EVALUATION OF TIME AND FREQUENCY DOMAIN DATA-DRIVEN PID TUNING APPLIED TO PILOT PLANTS

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Abstract— This paper presents an evaluation of a time data-driven PID tuning restricted by frequency specification for closed-loop systems in pilot plants. It uses data collected from a specific closed-loop experiment to estimate frequency response and obtain time domain points. The initial PID tuning gains are adjusted in order to match the defined reference model and frequency response specializations using a constrained optimization technique. The proposed strategy is demonstrated in two laboratory scale processes, a thermal plant based on Peltier effect and a level control-loop in a quadruple-tank system.

Keywords— PID control, Data-driven tuning, Process Control, Gain Margin, Phase Margin

1 Introduction

Nowadays, fixed-order Proportional-Integrative-Derivative (PID) controllers are still the most popular controller types applied to systems. Some authors estimates that about 90% of the operational control-loops in the world have at least one PID controller running (Jelali, 2012). This acceptance is justified by the simple structure presented that provides an easy understanding of the parameters physical meanings. This allows that the operators' experience can be used in controller designing (Wakitani et al., 2013). Even with these facilities, the PID tuning are still very challenging to the operators. According to the recent survey of (Bauer et al., 2016), the main cause for malfunction in closed-loops are the wrong tuning values.

Data-driven or model-free tuning techniques adjust the controller gains directly by using operational or generated data from an experiment instead of an explicit parametric model (Hou and Wang, 2013). In most of the cases, it is used a reference model to describe the control system objective and an optimization is performed to minimize the deviation between the plant and model according to a specified cost function. An overview of these techniques can be found in (Bazanella et al., 2011). Recently, it was developed a new technique that the parameters increments are computed by shaping directly the reference model closed-loop step time response (Gao et al., 2017).

Laboratory scale process have been used as an essential tool in academic studies, helping students to understand industrial applications and close the gap between theory and practice (Feisel and Rosa, 2005). Hence, pilot plants have become popular in most of the universities to demonstrate control-loops operations with common industrial equipments, norms and protocols.

In this paper, a closed-loop data-driven PID tuning technique is evaluated in two pilot plants with different behaviors. The gains increments are optimally computed using time and frequency domain data collected from a specific experiment designed by (Barroso et al., 2015). The time response is shaped to match a desired closed-loop reference model subjected to a frequency constraint, using an extended version of the cost function from (Moreira et al., 2018) that improves the optimization problem from (Gao et al., 2017). This method does not require any parametric process identification, only a time delay estimation. The performance is assessed using gain and phase margins requirements of an IMC-PI tuning and a time domain criteria.

This paper is organized as follows: The problem statement is presented in Section 2. The data-driven tuning strategy is developed using time and frequency domain data in Section 3. The reference model selection is discussed in Section 4. The experiment design is explained in Section 5 and the experimental results for both laboratory scale plants are presented and evaluated in Section 6. The conclusions are discussed in Section 7.

2 Problem Statement

It is analyzed a single-input single-output (SISO) closed-loop as shown in Figure 1. As $r(t)$ the reference signal, $e(t)$ the error signal, $C(s)$ the implemented PID controller, $u(t)$ controller action signal, $G(s)$ the process and $y(t)$ the output signal.

The PID controller has the following form:

$$C(s) = K_p + \frac{K_i}{s} + \frac{sK_d}{T_f s + 1} \qquad (1)$$

where K_p, K_i and K_d are the respectively Propor-

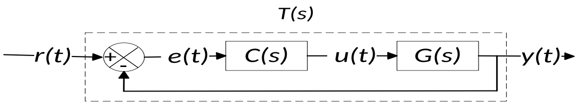

Figure 1: Closed-Loop System

tional, Integrative and Derivative tuning gains, T_f is the first-order derivative filter time constant.

The problem can be stated as: A closed-loop $T(s)$ in a pilot plant has a PID controller tuned, $C(s)$, with arbitrary values. It is defined a new closed-loop reference model $T_r(s)$, then, it is necessary to compute the new controller parameters in order to shape the reference model and satisfy a constraint frequency point.

3 PID Constrained Data-driven Tuning

The new controller tuned $\overline{C}(s)$ is described by the following equations:

$$\overline{C}(s) = (K_p + K_p^{\Delta}) + \frac{(K_i + K_i^{\Delta})}{s} + \frac{s(K_d + K_d^{\Delta})}{T_f s + 1} \tag{2}$$

$$\overline{C}(s) = \left(1 + \frac{K_p^{\Delta} + \frac{K_i^{\Delta}}{s} + \frac{K_d^{\Delta} s}{T_f s + 1}}{C(s)}\right) C(s) \tag{3}$$

where K_p^{Δ}, K_i^{Δ} and K_d^{Δ} are the Proportional, Integrative and Derivative gains increments respectively.

In (Gao et al., 2017), a method that calculates the optimal increments for the PID controller parameters to approximate the closed-loop to a specified reference model $T_r(s)$ are proposed. This is done by a time domain data-driven retuning approach that does not require a complete parametric process identification. The procedure is stated in the following Lemma.

Lemma 1 *Using time domain data collected from a closed-loop step change experiment or generated in operational procedures, it is possible to obtain the optimal increments vector* $\theta_0 = \begin{bmatrix} K_p^{\Delta} & K_i^{\Delta} & K_d^{\Delta} \end{bmatrix}^T$ *that solves the following optimization problem:*

$$\min_{\theta_0} J_1 = ||\Omega - \Phi\theta_0||_2^2 \tag{4}$$

where:

$$\Omega = \begin{bmatrix} H_r(T_s) - H_T(T_s) \\ H_r(2T_s) - H_T(2T_s) \\ \vdots \\ H_r(NT_s) - H_T(NT_s) \end{bmatrix} \tag{5}$$

$$\Phi = \begin{bmatrix} H_{\Delta}^1(T_s) & H_{\Delta}^2(T_s) & H_{\Delta}^3(T_s) \\ H_{\Delta}^1(2T_s) & H_{\Delta}^2(2T_s) & H_{\Delta}^3(2T_s) \\ \vdots & \vdots & \vdots \\ H_{\Delta}^1(NT_s) & H_{\Delta}^2(NT_s) & H_{\Delta}^3(NT_s) \end{bmatrix} \tag{6}$$

as $H_r(kT_s)$ and $H_T(kT_s)$ are the respective $T_r(s)$ and $T(s)$ responses sample for an excitation reference signal at kT_s, as T_s the sampling time. Furthermore, $H_{\Delta}^i(kT_s)$, with $i = 1, 2, 3$, are calculated by simulating the transfer functions product $S_r(s)\Delta_i(s)$ using $H_T(kT_s)$ as input.

The gains are computed by the least square estimation:

$$\theta_0 = (\Phi^T\Phi)^{-1}\Phi^T\Omega \tag{7}$$

Proof: The development uses the relations between the closed-loop system and reference model sensitive functions $S(s)$ and $S_r(s)$ respectively, in the equation:

$$S(s) = S_r(s) + \frac{S_r(s)T(s)}{C(s)}\left[K_p^{\Delta} + \frac{K_i^{\Delta}}{s} + \frac{sK_d^{\Delta}}{T_f s + 1}\right] \tag{8}$$

Further details and the complete development can be found in (Gao et al., 2017). □

In the Lemma of (Moreira et al., 2018), the optimization problem described in Lemma 1 is improved to guarantee system robustness and stability characteristics as gain or phase margins for a PI controller. This Lemma can be also expanded for a PID controller.

Lemma 2 *Using time and frequency domain data collected from a closed-loop experiment or generated in operational procedures, it is possible to obtain the optimal increments vector* $\theta = \begin{bmatrix} K_p^{\Delta} & K_i^{\Delta} & K_d^{\Delta} \end{bmatrix}^T$ *that solves the constrained optimization problem:*

$$\begin{gathered} \min_{\theta} J_2 = ||\Omega - \Phi\theta||_2^2 \\ \textit{subject to } \mathbf{A}\theta - \mathbf{b} = \mathbf{0} \end{gathered} \tag{9}$$

As the optimization problem (9) is convex and the matrices are constant, the solution vector θ can be obtained by the constrained least square estimator analytic formula:

$$\theta = \theta_0 - (\Phi^T\Phi)^{-1}\mathbf{A}^T[\mathbf{A}(\Phi^T\Phi)^{-1}\mathbf{A}^T]^{-1}[\mathbf{A}\theta_0 - \mathbf{b}] \tag{10}$$

where θ_0 is the solution of the unconstrained least square problem.

Proof: The constraint equations are obtained by comparing the resulted $\overline{L}(s)$ and reference $L_r(s)$ loop gains:

$$\overline{L}(s) = \overline{C}(s)G(s) = L_r(s) \tag{11}$$

$$\overline{C}(s) = \frac{L_r(s)}{G(s)} \tag{12}$$

Using the equation (3) at (12):

$$\left(1 + \frac{K_p^{\Delta} + \frac{K_i^{\Delta}}{s} + \frac{K_d^{\Delta} s}{T_f s + 1}}{C(s)}\right) C(s) = \frac{L_r(s)}{G(s)} \tag{13}$$

$$C(s) + K_p^{\Delta} + \frac{K_i^{\Delta}}{s} + \frac{K_d^{\Delta} s}{T_f s + 1} = \frac{L_r(s)}{G(s)} \quad (14)$$

$$K_p^{\Delta} + \frac{K_i^{\Delta}}{s} + \frac{K_d^{\Delta} s}{T_f s + 1} = \frac{L_r(s) - L(s)}{G(s)} \quad (15)$$

Where $L(s) = C(s)G(s)$. The domain is changed from Laplace to frequency, using $s \to j\omega$:

$$K_p^{\Delta} + \frac{K_i^{\Delta}}{j\omega} + \frac{j\omega K_d^{\Delta}}{j\omega T_f + 1} = \frac{L_r(j\omega) - L(j\omega)}{G(j\omega)} \quad (16)$$

$$\left(K_p^{\Delta} + \frac{T_f \omega^2 K_d^{\Delta}}{1 + (T_f\omega)^2}\right) + j\left(\frac{\omega K_d^{\Delta}}{1 + (T_f\omega)^2} - \frac{K_i^{\Delta}}{\omega}\right) = \frac{L_r(j\omega) - L(j\omega)}{G(j\omega)} \quad (17)$$

The equation (17) is organized in matrices:

$$\begin{bmatrix} 1 & 0 & \frac{T_f\omega^2}{1 + (T_f\omega)^2} \\ 0 & -\frac{1}{\omega} & \frac{\omega}{1 + (T_f\omega)^2} \end{bmatrix} \begin{bmatrix} K_p^{\Delta} \\ K_i^{\Delta} \\ K_d^{\Delta} \end{bmatrix} = \begin{bmatrix} \Re\left(\frac{L_r(j\omega) - L(j\omega)}{G(j\omega)}\right) \\ \Im\left(\frac{L_r(j\omega) - L(j\omega)}{G(j\omega)}\right) \end{bmatrix} \quad (18)$$

Hence:

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & \frac{T_f\omega^2}{1 + (T_f\omega)^2} \\ 0 & -\frac{1}{\omega} & \frac{\omega}{1 + (T_f\omega)^2} \end{bmatrix} \quad (19)$$

$$\mathbf{b} = \begin{bmatrix} \Re\left(\frac{L_r(j\omega) - L(j\omega)}{G(j\omega)}\right) \\ \Im\left(\frac{L_r(j\omega) - L(j\omega)}{G(j\omega)}\right) \end{bmatrix} \quad (20)$$

□

Therefore, it is possible to obtain the controller gains that shapes the reference model and it has the same response for a certain frequency data. The reference model selection chosen in this paper is discussed in the following section.

4 Reference Model Selection

In order to apply the tuning strategy described in previous section, it is necessary to define a reference model. Many transfer functions can be used according to the user specification. The simplest case is a FOPTD:

$$T_r(s) = \frac{1}{\tau_c s + 1} e^{-\tau_d s} \quad (21)$$

where τ_c is the parameter closed-loop tuning and τ_d is the process delay.

In this paper, it is assumed that the reference model is tuned according to the IMC PI rules from (Rivera et al., 1986). For this control system design, it is possible to define the $T_r(s)$ by selecting the desired gain A_m or phase margins ϕ_m. This is done by the development in (Acioli Júnior and Barros, 2011) and (Ho et al., 2001) that obtained the following equations:

$$\tau_c = \beta \tau_d \quad (22)$$

$$\beta = \frac{2A_m}{\pi} - 1 \quad (23)$$

$$\phi_m = \frac{\pi}{2}\left(1 - \frac{1}{A_m}\right) \quad (24)$$

Therefore, by measuring the time delay τ_d and defining A_m, ϕ_m or β, it is possible to define $T_r(s)$. Moreover, the gain and phase margins can be estimated and used for comparison with the specified reference model. An experiment design that estimates the margins for the reference model selection and performance assessment is presented in the next section.

5 Experiment Design

As described in the previous section, it is required one frequency response point to perform the tuning procedure. Hence, the closed-loop needs to be excited to obtain the desired information. In (Barroso et al., 2015), it is proposed a closed-loop excitation signal able to estimate the process delay, gain and phase margins. This is done by applying a reference composed as the sequence of three different signals: a step, a standard relay test (Åström and Hägglund, 1984) and a phase margin experiment (de Arruda and Barros, 2003). A simple example of this excitation signal applied in a arbitrary plant is shown in Figure 2.

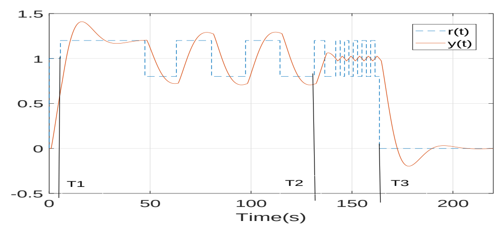

Figure 2: Proposed Excitation Signal Example

5.1 *Gain and Phase Margins Estimation*

Based on the collected data, it is possible to calculate the oscillations crossover and critical frequencies, ω_g and ω_c respectively. Initially, it is necessary to measure a stable limit cycle period during the time intervals $[T_1; T_2]$ and $[T_2; T_3]$ to obtain the estimations $\widehat{\omega}_g$ and $\widehat{\omega}_c$ respectively. Hence, each process frequency response ($G(j\widehat{\omega}_g)$ and $G(j\widehat{\omega}_c)$) can be estimated using the Discrete Fourier Transform (DFT) data from the chosen stable limit cycles.

Thus, assuming that the controller transfer function $C(s)$ is known, the frequency responses $C(j\widehat{\omega}_g)$ and $C(j\widehat{\omega}_c)$ can be calculated. Then, the gain $\widehat{A}_m$ and phase margins $\widehat{\phi}_m$ are estimated by:

$$\widehat{A}_m = \frac{1}{|G(j\widehat{\omega}_c)C(j\widehat{\omega}_c)|} \tag{25}$$

$$\widehat{\phi}_m = \pi + \angle G(j\widehat{\omega}_g)C(j\widehat{\omega}_g) \tag{26}$$

Therefore, it is possible to estimate two frequencies points and utilize them in the tuning method. Moreover, the estimated margins $\widehat{A}_m$ and $\widehat{\phi}_m$ can be used to evaluate the control system performance by comparing with the reference margins A_{ref} and ϕ_{ref} stated by the reference model $T_r(s)$.

6 Application to the Pilot Plants

In order to evaluate the technique efficiency in real processes, the proposed data-driven tuning strategy was applied to two laboratory-scale plants with different characteristics. In each of them, it was chosen a SISO control-loop tuned with an arbitrary PID. The reference closed-loop model was specified to behave as a FOPTD described in equation (21) and it is defined that the gain reference margin, A_{ref}, is equal to 3 and the reference phase margin, ϕ_{ref}, by equation (24) is 60º. In both cases, it is used the critical frequency in the constraint matrices. The required information is obtained from the proposed excitation signal application by the procedures discussed previously.

The experimental results are assessed using the gain ($\widehat{A}_m$) and phase margin ($\widehat{\phi}_m$) estimations. Moreover, the time performance is also evaluated by the normalized root mean square (NRMSE) criteria:

$$\epsilon = 100\left(1 - \frac{||y(kT_s) - \hat{y}(kT_s)||}{||y(kT_s) - mean(y(kT_s))||}\right) \tag{27}$$

where kT_s is the sampling instants, T_s is the sampling time, $y(kT_s)$ is the actual output of the process, $\hat{y}(kTs)$ is the estimated output and $mean(y(kT_s))$ the process output mean. As the proposed reference signal has different duration for each tuning, the index ϵ is computed for a step response.

6.1 Thermoelectric Process

The experimental setup is a laboratory-scale thermoelectric process made up of two Peltier elements with independent activation by H bridge circuits in a thermally coupled arrange. In addition to the Peltier modules, the plant has four aluminum plates, four LM35 temperature sensors, two fans, two heat exchangers, a PLC (Programmable Logic Controller) and a PC with SCADA (Supervisory Control And Data Acquisition). The communication between the PC and

Table 1: Estimated Parameters for Thermoelectric Process

	$\widehat{A}_m$	$\widehat{\phi}_m$	$\widehat{\omega}_c$	$\widehat{\omega}_g$
Initial	6.0006	75.8547	0.0763	0.0149
Final	2.9922	68.2411	0.0838	0.0296
Reference	3	60	0.1212	0.0313

PLC is based in OPC (OLE for process control) architecture client. The pilot plant schematic is illustrated in Figure 3. Based on the inputs and outputs available in the module, it was chosen as input the PWM duty cycle (%) applied in the Peltier module and the measured temperature in an arbitrary plate as output ($°C$).

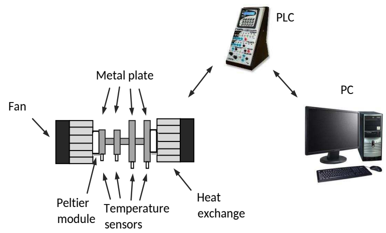

Figure 3: Thermoelectric Process schematic

Initially, the PID controller was tuned using arbitrary values, equation (28). Then, the proposed reference signal was applied to the closed-loop. The output and reference signals behaviors are shown in Figure 4.

$$C_1(s) = 2.351 + \frac{0.0244}{s} + \frac{18.2649s}{0.1s + 1} \tag{28}$$

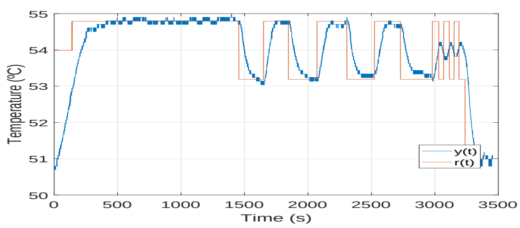

Figure 4: Experiment Behavior for the Initial Tuning in Thermoelectric Process

Based on the collected data and the procedure discussed previously, it was possible to estimate gain margin, phase margin, critical and crossover frequencies as listed in Table 1.

It is assumed that the process has a time delay of $17s$. Then, the reference model is defined according to the requirements defined previously and the equations (23) and (24):

$$T_{r1}(s) = \frac{1}{15.47s + 1}e^{-17s} \tag{29}$$

As the estimated margins do not match with the desired model, listed in Table 1, it is necessary to tune the PID parameters. The data-driven technique computed the new controller using the collected information:

$$\overline{C}_1(s) = 5.4979 + \frac{0.0427}{s} + \frac{47.9678s}{0.1s+1} \tag{30}$$

The proposed excitation signal was applied again in the closed-loop using the same conditions to performance assessment. Using the data collected from the new experiment, it was obtained the new estimated gain margin, phase margin, critical and crossover frequencies as listed in Table 1. The NRMSE index is obtained is 56.45% and 73.3% for initial and final tunings respectively. The step response for both tunings is illustrated in Figure 5.

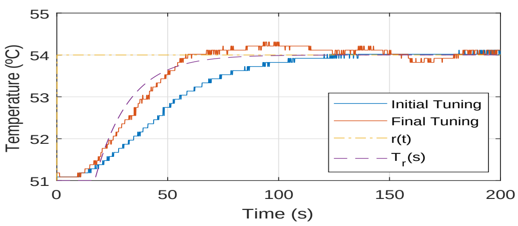

Figure 5: Reference Step Experiment in Thermoelectric Process

The margins estimations are much closer to the reference than the estimated using the initial PID controller and the NRMSE was increased for the new tuning. Hence, it is possible to verify that the computed gains improved the system performance.

6.2 Quadruple-Tank Coupled System

The proposed strategy was applied also in a level control-loop of the quadruple-tank coupled system didactic plant, shown in Figure 6. This plant has four tanks of different sizes, two hydraulic pumps, two frequencies inverters, six differential pressure transmitters, two electric valves, PLC and a PC with SCADA. Further details can be found in (Santos et al., 2009).

Figure 6: Quadruple-Tank Coupled Plant

It was chosen a SISO level control loop available, where the input is the valve opening (%) and output is the tank level (%). The PID controller was initially tuned with the values in equation (31). As the previous process, the initial gain margin, phase margin, critical and crossover frequencies were estimated by the procedure discussed, listed in Table 2. The output and reference signals behaviors are shown in Figure 7.

Table 2: Estimated Parameters for Quadruple-Tank Coupled Plant

	$\widehat{A}_m$	$\widehat{\phi}_m$	$\widehat{\omega}_c$	$\widehat{\omega}_g$
Initial	4.6086	65.8671	1.1424	0.1454
Final	2.9454	63.0252	1.1424	0.2087
Reference	3	60	1.1448	0.2953

$$C_2(s) = 1.93 + \frac{0.0877}{s} + \frac{3.06s}{0.1s+1} \tag{31}$$

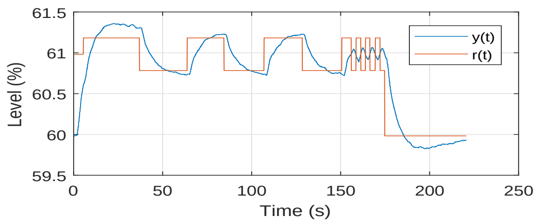

Figure 7: Experiment Results for the Initial Tuning in Quadruple-Tank Coupled System

Based on the requirements defined in this section, assuming a time delay of 1.8s and using equations (23) and (24), the reference model is:

$$T_{r2}(s) = \frac{1}{1.638s+1}e^{-1.8s} \tag{32}$$

The respective margins and frequencies are listed in Table 2. Applying the data-driven tuning technique proposed, it is possible to obtain the new controller gains:

$$\overline{C}_2(s) = 3.14 + \frac{0.21}{s} + \frac{4.32s}{0.1s+1} \tag{33}$$

The new gain margin, phase margin, critical and crossover frequencies were estimated and listed in Table 2. The NRMSE obtained was 55.65% and 60.43% for initial and final tunings respectively. This small improvement can be explained by the process physical limitations and nonlinearities and the controller structure that do not allow a better fit. However, the resulted margins have values closer to the specifications. The step response for both tunings is illustrated in Figure 8.

7 Conclusions

In the previous sections, it was discussed a closed-loop data-driven PID tuning technique using time and frequency domain responses. From a given PID controller in a closed-loop, the optimal increments gains are computed in order to adjust the closed-loop behavior closer as possible to a reference model constrained by a specific frequency response point. To perform this technique, it is

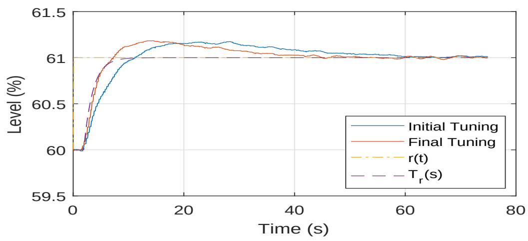

Figure 8: Reference Step Experiment in Quadruple-Tank Coupled System

necessary to have one frequencies point. The data is obtained by applying the an establish reference signal capable to estimate crossover and critical frequencies. To validate the proposed tuning method, the technique is demonstrated in two pilot plants with different behaviors, a thermal plant based on Peltier effect and a level control loop of a quadruple-tank system.

Based on the computed indexes ϵ, $\widehat{A}_m$ and $\widehat{\phi}_m$, the results were capable to adjust the system performance to make the closed-loops have a similar response to the defined reference model and the desired frequency specifications, even with the controller structure limitations and process nonlinearities. Therefore, this data-driven tuning technique can be used to improve closed-loops performances.

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