_{Perf} \tag{11}$$

In this sense, a desirable optimality degree of 60% can be interpreted as a 40% of degradation. The general concept is exactly the same, but just the way of interpretation is changed.
Using a similar idea to the one exposed in Section 2.4, we look for a tuning methodology that uses the degradation as a parameter design, in order to increase the robustness of the system. The previous exposed procedure tries to achieve that, allowing a degradation in the performance, the system's robustness can be increased.
We will define a broad classification, in order to fix the levels according to the information provided in Fig. 2. In this sense, it will be used the degradation of the system performance, Deg as a design parameter.
So, the aim is to obtain profiles of M_s^d for the range of $\tau \in [0.1, 2.0]$. Therefore, the selected optimality degree level must intersect each one of the curves corresponding to each one of the plants. To get a degree of optimality higher than 75%, the range of considered robustness should be extended to values greater than $M_s^d = 2.0$, but this value is the minimum acceptable robustness. From the other side, to have an optimality degree lower than 45% the robustness values must be lower than $M_s^d = 1.4$, that is considered as a high robustness level, therefore to decrease the degree of optimality to less than 45% (meaning a degradation more than 55%), is not justified.
Then, the range of application was established as $Deg \in [0.25, 0.55]$ and therefore the classification as,

- Low degradation - $Deg = 0.25$
- Medium-low degradation - $Deg = 0.35$
- Medium-high degradation - $Deg = 0.45$
- High degradation - $Deg = 0.55$

As it was said above, for each stated degradation level and each τ, it is found the corresponding M_s^d value. Then, the set of robustness values determines the M_s^d profile, that is used in the proposed generic tuning (8) and (9), to determine sets for each parameter of the PID controller. Therefore, with all the parameters sets, the tuning rule can be formulated.
Once again, following a similar idea to that described for the M_s^d case, the aim is to provide a simple tuning and for that, we take advantage of the good fitting that equations (7) provide. So, the sets for each PID parameter and for each degradation level, are approximated to fit the corresponding equations form.
The tuning rule remains expressed, according to the form in (7), but the a_i, b_i and c_i constants are given in Table 2, according to the *allowed degradation* level in the system's performance, Deg^a.

Table 2. PID tuning settings for allowed performance degradation

constant	$Deg^a = 0$	$Deg^a = 0.25$	$Deg^a = 0.35$	$Deg^a = 0.45$	$Deg^a = 0.55$
a_1	1.1410	0.8787	0.7490	0.6292	0.5252
b_1	-0.9664	-0.9280	-0.9348	-0.9444	-0.9492
c_1	0.1468	0.2033	0.2669	0.3195	0.3494
a_2	1.0860	0.8154	0.8664	0.8871	0.8755
b_2	0.4896	0.6431	0.6033	0.5847	0.5830
c_2	0.2775	0.4502	0.3874	0.3466	0.3275
a_3	0.3726	0.2794	0.2757	0.2804	0.2949
b_3	0.7098	0.8765	0.8698	0.8471	0.8123
c_3	-0.0409	-0.0149	-0.0070	-0.0037	-0.0055

Table 2 shows, in the first column, the case for $Deg^a = 0$, that is exactly the same to the one in Table 1 for M_s^d free (without any constraint), but it is included here in order to give completeness to the approach. Note also that, to keep the same tuning expressions (7) provides even more uniformity and simplicity to the proposed approach.
The evaluation of the above proposed tuning rule has to be

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done taking into account both performance and robustness issues. In order to study the system's performance, in Fig. 3 there are the indexes J_{rd}, for each case of Deg^a. Note that, with this information and using (10) and (11), it is possible to find the resulting degradation values, as they are shown in Fig. 4.

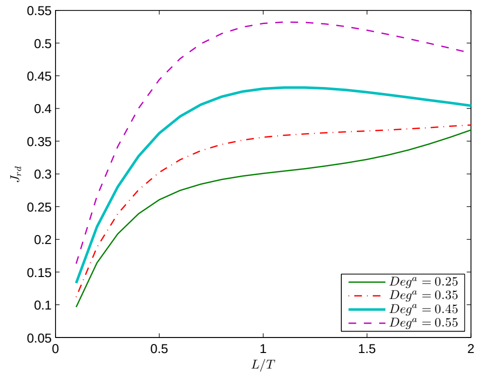

Figure 3. Combined index J_{rd} for each degradation level tuning.

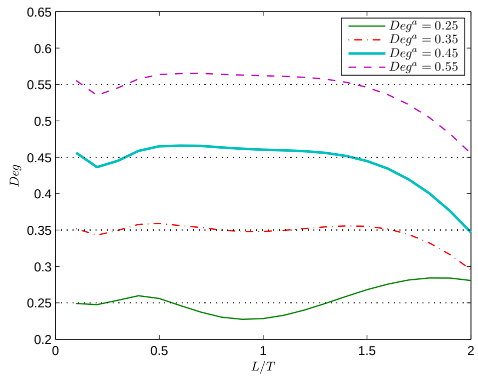

Figure 4. Accomplishment of the fixed degradation level tuning.

Once more, it is important to see how the changes in the performance (due to the imposed degradation), affects the achieved robustness for the system. Fig. 5 shows this evaluation, where the optimality decreases (i.e. degradation increases), the robustness of the system grows up. This is an important aspect because these M_s values represent the profile that should be accomplished in order to achieve the fixed degradation (meaning a certain degree of optimality).

It can be seen, all results are in agreement regarding to the well known performance/robustness ratio.

5. EVALUATION EXAMPLE

In order to evaluate the proposed tuning, we will consider the following fourth order controlled process

$$P_1(s) = \frac{1}{\prod_{n=0}^{3}(\sigma^n s + 1)} \tag{12}$$

with $\sigma = 0.50$ taken from Åström and Hägglund (2000). Using a two-point identification procedure (Alfaro, 2006), a FOPDT model was obtained as: $K = 1.0$, $T = 1.247$ and $L = 0.691$.

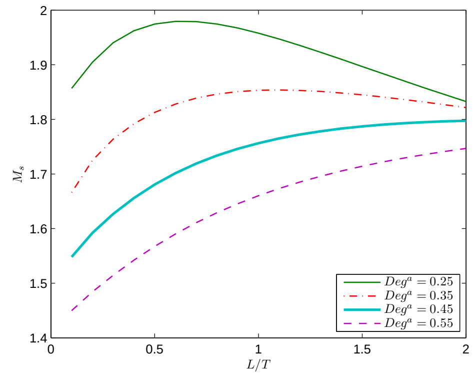

Figure 5. Achieved robustness M_s for each degradation level tuning.

Table 3. Particular process - PID controller parameters for P_1 ($\sigma = 0.50$)

Tuning	Deg^a	K_p	T_i	T_d
Proposed (levels)	0.25	1.723	1.257	0.189
	0.35	1.568	1.240	0.197
	0.45	1.418	1.216	0.207
	0.55	1.269	1.182	0.221

Table 4. Particular process P_1 ($\sigma = 0.50$) - Controller evaluation

Tuning	Deg^a	Deg^r	M_s^r	J_r	J_d	J_{rd}
Proposed (levels)	0.25	0.2508	1.9780	1.4229	0.7568	0.3024
	0.35	0.3575	1.8217	1.4421	0.8208	0.3609
	0.45	0.4657	1.6923	1.4755	0.8954	0.4392
	0.55	0.5645	1.5800	1.5283	0.9871	0.5438

From the FOPDT model and using tuning (7) for each fixed degradation level in Table 2, the PID parameters can be obtained. Tunings are shown in Table 3.

Table 4 gives the performance and robustness values provided by each tuning. Also, in Fig. 6 the control system's and controller's output are shown for each allowed degradation level.

It can be concluded that the levels version has a good accuracy with respect to the selected value of the allowed performance degradation, providing at the same time an increase in the robustness.

6. CONCLUSIONS

The control system's *trade-off* between performance and robustness, can be studied from two points of view. First, as it was shown in Section 2.4, selecting a desirable value for robustness and facing to the resulting performance degradation.

In this paper, we formulated the problem from the other side, selecting an allowed performance degradation in order to get a higher robustness, respect to the case with zero degradation. The proposal is presented for some degradation levels using a qualitative classification.

Results are presented as autotuning formulae, maintaining the same simplicity shown before for other proposed PID tuning approaches. The example shows the accuracy and the benefits of the contribution.

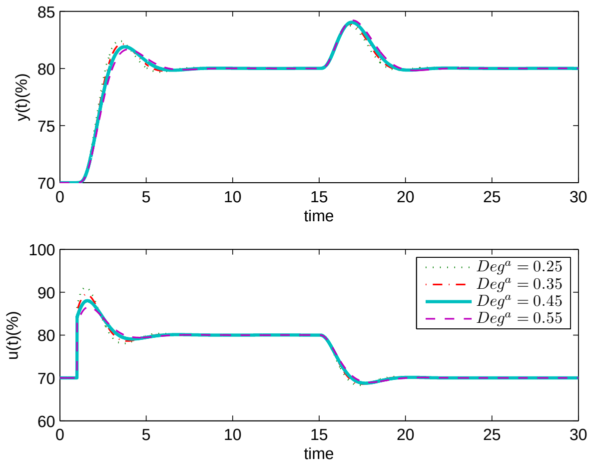

Figure 6. Particular process P_1 - Proposed method ($\sigma = 0.50$).

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