EXPERIMENTAL RESULTS FOR CLOSED-LOOP EVALUATION AND REDESIGN OF PI CONTROLLERS SATISFYING CLASSICAL ROBUSTNESS MEASURES

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Abstract— In this paper a procedure for closed-loop evaluation and PI controller redesign using a relay-based experiment is applied to a laboratory-scale thermal process. This procedure was originally proposed in (Acioli Jr. and Barros, 2011). The aim of the procedure is to evaluate the actual closed-loop using classical robustness measures and, if necessary, redesign the PI controller to achieve a closed-loop with classical robustness measures around the desired specifications.

Keywords— Methods in control, PID Control, Relay Experiment, Performance Evaluation, System Identification.

Resumo— Neste trabalho, um procedimento para avaliação e reprojeto de controladores PI em malha fechada utilizando experimento baseado no relé é aplicado em um processo térmico de escala laboratorial. Esse procedimento foi originalmente proposto em (Acioli Jr. and Barros, 2011). O objetivo do procedimento é avaliar a malha fechada atual utilizando medidas clássicas de robustez e, se necessário, reprojetar o controlador PI para obter um malha fechada com medidas clássicas de robustez próximas da especificação desejada.

Palavras-chave— Métodos em controle, Controle PID, Experimento do Relé, Avaliação de Desempenho, Identificação de Sistemas.

1 Introduction

Process control aims at maintaining certain variables within their desirable operational limits and usually is implemented through several control levels. The first level is regulatory control, which uses the PID control algorithm to provide stability and fast response to load disturbances. At a second control level, we have the Advanced Process Control (APC) systems. In this hierarchically control structure, well tuned PID controllers are prerequisites for successful APC implementation.

Despite the fact that many PI/PID tuning methods have been proposed in literature, see (O'Dwyer, 2006) for an extensive list of references, many regulatory control loops are still found poorly tuned (Skogestad, 2003). In this sense, closed-loop performance evaluation and controller redesign are necessary.

One approach to evaluate the closed-loop performance is estimate gain and phase margins (GPM). GPM are classical measures of closed-loop robustness in frequency-domain and are often used as specifications to design PID controllers. Several GPM tuning methods have been proposed in literature. Some are based on graphical methods which are not suitable for PID autotuning whilst others are based on simple models using approximation which do not guarantee that the specification will be achieved, as in (Ho et al., 1995). Model-based tuning techniques that rely only on open-loop simple dynamics may have poor performance when the process is too complex. There are some iterative procedures as the one presented in (de Arruda and Barros, 2003), which uses an ad hoc iterative algorithm. Other techniques are based on numerical methods as the one presented in (Karimi et al., 2003).

Another way to perform PID controller redesign is a model-based approach. In this, a process model is estimated from a closed-loop identification technique and the PID controller is designed using the model. For PID controller design purpose, the model that receives most attention is first-order plus time delay (FOPTD) model. The IMC-PID formula for PID controller design proposed in (Riva et al., 1986) is a model-based approach that uses FOPTD model. It is attractive to industrial users because it has only one tuning parameter, namely the IMC filter τ_{cl}, which is related to the closed-loop time constant.

In (Ho et al., 2001), the IMC-PID design is examined from the frequency-domain point of view. Analytical equations for GPM are derived for the IMC-PID design. Recently, the authors proposed a procedure for closed-loop evaluation and PI controller redesign based on the knowledge of GPM, crossover and critical frequencies, and a FOPTD process model (Acioli Jr. and Barros, 2011). The GPM with corresponding critical and crossover frequencies are estimated using a closed-loop relay-based experiment. The FOPTD process model is estimated using the relay experiment data. The identification technique solves a time least-squares problem subject to a constraint in the crossover frequency.

In this paper, the procedure proposed in (Acioli Jr. and Barros, 2011) is revised. The procedure is applied to a laboratory-scale thermal process. The paper is organized as follows. In Section 2, the problem statement is presented. The closed-loop evaluation and FOPTD identification using a relay-based experiment is presented in Section 3. In Section 4, the PI controller redesign method is described. The experimental result is discussed in Section 5 followed by conclusion in Section 6.

2 The Problem Statement

Consider the closed-loop shown in Fig.1. The process transfer function $G(s)$ is represented by a simple FOPTD model

$$G(s) = \frac{K_p}{\tau s + 1} e^{-ls}, \tag{1}$$

while the PI controller is $C(s) = K_c(1 + \frac{1}{T_i s})$.

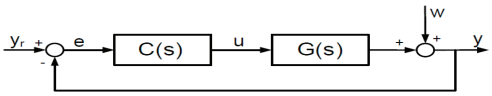

Figure 1: The Closed-Loop

Assume that $C(s)$ was defined using IMC-PI design settings for setpoints presented in (Riva et al., 1986). The IMC-PI formula is given by

$$K_c = \frac{\tau}{K_p(\tau_{cl} + l)}, \tag{2}$$

$$T_i = \tau, \tag{3}$$

where, K_p, τ and l are the FOPTD model parameters, and τ_{cl} is the IMC-PI tuning specification parameter. The loop gain transfer function ($L(s) = G(s)C(s)$) for the IMC-PI design is given by

$$L_{imc-pi}(s) = \frac{e^{-ls}}{s(\tau_{cl} + l)}. \tag{4}$$

By definition, the gain margin (A_m) and phase Margin (ϕ_m) of a closed-loop is

$$A_m = \frac{1}{|L(j\omega_c)|} \text{ and } \phi_m = \pi + \angle L(j\omega_g),$$

where ω_c and ω_g, critical and crossover frequencies respectively, are obtained from $\angle L(j\omega_c) = -\pi$ and $|L(j\omega_g)| = 1$.

The problem statement is: Given a closed-loop system, evaluate robustness and performance through gain and phase margins and estimate a FOPTD process model using relay experiment data jointly with the crossover frequency as constraint. If necessary, redesign the controller to match the desired specifications.

3 Closed-Loop Evaluation and FOPTD Identification

The closed-loop is evaluated from the GPM point of view. These margins are estimated experimentally using a relay-based experiment performed in the closed-loop system. Another information estimated using the relay experiment data is a FOPTD model. These information are used to redesign the PI controller.

3.1 Gain and Phase Margins Estimation

The relay-based experiment used here is a combined of two relay experiments, namely here as Gain Margin and Phase Margin experiments. In this section, the relay experiments are revised and the estimation of GPM with corresponding ω_c and ω_g frequencies are shown.

3.1.1 Gain Margin Experiment

The standard relay test presented in (Åström and Hägglund, 1995) is used to estimate the critical point and frequency. It can be shown (see (Schei, 1994)) that if this relay test is applied to a closed-loop $T(s) = \frac{Y(s)}{Y_r(s)} = \frac{L(s)}{1+L(s)}$, the limit cycle occurs at the critical frequency of the $L(s)$, i.e $L(j\omega_c) = G(j\omega_c)C(j\omega_c)$.

The estimation of critical frequency $\hat{\omega}_c$ is obtained from the frequency of the limit cycle. $G(j\hat{\omega}_c)$ is estimated computing the DFT of one period of the process input u and output y when the relay oscillation is present and steady. With the knowledge of $C(s)$, we can compute $C(j\hat{\omega}_c)$. The closed-loop gain margin is computed as

$$\hat{A}_m = \frac{1}{|L(j\hat{\omega}_c)|} = \frac{1}{|G(j\hat{\omega}_c)C(j\hat{\omega}_c)|}. \tag{5}$$

3.1.2 Phase Margin Experiment

The relay feedback structure applied for crossover frequency point estimation of the loop transfer function is presented in Fig. 2.

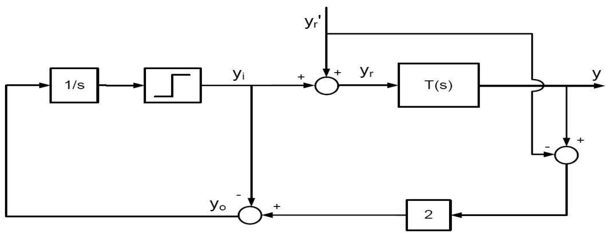

Figure 2: Phase Margin Experiment.

If this relay structure is applied to a closed-loop $T(s)$, the limit cycle occurs at the crossover frequency of $L(s)$, i.e $|L(j\hat{\omega}_g)| \approx 1$ (Schei, 1994).

The setpoint $y_r(t)$ is the excitation applied to $T(s)$. $\hat{\omega}_g$, $G(j\hat{\omega}_g)$ and $C(j\hat{\omega}_g)$ are estimated in a similar way to the Gain Margin Experiment. The closed-loop phase margin is computed as

$$\hat{\phi}_m = \pi + \angle L(j\hat{\omega}_g) = \pi + \angle\left(G(j\hat{\omega}_g)C(j\hat{\omega}_g)\right).$$

3.2 Closed-Loop FOPTD Identification using frequency-domain constraint

A FOPTD model is estimated using the relay experiment data described in previous section. The identification technique solves a time least-squares optimization subject to a equality frequency-domain constraint. The constraint is the process frequency point in crossover frequency. The identification technique was presented in (Acioli Jr. et al., 2006) and is revised here.

3.2.1 Least-Squares Optimization using Equality Constraint

Lemma 1 *Assume the parameters to be optimized $\hat{\theta}$, that data is grouped in a vector from yielding matrices Y and Φ, and the constraints are expressed in matrices M and γ. The least-squares optimization problem with constraints is defined as*

$$\min_{\hat{\theta}} J = \left(Y - \Phi\hat{\theta}\right)^T \left(Y - \Phi\hat{\theta}\right) \tag{6}$$

subject to

$$M\hat{\theta} = \gamma. \tag{7}$$

By defining $E = 2\Phi^T\Phi$ and $F = 2\Phi^T Y$, the solution is

$$\lambda^T = \left[ME^{-1}M^T\right]^{-1}\left[\gamma - ME^{-1}F\right],$$
$$\hat{\theta} = [E]^{-1}(F + M^T\lambda^T).$$

Proof: In order to find the solution, one uses the equivalent optimization problem in relation to $\hat{\theta}$ and λ (vector of Lagrange Multipliers). The equivalent problem is given by

$$\min_{\hat{\theta},\lambda} J = \left(Y - \Phi\hat{\theta}\right)^T \left(Y - \Phi\hat{\theta}\right) + \lambda(\gamma - M\hat{\theta}).$$

For more details see (Wang et al., 2005). □

3.2.2 Identification of the FOPTD model

The identification algorithm uses the following approximation for the FOPTD model

$$G(s) = \frac{K_p(1 - ls)}{\tau s + 1}, \tag{8}$$

Lemma 2 *From Eq. 8 we can define the regression vector with the available relay experiment data being discrete-time*

$$y(t) = \phi(t)\theta, \tag{9}$$

where

$$\phi(t) = \begin{bmatrix} -\int_0^t y(v)\,dv & \int_0^t u(v)\,dv & u(t) \end{bmatrix}^T,$$
$$\theta = \begin{bmatrix} \alpha = \frac{1}{\tau} & \beta = K_p\alpha & \delta = \beta l \end{bmatrix}. \tag{10}$$

Proof: Details see (Acioli Jr. et al., 2006). □

Lemma 3 *From Eq. 8, the equality frequency-domain constraint is defined through the following regression vector which is obtained using the linear form in Eq. 7*

$$\hat{z} = x^T(\hat{\omega}_g)\hat{\theta},$$

with, $\hat{z} = j\hat{\omega}_g\hat{G}(j\hat{\omega}_g)$ and
$x^T(j\hat{\omega}_g) = \begin{bmatrix} -\hat{G}(j\hat{\omega}_g) & 1 & -j\hat{\omega}_g \end{bmatrix}$.

Proof: Details see (Acioli Jr. et al., 2006). □

Lemma 2 and 3 defines the regression vectors for FOPTD model identification using the least-squares optimization problem defined in lemma 1. The final estimate obtained is $\left\{\hat{\tau} = \frac{1}{\hat{\alpha}},\quad \hat{K_p} = \frac{\hat{\beta}}{\hat{\alpha}},\quad \hat{l} = \frac{\hat{\delta}}{\hat{\beta}}\right\}$.

4 The PI Controller Redesign Method

In this section, the PI controller redesign method is described. It is based on estimated gain and phase margins (GPM), and FOPTD model. Firstly, the IMC-PI design is examined from the frequency-domain point of view. Equations for typical specifications such as GPM are derived.

4.1 Frequency-Domain Characterization of the IMC-PI Design

Consider the basic definitions of the GPM, the following set of equations is obtained:

$$\angle G(j\omega_c)C(j\omega_c) = -\pi, \tag{11}$$

$$|G(j\omega_c)C(j\omega_c)| = \frac{1}{A_{dm}}, \tag{12}$$

$$|G(j\omega_g)C(j\omega_g)| = 1, \tag{13}$$

$$\angle G(j\omega_g)C(j\omega_g) + \pi = \phi_{dm}, \tag{14}$$

where A_{dm} and ϕ_{dm} are desired GPM.

Lemma 4 *Using the same procedure presented in (Ho et al., 2001) analytical relations between $\tau_{cl} = \beta l$, A_{dm}, ϕ_{dm} and ω_g are defined:*

$$\omega_g l = \frac{1}{(1+\beta)}, \tag{15}$$

$$\phi_{dm} = \frac{\pi}{2} - \frac{1}{(1+\beta)}, \tag{16}$$

$$A_{dm} = \frac{\pi}{2}(1+\beta). \tag{17}$$

Proof: Consider the PI controller designed using IMC-PI formula (Eqs. 2 and 3) it is given by

$$C_{imc}(s) = \frac{\tau}{K_p(\tau_{cl} + l)}\left(1 + \frac{1}{\tau s}\right), \tag{18}$$

substituting Eqs. 1 and 18 into Eqs. 11-14 gives

$$\phi_{dm} = \frac{\pi}{2} - \omega_g l, \tag{19}$$

$$\omega_g = \frac{1}{\tau_{cl} + l}, \tag{20}$$

$$A_{dm} = \omega_c(\tau_{cl} + l), \tag{21}$$

$$0 = \frac{\pi}{2} - \omega_c l. \tag{22}$$

Solving Eq. 22 gives a constant $\omega_c l = \frac{\pi}{2}$. Consider $\tau_{cl} = \beta l$ into Eqs. 19-21 we obtain the relations defined in Lemma 4. For more details see (Acioli Jr. and Barros, 2011). □

From Eqs. 16-17, gain and phase margins for the IMC-PI design can be related

$$\phi_{dm} = \frac{\pi}{2}\left(1 - \frac{1}{A_{dm}}\right). \quad (23)$$

Equation 23 gives the achievable margins and Fig. 3 shows the curve for the above relationship. For the IMC-PI design, only GPM combinations along the curve can be obtained. Using Eq. 17 the parameter β can be related to A_{dm}

$$\beta = \frac{2A_{dm}}{\pi} - 1. \quad (24)$$

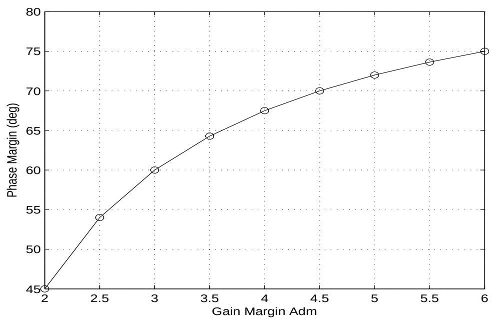

Figure 3: GPM for IMC-PI design

4.2 Relay-Based Gain and Phase Margins PI Controller Redesign

In order to achieve gain or phase margin specification, a PI controller redesign method was proposed in (de Arruda and Barros, 2003). This method are revised here.

Consider the closed-loop system (Fig. 1) and A_{dm}, ϕ_{dm} specifications. To achieve these specifications, the redesigned controller must satisfy the Eqs. 11-14. In (de Arruda and Barros, 2003), an iterative procedure was proposed to PI controller tuning based on gain and phase margins. Here, the redesign methods for each one specification are used separately.

Controller Redesign for Desired Gain Margin: The controller gain can be calculated for achieving the gain margin A_{dm} using Eq. 12. That is, with the current estimated gain margin, $\hat{A}_m$, and the estimated critical frequency, $\hat{\omega}_c$, one can compute the controller proportional gain, K_c^{gm}, from $K_c^{gm} = \frac{K_c \hat{A}_m}{A_{dm}}$. The redesigned controller for a desired gain margin is

$$C^{gm}(s) = K_c^{gm}\left(1 + \frac{1}{T_i s}\right). \quad (25)$$

Controller Redesign for Desired Phase Margin: The controller parameters can be calculated for achieving ϕ_{dm} using Eq. 14. This redesign method is separated into two parts:

1. Determine T_i^{pm} such that Eq. 14 is satisfied,

$$T_i^{pm} = \frac{\tan\left[-\pi + \phi_{dm} - \hat{\phi}_m + \tan^{-1}(\hat{\omega}_g T_i)\right]}{\omega_g^k}.$$

2. Now, update the controller proportional gain K_c^{pm} such that the loop gain at the frequency $\hat{\omega}_g$ is equal to one,

$$K_c^{pm} = K_c \frac{\sqrt{(1/T_i)^2 + \hat{\omega}_g^2}}{\sqrt{(1/T_i^{pm})^2 + \hat{\omega}_g^2}}. \quad (26)$$

The redesigned controller for a desired phase margin is given by

$$C^{pm} = K_c^{pm}\left(1 + \frac{1}{T_i^{pm} s}\right). \quad (27)$$

4.3 The PI Controller Redesign Procedure

The proposed PI controller redesign procedure is described here. The following steps are defined.

1. Consider a initial closed-loop $T(s)$. A relay-based experiment is performed in $T(s)$;

2. Using the relay data, $T(s)$ are evaluated from classical robustness measures ($\hat{A}_m$, $\hat{\omega}_c$, $\hat{\phi}_m$, $\hat{\omega}_g$) point of view. Other information estimated is a FOPTD model (see section 3);

3. If the closed-loop evaluation is not satisfactory, a point of the curve in Fig. 3 is specified. A GPM pair is also specified ($\hat{A}_{dm}$ and $\hat{\phi}_{dm}$). From $\hat{A}_{dm}$ the parameter β is specified using Eq. 24;

4. Using the specifications (A_{dm}, ϕ_{dm} and β), three new PI controller is designed. $C^{imc}(s)$ from Eqs. 2-3, $C^{gm}(s)$ from Eq. 25 and $C^{pm}(s)$ from Eq. 27;

5. A criterion is applied to define the redesigned controller ($C^{red}(s)$) from $C^{imc}(s)$, $C^{gm}(s)$ and $C^{pm}(s)$. It is defined as

   - If $\hat{A}_m > A_{dm}$ the controller proportional gain (K_c) should be increased, else instead;
   - If $\hat{\phi}_m > \hat{\phi}_{dm}$ the controller integral time (T_i) should be decreased, else instead;
   - Observing the first assumption, K_c is chosen from $C^{imc}(s)$ and $C^{gm}(s)$ as the most conservative one.

- Observing the second assumption, T_i is chosen from $C^{imc}(s)$ and $C^{pm}(s)$ as the most conservative one.

6. The new closed-loop system is evaluated. In the case where the closed-loop evaluation is satisfactory the procedure ends. Otherwise, return to step 3 and the procedure is repeated from this new closed-loop system.

4.4 Simulation Example

Consider the process $G_{ex}(s) = \frac{(2s+1)}{(10s+1)(0.5s+1)}e^{-s}$ and the initial PI controller $C_{i_{ex}}(s) = 1.68\left(1 + \frac{1}{13.53s}\right)$.

The closed-loop are evaluated using a relay-based experiment. The GPM are estimated through the relay experiment data as $\hat{A}_m = 4.13$ and $\hat{\phi}_m = 102.46°$. The critical and crossover frequencies is estimated as $\hat{\omega}_c = 2.24\ rad/s$ and $\hat{\omega}_g = 0.13\ rad/s$. The estimated FOPTD model is $\hat{G}_{ex}(s) = \frac{0.8719}{7.356s+1}e^{-0.589s}$.

The desired gain margin specification is $A_{dm} = 2.5$. From Eq. 23-24 we obtain $\phi_{dm} = 54°$ and $\beta = 0.5915$. Using these specifications, new controllers are computed. Their parameters are shown in Table 1

Table 1: New Controller Parameters

	$C^{imc}(s)$	$C^{gm}(s)$	$C^{pm}(s)$
K_c	9.0065	2.7757	0.3832
T_i	7.3556	13.53	1.5816

Using the redesign procedure (step 5), the redesigned controller is given by

$$C^{red}(s) = 2.7757\left(1 + \frac{1}{7.3556s}\right). \quad (28)$$

The new closed-loop is evaluated. The GPM and, critical and crossover frequencies are estimated: $\hat{A}_m = 2.54$, $\hat{\phi}_m = 89°$, $\hat{\omega}_c = 2.1\ rad/s$ and $\hat{\omega}_g = 0.26\ rad/s$.

The redesigned closed-loop has converged towards the desired specifications. The closed-loop performance has been improved (see Fig. 4).

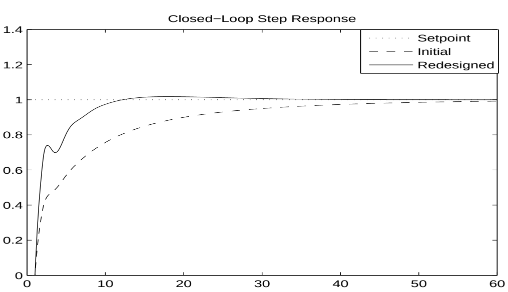

Figure 4: Closed-Loop Step Response

5 Experimental Results

In this section the procedure for closed-loop evaluation and PI controller redesign using a relay-based experiment is applied to a laboratory-scale thermal process.

5.1 Experimental Setup description

The experimental setup is a laboratory-scale thermoelectric system. This consists of two peltier modules, two LM35 temperature sensors, a metal plate, two heat exchangers, two fans, a PLC (Programmable Logic Controller) and a PC with supervisory system. The peltier modules act as heat pumpers on two sections of a flat metal plate heat load. The heat exchangers and fans are used to transfer heat from the opposite faces of each peltier module. The process works as a coupled two-input two-output process. Power is applied using PWM actuators while the temperatures are measured using LM35 sensors. In (Barros et al., 2008) the experimental setup is described in details.

The dynamic behavior of a thermoelectric system results in a complex model and nonlinear. For control purposes, a model reduction can be made.

In this paper, the thermoelectric system was used as a single-input single-output (SISO) process with input 2 (u_2) as manipulated variable and output 2 (y_2) as controlled variable.

5.2 Results

Consider the initial closed-loop with $G_{exp}(s)$ (SISO thermoelectric process) and initial controller $C_{expinicial}(s) = 0.234\left(1 + \frac{1}{2.243s}\right)$, where the controller integral time (2.243) is given in minutes.

The closed-loop are evaluated using a relay-based experiment shown in Fig. 5. The GPM are estimated through the relay experiment data as $\hat{A}_m = 2.4$ and $\hat{\phi}_m = 34.2°$. The critical and crossover frequencies is estimated as $\hat{\omega}_c = 0.09\ rad/s$ and $\hat{\omega}_g = 0.045\ rad/s$. The estimated FOPTD model is $\hat{G}_{exp}(s) = \frac{0.636}{31.93s+1}e^{-279s}$.

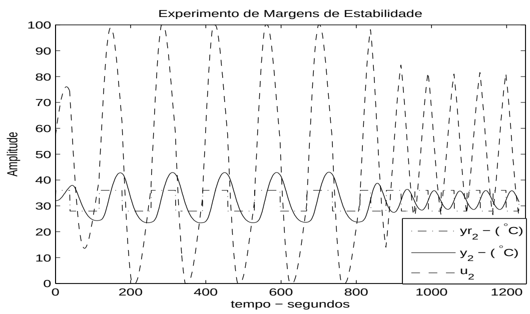

Figure 5: Relay-Based Experiment

For the controller redesign, the desired specifications are $A_{dm} = 2.5$, $\phi_{dm} = 54°$ and $\beta = 0.591$.

The parameters of the new controllers are shown in Table 2.

Table 2: New Controller Parameters

	$C^{imc}(s)$	$C^{gm}(s)$	$C^{pm}(s)$
K_c	0.113	0.225	0.973
T_i (min)	0.532	2.83	10.77

Using the redesign procedure (step 5), the redesigned controller is

$$C^{red}(s) = 0.225\left(1 + \frac{1}{10.77s}\right). \qquad (29)$$

The new closed-loop is evaluated. The GPM and, critical and crossover frequencies are estimated: $\hat{A}_m = 4.6$, $\hat{\phi}_m = 52.44°$, $\hat{\omega}_c = 0.12\ rad/s$ and $\hat{\omega}_g = 0.019\ rad/s$. The result is around to the specifications and the redesigned become more stable as specified (see Fig. 6).

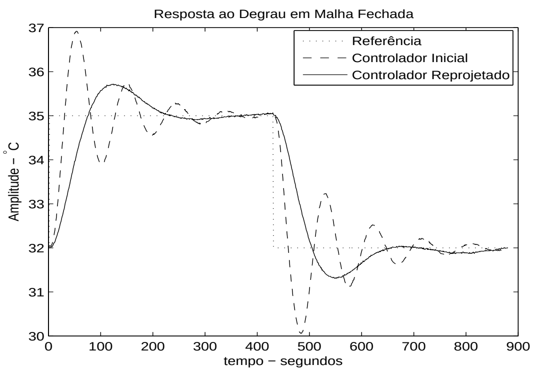

Figure 6: Closed-Loop Step Response - Experimental

6 Conclusion

In this paper, an experimental result of applying the procedure for closed-loop evaluation and PI controller redesign proposed in (Acioli Jr. and Barros, 2011) was presented. The closed-loop system is evaluated using a relay-based experiment to estimate classical robustness measures and a FOPTD process model. Using these information, a PI controller redesign is performed to achieve a new closed-loop system with gain and phase margins around to desired specifications.

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