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APPLICATION OF A METHOD FOR TUNING PID CONTROLLERS BASED ON A MONO-OBJECTIVE OPTIMIZATION PROBLEM

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Abstract. *The proportional-integral-derivative controller (PID) are widespread in the industry, due to its ease of use, since the choice depends primarily on three parameters. Often the choice of parameters is not properly carried out resulting in poor control design. Several methods were and have been created aiming to solve this problem, looking for values that are able to offer the controlled system some specific features. The tuning method studied in this work is based on frequency response and proposes to carry out the selection of the PID controller parameters from the set of a single variable, which is able to provide the controlled system with a minimum integral error (IE) presenting a fixed phase margin and minimum gain margin. It is seen that to find the appropriate parameters through this tuning method it is necessary to find the solution of a mono-objective optimization problem. In order to apply this method, it was developed a low-cost experimental bench, where it is possible to perform a temperature control. Firstly, the identification of the mathematical model of the experimental bench was developed, and then the temperature control was tested according to the proposed method. The experimental results demonstrate the effectiveness of the method.*

Keywords: *PID controllers, Tuning method, Optimization, System identification, Temperature control.*

1. INTRODUCTION

The PID controllers, that are commercially available since the 1930s (Seborg et al., 2004), are a widely used control strategy even with advances in research on new techniques of control, which occupies, according Barçante (2011) *apud* Desborough and Miller (2002), about 97% of the feedback control industry. In fact, it has been achieved with PID controllers several advantages: simple structure, easiness to implement, very well applicable to various types of processes, as well as the possibility of obtaining desired characteristics in the controlled system with essentially the changes of three characteristic parameters of your control equation.

The PID controller operates the system by sending a control signal u seeking to reduce error e, in other words, reduce the difference between the desired value (reference) y_r and the current value (output) y. The model control system used in this work can be seen in Fig. 01.

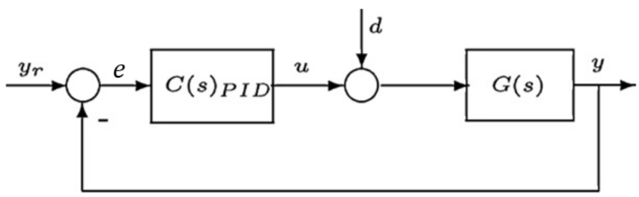


Figure 1. Control system representing the PID controller operating in a plant. Sanchis et al. (2010).

Full action of a PID controller depends on its structure, in other words, each part is arranged as a single controller. This work will use the ‘‘non-interactive’’ structure, or also called parallel action (Seborg et al., 2004), by the fact that the derivative action does not interfere with integral action. There are some other modified forms of PID controllers, such as the PI-D and I-PD, which may be best studied in Ogata (2003). There are other types of structures that may be found in Åström and Hägglund (1995), Faccin (2004), Fermino (2014), among other authors.

For a non-interactive PID controller structure, it is understood that its complete action is taken by the algebraic sum of three actions: proportional, integral and derivative (Campestrini, 2006), namely:

$$U(s) = K_p \left(1 + \frac{1}{T_i s} + T_d s\right) E(s) \tag{1}$$

A disadvantage of this type of action is its high sensitivity to high frequency errors such as noise in the process (Campestrini, 2006). One way to work around this problem is to apply a filter at the derivative term. A PID controller with a high-frequency filter has the following equation:

$$U(s) = C(s)E(s) = K_p \left(1 + \frac{1}{T_i s} + \frac{T_d s}{1 + \left(\frac{T_d s}{N'}\right)}\right) E(s) \tag{2}$$

One way to write the equation of the PID controller is a function of controller zeros. Thus, eq. (2) can be represented as it follows:

$$C(s) = K_i \left(1 + \frac{s}{z_c}\right)^2 / s \left(1 + \frac{s}{z_c N}\right) \tag{3}$$

In order to obtain eq. (3) it is necessary to consider the controller zeros (z_c) as equal values and also to consider the following equations:

$$K_p = K_i \left(\frac{2}{z_c} - \frac{1}{z_c N}\right); \qquad T_d = \frac{1}{2z_c - \frac{z_c}{N}} - \frac{1}{z_c N}; \qquad T_i = \frac{2}{z_c} - \frac{1}{z_c N}; \qquad N' = \frac{z_c N}{2z_c - \frac{z_c}{N}} - 1 \tag{4}$$

Note that in eq. (3), that PID controller may be tuned only if one finds the controller zeros z_c and integral gain K_i. In this work, the proposed tuning method for PID controller is obtained through eq. (3).

Åström and Hägglund (1995) recommend to filter parameter value between 8 and 20. Seborg et al. (2004) and Sanchis et al. (2010) suggest a value between 5 and 20. According to Sanchis et al. (2010), if the high frequency noise measurement is considered small, another high N value can be chosen. Otherwise, if the high frequency measurement noise is very influential in the process, a low value should be selected. In most cases it is used N = 10.

The process performed to choose parameters in eq. (2) is called PID tuning. According Åström and Hägglund (1995), the tuning of a large part of PID controllers found in the industry are poorly implemented, and several times, it is not applied a derivative action controller in the process. Because of this, the tuning methods have been the targets of extensive amount of research studies which seek to make existing methods better or even to develop new techniques.

In this work, it will be performed an application of a PID controller tuning method found in Sanchis et al. (2010), which proposes to make the choice of the parameters of the PID controller based on frequency response. From the setting of a single variable, the controller is able to provide the system a minimum controlled IE (integral error) and to have a fixed phase margin and minimum gain margin. It can be seen that to calibrate this variable properly it is needed to solve an optimization problem based on non-linear constraints.

For temperature control of the experimental bench, firstly the definition of the mathematical model through a plant identification technique will be carried out, and then, from this model, parameters of the PID controller will be calculated through the application of the presented tuning method.

Then, some tests are performed, such as changing temperature *setpoints* and inserting disturbances in the process. Thus, several conclusions based on experimental procedure are earned and included at the end of this work.

2. TUNING METHOD BASED ON A MONO-OBJECTIVE OPTIMIZATION PROBLEM

This step introduces the method found in Sanchis et al., (2010), showing the procedure to obtain the parameters of the PID controller. This PID controller tuning method seeks to reduce the IE of controlled system, setting a phase margin and a minimum gain margin for the process.

The procedure is based on the pursuit of an appropriate value, the search for the single adjustment variable, which facilitates its implementation and provides a low computational cost. The main advantage of this method is its applicability in a large class of linear systems, including systems with dead time and systems with non-minimum phase.

Before setting out the method, some important settings are displayed.

Definition 3.1 - Gain Margin (γ_m): *gain margin is defined as the change in open loop gain, expressed in decibels, when there is a lag of 180 ° so that the closed-loop system becomes unstable.*

The frequency at which the phase difference is 180° is defined as the *phase crossover frequency* (ω_{cp}). The recommended range of gain margin varies according to different authors. Some values suggested by some authors are:

- $\gamma_m > 6\ dB$ (Ogata, 2003);
- $6\ dB \leq \gamma_m \leq 14\ dB$ (Åström; Hägglund, 1995; Barçante, 2011; Vilanova; Visioli, 2012);
- $\gamma_m > 4{,}6\ dB$ (Ketzer, 2013);

- $6\ dB \leq \gamma_m \leq 8\ dB$ (Johnson *et al.*, 2005).

Definition 3.2 - Phase Margin (ϕ_m): *Phase margin is defined as the delay additional phase for which the system reaches the threshold of instability.*

This gap is calculated in the gain crossover frequency (ω_{cg}), frequency at which the magnitude of the transfer function $|G\ (j\omega)|$ values 1. (Ogata, 2003). Good values for phase margin are in the range of $30° \leq \phi_m \leq 60°$ (Astrom; Hägglund, 1995; Johnson et al., 2005; Ketzer, 2013; Ogata, 2003; Vilanova; Visioli, 2012).

Definition 3.3 - Integral Error (IE): *is the integral of the error in time and is defined as:*

$$IE = \lim_{t\to\infty} \int_0^t e(\tau) d\tau \qquad (5)$$

With these settings clarified, proposed method can be presented. This method is, in short, an optimization problem mono-objective that can be written as follows:

$$max \left(K_i(\omega_{cg}, a) = \frac{\omega_{cg}\left(\sqrt{1+\left(\frac{a}{N}\right)^2}\right)}{|G(j\omega_{cg})|(1+a^2)} \right)$$
$$\text{subject to} \begin{cases} \phi_m \geq \phi_{m,r} \\ \gamma_m \geq \gamma_{m,r} \\ \omega_{cg} \geq 0 \\ a > 0 \end{cases} \qquad (6)$$

where $K_i(\omega_{cg}, a)$ is the objective function and should be maximized because the IE index is inversely proportional to the gain K_i (Åström and Hägglund (1995), Garpinger (2012)); a is the parameter that should be adjusted to obtain the optimal solution and is defined as $a = \omega_{cg}/z_c$; $|G\ (j\omega_{cg})|$ is the magnitude of the transfer function of the process in the gain crossover frequency.

With the phase margin constraints and gain margin, a system with adequate performance and robustness is achieved (Sanchis et al, 2010). According Seborg et al., (2004), the gain margin and phase margin can be used, in many cases, such as strength indicators. This is because the gain margin and phase margin stability are safety margins, in other words, if one imposes appropriate values for these parameters, chances that the system may resist to uncertainties that may have happened in the modeling process or that may occur through disturbances in the system will be increased, thus making it more robust (Ketzer, 2013).

Objective function is obtained by performing the following procedure:

- Calculate $|C(j\omega_{cp})|$, using the definition of a, and apply it in the definition of final gain crossover frequency considering the controlled system (Fig. 1): $|C(j\omega_{cp})||G(j\omega_{cp})| = 1$.
- Isolate K_i in expression calculated in last step.

The solution to this optimization problem requires the observation of two curves obtained during the method: $K_i(a)$ and $\gamma_m(a)$. Both curves require a prior knowledge of the transfer function and appear by assigning values to parameter a. Romero (2011) presents these curves for some very common mathematical models in real systems: functions with poles with multiplicity greater than 1, distinct poles, with pure integrators and critical cases as systems with time delay and phase non-minimal.

Curves have very similar formats, always showing up in curve $K_i(a)$ in a range $0 < a \leq 5$. The maximum value of this curve is given the name K_{imax} and the corresponding value of a is a_1. The curve γ_m also shows a similar behavior for the tested models in which the γ_m value must grow to decrease a from a_1. These curves for the phase transfer function non-minimal (eq. (7)), found in Sanchis et al. (2010), are shown in Fig. 02

$$G = -2(s-2)/(s+1)^3 \qquad (7)$$

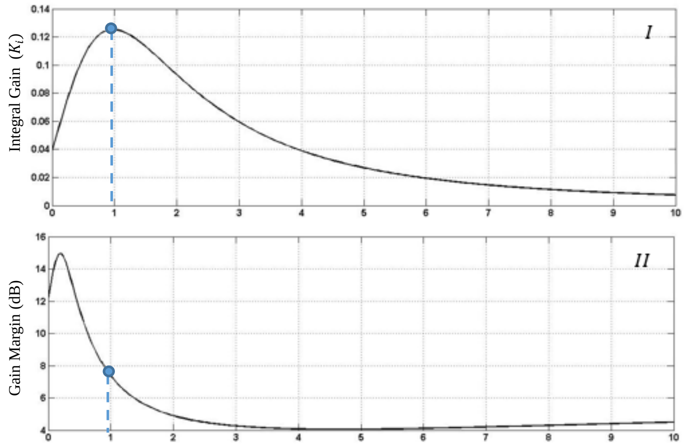


Figure 2. Graphics $K_i \times a$ (I) and $\gamma_m \times a$ (II). Marked in the figure is the point a_1.

As the phase margin constraint is fulfilled in the course of obtaining the objective function, then it is left the gain margin constraint to be fulfilled. This restriction is enforced through an interactive method, which performs the search for the a value in one interval $0 < a \leq a_1$ until the value of $\gamma_m \leq \gamma_{m,r}$.

Tuning method (solution from optimization problem described in eq. (6)) is proceeded in the following steps:

1. $\phi_m = \phi_{m,r}$;
2. Generate the curves $K_i(a)$ e $\gamma_m(a)$ to margin phase ϕ_m;
3. Find the $K_{i_{max}}$ and consequently a_1;
4. Check $\gamma_m(a_1) \geq \gamma_{m,r}$:
   - If **YES**: the PID controller can be obtained with controller zeros and K_i (eq. (3)). Then, tuning ends.
   - if **NOT**: seek a value at $0 < a < a_1$ until $\gamma_m(a) \geq \gamma_{m,r}$. From the a value able to satisfy this constraint, tune PID controller (finished tuning). If there is no value a able to fulfill it, do step 5.
5. Check $\gamma_m \leq 70$ °:
   - if **YES**: do $\phi_m = \phi_m + 5°$ and return to step 2.
   - if **NOT**: tuning the PID controller from the a value that provides the biggest margin gain value γ_m. The tune ends.

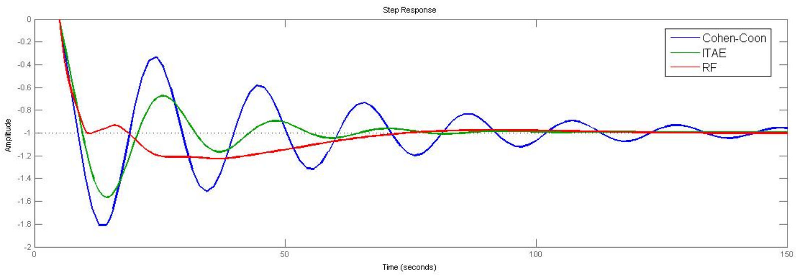
The aim of this tuning method is to find the a value can maximize the value of K_i (minimize IE) according to the restrictions. The above algorithm is capable of it. First it is found the maximum value of K_i (which intrinsically already meets the phase margin requirement) and then it verifies compliance or not to the gain margin requested.

Further details on how to find the objective function, the curves K_i (a) and $\gamma_m(a)$, some examples and simulations are found in Sanchis (2010). A curious reader can find the procedures in more details in Louzada Neto (2015).

3. SIMULATIONS

In order to investigate the behavior of the tuning method described in section 2 and to compare this method with others PID tuning methods, some tuning methods were carried out through some computational simulations. The transfer function obtained through the experimental procedure is presented in section 4.2. This function represents the dynamics of experimental bench, and it was used in simulations.

Three tuning methods were used: Cohen-Coon, ITAE-r, and the method shown in this work (called RF). Results were found from a step input and are presented on Fig. 3.



Tuning Method	IE	IAE
Cohen-Coon	7.712	26.13
ITAE-r	13.17	23.55
RF ($\gamma_{m,r} \geq 6\ dB$)	0,6707	15,6

Figure 3. On left: Step Response. On right: the performance indices.

The IE index should be analyzed carefully, because its low value does not always indicate a response with good performance. For this reason, the IAE (integral absolute error) index was used too. The IAE is calculated as the integral of the absolute value of the error in time.

Furthermore, it is possible to analyze settling time and overshoot (%OS). RF method showed a small settling time, around 70 s, in comparison to the system without controller (Fig. 5) and to other tuning methods. However, there is an overshoot increment in this case, about 20%. Even so, RF method presents better %OS than other methods. In short, results obtained by simulation show that the RF tuning method has the best IE and IAE indices, when compared to the others two methods.

4. EXPERIMENTAL PROCEDURE

Temperature control is present in several important applications in industry, such as industrial furnaces, boilers, ovens, and other miscellaneous and is essential to proper functioning (Martins et al., 2010). Furthermore, according Seborg et al. (2004), thermal systems have a high difficulty level to control. Thus, a good way to verify the applicability of the tuning method presented in item 3 in real systems is through an environment where temperature control is possible.

A bench was developed to implement the method, seeking to represent an environment in which there is a heat source and where it is necessary to maintain the desired temperature levels.

Temperature control is accomplished through variable speed coolers (small fans), which receive signal from the controller. The construction and implementation procedure of the method is presented in more detail below.

4.1 Construction and operation of experimental bench

The bench was constructed with the use of 2 mm thick acrylic plates, such as to divide two environments: a larger (environment "A"), where the temperature is controlled, and a smaller (environment “B”). In each there is an incandescent 60 W lamp, responsible for providing heat to the system.

The responsible for temperature control are coolers (actuators), on which variation of the voltage causes variation of the the angular velocity of the blades, and can be deployed within 12 V. Both are arranged to transfer air between the environments "A" and "B" and between the internal and external environment.

Temperature measurement in the environment "A" is performed by a LM35 sensor used for ease of implementation, which performs the measurement linearly by a factor of 10 $mV/°C$, and presents a -55 $°C$ to 150 $°C$ measurement range , with a typical error of ± 0.2 ° C, which is acceptable for this application..

Hardware used to operate as a PID controller is the Arduino UNO model, an electronic board which is included a microcontroller, various digital and analog input and output pins, and an input/output USB, which allows communication with a computer. It was chosen because it is an open-source platform, which means that there is an extensive content published about the operation, applications, which facilitates the search for information.

With Arduino it was also possible to perform the acquisition of the counter data through its communication with the ScadaBR software. This is a software, available freely, able to create supervisory environments where the generation of graphs and reports are possible, control access to data and commands, among others functions. The software ScadaBR has the possibility of adding a moving average filter, and this filter was used in the data received from LM35.

Arduino, as described above, performs two roles in this bench: controller, when it sends the control signal to the coolers; and data acquisition board, LM35 sensor sending information to the ScadaBR.

The physical layout of the items used for the operation of bench can be seen in the photo below, shown in Fig. 04.

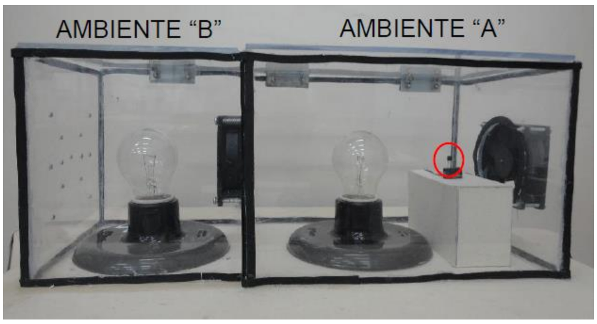


Figure 4. Photo showing the experimental bench. Circulated red, is the LM35 sensor.

As seen in the previous section, the tuning method depends on the knowledge of the mathematical model of the system, therefore, before the control step it is needed to identify the mathematical model of the dynamics of bench.

4.1 Identification System

System identification methods are determining the mathematical model capable of representing the essential aspects of the dynamics of a system. In dynamic system control, these methods have become increasingly important, as the processes become more complex, in such a way to require modeling methods (identification) more accurate (Coelho, R.; Coelho, S., 2004).

There are several ways to classify methods of identification, such as the white box, gray box and black box. This classification divides the methods according to the knowledge of the system being modeled. Extremes are the white box models, in which there is good level of knowledge of the system and the laws of physics able to describe it, and the black box where there is little or no knowledge of the process, which is included the bench experiments (Aguirre, 2007).

This research area has grown considerably, as shown Johnson et al. (2005). In his book several classical techniques are presented as well as newer methods of identification.

For this work, there is a method for identification, based on the system excitation by step input, the necessary to find the mathematical model of the bench. In this type of method, it is imposed a step input to the system and through its time response, parameters are found to reproduce an approximate model (Coelho, R.; Coelho, S., 2004).

For this bench, it follows that the output signal, in other words, the variable to be controlled is the environmental temperature (T) and the input signal, the signal which is output from the controller, is voltage in coolers (U). The voltage is given in Volts (V) and the temperature in degrees Celsius.

Five tests were carried out with step input in each was applied to a different voltage level. The responses obtained, an example for an input voltage 9 V (Fig. 05), display characteristics of a first-order model with delay time (FOPTD), and can be written as eq. (8):

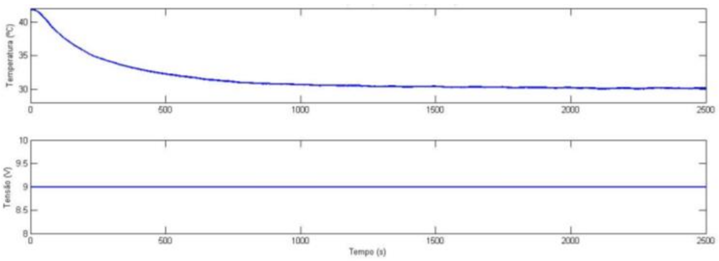


Figure 5. Application of a step input of 9 V (II) and the change in temperature (output signal) (I).

$$G(s) = K\frac{e^{-Ls}}{1+Ts} \tag{8}$$

K, physically, is equivalent to how temperature is changed for each unit of voltage applied to the coolers. The constant L is called dead time, and can be obtained directly in the early part of the response. This value corresponds to the time it takes the output to react after the input signal. There is also a constant τ called time constant (Aguirre, 2007). Once these three constants are obtained the mathematical model of the bench is defined.

The K gain, according to Yu (1999), can be obtained, for linear systems, in a simple manner, directly comparing the input with the output, as follows:

$$K = \frac{\Delta y}{\Delta u} = \frac{\Delta T}{\Delta V} \tag{9}$$

To find the value of dead time L, it can be seen in the responses, the time in which the temperature remains constant even with the actuating signal. The value found is about 5 seconds, and therefore, $L = 5$. The time constant τ was determined by Hägglund's method**.** According to this method, τ is the value of time in which the temperature reaches 63.2% of its final value (Coelho, R.; Coelho, S., 2004):

$$T(\tau) = 0{,}632\,\big(T(\infty) - T(L)\big) + T(L) \tag{10}$$

where $T(\infty)$ is the final temperature, obtained when it was stabilized, and temperature $T(L)$ is the temperature after the dead time. Table 01 shows the results obtained.

Table 1. Results taken from five experiments by step input.

ΔV	ΔT	K	$63{,}2\% \times T(\infty)$	τ
$6\ V$	$-8{,}163\ °C$	$-1{,}36$	$36{,}52\ °C$	$331{,}35$
$7{,}5\ V$	$-10{,}296\ °C$	$-1{,}37$	$35{,}8\ °C$	$260{,}12$
$9\ V$	$-12{,}2905\ °C$	$-1{,}366$	$34{,}23\ °C$	$287{,}8$
$10{,}5\ V$	$-12{,}835\ °C$	$-1{,}222$	-	-
$12\ V$	$-12{,}578\ °C$	$-1{,}048$	-	-

It can be seen on tab. 1, the process remains nearly constant gain up to a voltage value in the inlet 9 V. This voltage value is used as the maximum possible value to be supplied to the cooler to avoid possible errors relating to wrong choice K, or even nonlinear behavior of the system for voltages above this. In this way, it is defined K = 1,365. Performing an arithmetic average of the 3 values of time constant τ found in the tab. 1, define the time constant τ = 293.09. With the defined constants, that is the equation representing the dynamics of the process is:

$$G(s) = \frac{T(s)}{U(s)} = -1{,}365\,\frac{e^{-5s}}{1+293{,}09s} \tag{11}$$

To validate this transfer function, other tests for step input, now input 6 V, 7.5 V, 8 V and 9 V were performed and compared with the response to G(s). The results are showing in Fig. 05.

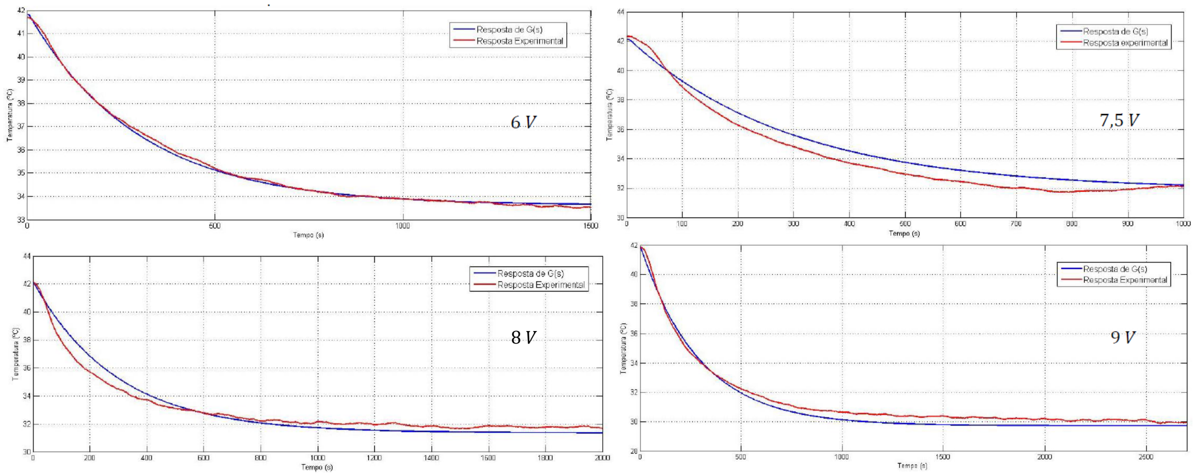


Figure 6. Comparison between response obtained using (s) (eq. (11)) and experimentally obtained.

Note that the results obtained with G(s) are very close to the results obtained by applying inputs step performed experimentally. There are slight variations, possibly appeared with the approximations made in modeling. The tuning method should overcome errors occurred in modeling and stabilize the temperature on the bench.

5. RESULTS

With possession of the model transfer equation of experimental bench, just perform the procedures presented in Section 3. For the definition of PID controller parameters, the following requirements were selected

- Required Phase Margin: $\phi_{m,r} \geq 60°$;
- Required Gain Margin: $\gamma_{m,r} \geq 6\ dB$ and $\gamma_{m,r} \geq 4\ dB$ (two controllers);
- High-Frequency filter parameter: $N = 10$.

From the phase margin requirement and N value defined, we have found the curves $K_i \times a$ e $\gamma_m \times a$, shown in Fig. 07.

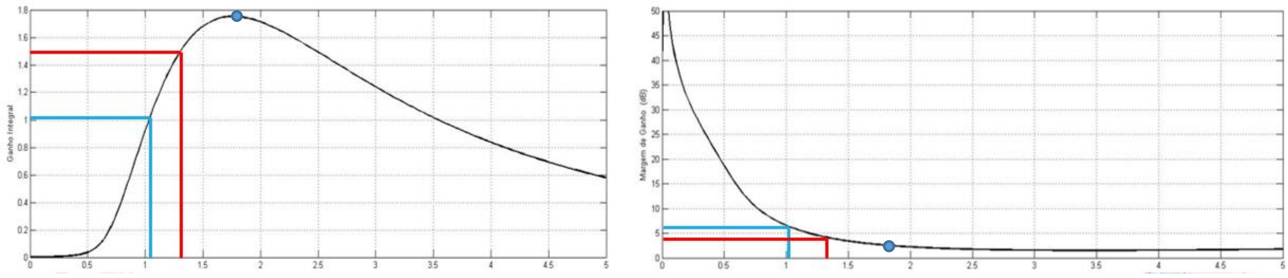


Figure 7. Graphs $K_i \times a$ and $\gamma_m \times a$ obtained for transfer function (s). The lines mark the points meet gain margin $\gamma_{m,r} \geq 6\ dB$ and $\gamma_{m,r} \geq 4\ dB$.

Figure 7 show similar behaviors to those obtained in section 3, showing, in the chosen interval, a maximum K_i value on the curve, in addition to a rise in gain margin when a_1 (1.78 -. Marked in Fig. 07) is decreased.

By performing the procedures for the tuning of the PID controller for the first test ($\gamma_{m,r} \geq 6\ dB$), it verifies that for maximum K_i, the gain margin is lower than 6 dB. To this minimum value of gain margin, is found $a = 1{,}04$ and through this value, was obtained the controller zero z_c = 0,0962 and the integral gain K_i = 1,0571. For the second test ($\gamma_{m,r} \geq 4\ dB$), the a value which reaches the value of gain margin 4 dB is a = 1.34. PID controller zero is 0,1016 and integral gain is K_i = 1,2991. Note, the controller zero will be positive, due the form used of PID controller (eq. (3)) and the restrictions ($a > 0$, $\omega_{cg} \geq 0$) in optimization problem described at eq. (6) (recall the definition of parameter a). This means which the zeros and poles added by PID controller, always will be located in left half-plan.

With these values, the control was implemented in bench using the eq. (3). The eqs. (12) represents the transfer function of PID controller tuning with FR method for each case ($\gamma_{m,r} \geq 6\ dB$ and $\gamma_{m,r} \geq 4\ dB$, respectively). The results obtained from the two controllers are showing in Fig. 08.

$$C(s) = \frac{1{,}0571\left(1+\frac{s}{0{,}0962}\right)^2}{s\left(1+\frac{s}{0{,}962}\right)} \quad (\gamma_{m,r} \geq 6\ dB) \quad ; \quad C(s) = \frac{1{,}2991\left(1+\frac{s}{0{,}1016}\right)^2}{s\left(1+\frac{s}{1{,}016}\right)} \quad (\gamma_{m,r} \geq 4\ dB) \tag{12}$$

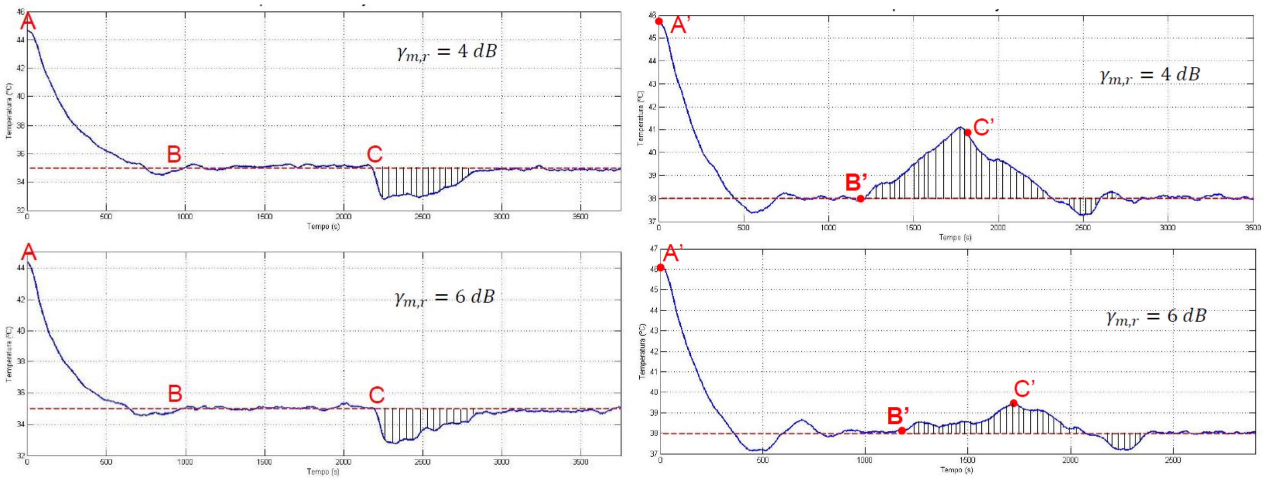


Figure 8. On the left are the results for the test 1 and to the right the results for test 2.

Two tests were conducted: in **test 01**, it was expected stabilization of uncontrolled system, then PID controller is turned on(instant "A"). In first test, the set point value was 35 °C. The instant "B" marks the time at which the temperature stabilizes. To simulate a disturbance, the cover of environment A was opened at instant “C” and maintained this way. After a time, the cover was closed. This procedure was performed for both controllers. The **test 02** was carried out for a reference value equal to 38 °C. The control is turned on (instant A’). After a while in the stabilized condition at the reference temperature, the lamp in environment “B” was turned on (instant B’), raising the temperature in environment “A”. This lamp stays on for a time equal to 600 s and turned off after this time (instant C').

5.1 Results Analysis

Note in Fig. 08, the results for the defined controllers from $\gamma_{m,r} = 4\ dB$ and $\gamma_{m,r} = 6\ dB$, basically have the same response in test 1. Both responses have %OS ≈ 5% (equivalent to 0.5 ° C) and a settling time $t_s \approx 800\ s$ (point "B"). Thus, a comparison is made between the responses obtained from the non-controlled system (Fig. 05) and the controlled system (Fig.08). In controlled system, there is a 20% reduction in settling time and a little increase in %OS, that was not present in the uncontrolled system.

In addition, the controlled process can get a good rejection of external disturbances, as it appears in the "C" point, when the cover of environment “A” was opened. This opening acts as a disturbance on the process, causing a sudden drop in temperature. This is due to the influence of external temperature (lab temperature) which it was around 25 ºC.

Even with the cover open, the control could bypass the external factors and return to the reference value, even for the system to gain margin equal to 4 dB, presenting a disadvantage compared to the system with a gain margin of 6 dB to possess a greater IAE (integral absolute error) index value (note that shaded area in Fig. 08 to the system with a margin of 4 dB is larger than the area to the system with 6 dB).

In the test 02 is more evident the difference between systems. Note that with the lighting of the lamp in environment "B" (point B') introducing an external disturbance to the process, the system with a margin gain of 6 dB get far superior results in terms of IAE compared to the system with gain margin 4 dB. Both controlled systems showed that they are able to overcome the action of external disturbances, however, with very different behaviors. Thus, it appears that the choice of an appropriate value for the gain margin of a process is essential if the system is to be controlled subject to many external factors, and if there is a good belief system modeling.

One can also see in test 02, as well as in test 01, there is an improvement of the settling time while there is an increase in %OS when compared to systems without control.

In this way, it makes sure that the method studied from Sanchis et al. (2010), it is able to provide great advantages to controlled systems, enabling an improvement in the time response by the choice of the phase margin and gain margin.

6. CONCLUSIONS

In this work, the implementation of a PID controller tuning method, which is based on the solution of a mono-objective optimization problem, in temperature control of bench experimental was performed. The results show the great capacity of the tuning method that enables improved time response by imposing phase margin and gain margin constraints. It notes that determining these constraints, the system robustness can be increased.

This has been proven through tests that enabled the introduction of external disturbances to the system, that even with possible errors occurring in the mathematical model of the bench identification process, the temperature has been stabilized by PID controller.

The experimental bench developed in this work have two main features: ease to use and low cost. From this bench, others researches can be performed: study about control's technique in real systems, like this work, and application of new identification methods. In addition, this bench will be available in further studies about the control theory, which may facilitate visualization of the theory in real system applications.

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8. RESPONSIBILITY NOTICE

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