VARIABILITY REDUCTION STRATEGY FOR PROCESSES WITH PID CONTROLLERS AND OSCILLATORY DISTURBANCES

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ABSTRACT

The quality and cost of several industrial product's plants are affected by variability and disturbances that appear in processes. Oscillatory disturbances are harmful both because they affect mechanical components and because their propagation leads to an increase in the variance of the plant. Poor performance of the control system plus oscillatory disturbances leads to a higher cost of production. This research develops a technique for reducing variability in control loops for processes with PID controllers against oscillatory disturbances by re-tuning the controller, obtaining better results than traditional tunings while decreasing cost production by reduction of process variance. A factorial experiment was designed to obtain tuning equations of the controller to attenuate the effect of an oscillatory disturbance to the control loop. Two experiments were performed: the proportional controller (P) and the other for the Proportional-Integral controller (PI). The response variable is lambda λ, which is the parameter that is varied in the range $\lambda = [-0.9t_0, 10t_0]$ for each experimental condition. The design concept of this control strategy is that when an oscillatory disturbance occurs, instead of designing the controller to reach the setpoint, it is re-tuned to act as the best possible filter. Due to this, a performance criterion was defined that sought to minimize the effect of an oscillatory disturbance. The equations developed in this research are limited to self-regulated processes, where proportional (P) or proportional-integral (PI) controllers are implemented. The ranges of the process parameters are those specified in this research. This technique is not limited or restricted to processes with a single control loop because the modification is done on each individual controller. This strategy can be extended to more controllers without additional mathematical developments since this self-tuning technique when operating on each controller individually, seeks to cancel a disturbance that affects each controller independent of the control action of other adjacent controllers. Each controller perceives a behavior and applies the technique to know if the source of the disturbance comes from itself or a disturbance, if the oscillation is not the cause of itself (the controller) then it is due to a disturbance. An index that seeks to minimize the amplitude of this oscillation is proposed. If the oscillation cannot fade, at least its impact can be decreased by reducing its amplitude. By reducing the amplitude, the output can be kept as close as possible to its average value, which is the setpoint from a control engineering perspective. The standard deviation is an ideal statistic for this function since it quantifies the amount of variation in a data set. A lower value of the standard deviation would indicate that the data tend to be closer to the mean (the setpoint). In contrast, a high value of the standard deviation would show that the data are spread over a wider area farther away from the setpoint.

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Keywords: PID Controllers, Oscillatory Disturbances

INTRODUCTION

Despite the significant advantages that the implementation of control loops brings, many times the results do not reach their maximum performance, this due to the poor tuning of the controller (among other reasons), which can lead to slow response, aggressive or oscillatory of the control loop, poor ability to reject disturbances, poor robustness, and even safety problems (Cardenas, 2019; Jelali, 2013), Bialkowski pointed out that only 20% of the controllers work well and actually decrease the variability of the process. Desborough and Miller (Desborough, 2002) mention that only a third of the controllers can be classified as acceptable, and the rest have an excellent opportunity for improvement. Due to this, controllers are frequently operated in manual mode or present a poor or acceptable performance; in fact, about two-thirds of all these controllers have an opportunity for improvement (Hugo, 2001; Hugo, 2021; Choudhury, 2008; Borrero-Salazar, 2019), shown in Figure. 1.

The most common causes of control performance deterioration are poor controller tuning, equipment failures, poor process design, interactions between loops, presence of non-linearities and oscillations. Of these behaviors, the presence of unwanted oscillations is usually more detrimental because it decreases the control system's performance and affects the mechanical components in the process. More than 30% of the control loops show an oscillatory behavior (Hägglund, 1995; Ding, 2021; Escalante-Hurtado, 2021; Jiménez-Cabas, 2020). These oscillations may have a particular origin, but they can spread rapidly from one loop to another and from one processing unit to another (Choudhury, 2008; Gómez Múnera, 2021; Zheng, 2021), such as feedback loops or interactions between control loops. These oscillations have been reported to increase process variability, causing lower quality products, high reject rates, increased energy consumption, and low average system performance (production capacity).

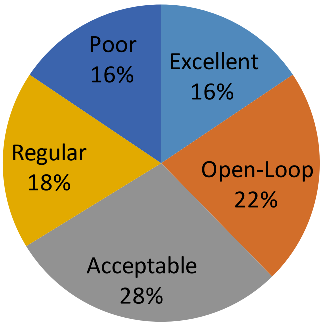

FIGURE 1
GLOBAL MULTI-INDUSTRY DEMOGRAPHICS OF CONTROL LOOP PERFORMANCE

The presence of oscillatory disturbances is detrimental not only because it affects the mechanical components of the process but also because the oscillatory effect spreads from one loop to another and from one process to another. This increase in variance results in poor process performance and variability in product quality, leading to economic and market losses. The literature review carried out indicates that both traditional and recently developed tuning strategies focus on improving the performance of the control loop under step or stable stimulus without considering the performance of the loop under induced and recurrent oscillations (Hägglund, 1995; Ding, 2021, Patwardhan, 2008; Wang, 2021; Nowak, 2020).

Considering that the existence of oscillatory disturbances derived from dynamics upstream of the process is regarded as a possible cause of action of the control loop (Choudhury,

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2008), the present work presents the development of a controller tuning technique with which it is sought to reduce variability in the face of oscillatory disturbances.

Control Loop System

This research applies to processes that respond with a bounded response when affected by a bounded input (also called Self-regulating processes); the system "regulates" itself to a new bounded value (Smith, 2005; Jiménez-Cabas, 2020). Most of industrial plants have this type of behavior, i.e., thermal-mechanical, and chemical, where variables like pressure, temperature, level, etc., are measured and controlled. The most commonly used controller is the PID type (Gao, 2016; Wang, 2021). These controllers frequently are not tuned for oscillating input disturbances; they regularly are tuned for step-like inputs. The typical control system configuration is shown in Figure 2.

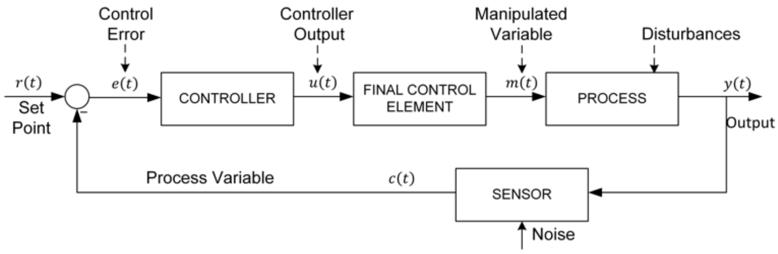

FIGURE 2
BLOCK DIAGRAM OF THE COMPONENTS OF A CLOSED-LOOP CONTROL SYSTEM

The general structure of a Proportional-Integral-Derivative PID controller is shown in(1). The tuning of a controller refers to K_C, τ_I and τ_D, also called tuning values. The tuning values selection is chosen in such a way that the desired behavior is obtained in the response of the control loop, in other words, that its dynamic characteristic, or "personality," is the desired one; This is done by taking into account both the controller and the other elements in the control loop (Smith, 2005; Múnera, 2020). These tuning parameters are chosen by optimizing an objective function or cost function that assesses the performance of the PID controller under a certain pre-defined or expected "personality" (Sahib, 2016).

$$u(t) = \bar{u} + K_C e(t) + \frac{K_C}{\tau_I}\int e(t)\,dt + K_C \tau_D \frac{de(t)}{dt} \tag{1}$$

Usually, control loops have been tuned under the assumption of a step like input either in the setpoint $C^{SET}(s)$ or in the disturbance $D(s)$ and performance criteria based on control error have been proposed (Rise Time, Settling Time, Decay Ratio, Overshoot, IAE, etc.) since the behavior of the closed-loop transfer function (CLTF) has a nature of a second-order system under-damped response. However, oscillating inputs have not been used for tuning controller design. Numerical simulation and Frequency Response Techniques are used in this research to analyze the above situation. The main variables are input disturbances and outputs from processes. The effect of an oscillating disturbance input in the process output controlled variable is analyzed.

Performance Criteria

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The following section analyzes the output of a control system in closed-loop. The reader is advised to recall that the closed-loop transfer function (CLTF) behavior has a nature of a second-order system under-damped response. For a step type input with magnitude Δx, $x(t)=\Delta x u(t)$, the output takes the form:

$$C(t)=K\Delta x\left[u(t)-\frac{1}{\sqrt{1-\zeta^2}}e^{-(\zeta/\tau)^t}\sin(\psi t+\phi)\right], \tag{2}$$

where $\psi=\sqrt{1\text{-}\zeta^2}\Big/\tau$ is the frequency in rad/s and $\phi=\tan^{-1}\left(\sqrt{1\text{-}\zeta^2}\Big/\tau\right)$ is the phase angle in rad.

Equation (2) shows that a step input causes an oscillatory behavior in the loop by some time; however, after some time, say $t=t_s$, the oscillatory part vanishes, as indicated by the term $e^{-(\zeta/\tau)^t}$. However, for an oscillatory input, for example, sinusoidal, with an amplitude A and a frequency ω, $x(t)=A\sin(\omega t)$, the output has the form:

$$C(t)=KADe^{-(\zeta/\tau)^t}\sin(\psi t+\phi)+\frac{KA}{\sqrt{\left(1-\tau^2\omega^2\right)^2+\left(2\zeta\tau\omega\right)^2}}\sin(\omega t+\theta), \tag{3}$$

where $\theta=\tan^{-1}\left(2\zeta\tau\omega\Big/\left(1\text{-}\tau^2\omega^2\right)\right)$ is the phase angle in radians.

The values of the first term are not very relevant since this term fades over time. The importance is that after that time, the output becomes an oscillatory output, in this case an oscillatory sinusoidal-like, as is shown by the second term $\sin(\omega t+\theta)$, with the same frequency as the frequency of the input signal. The amplitude and phase angle of the output are functions of the input signal frequency.

Traditionally, several investigations have used indices or performance criteria based on loop behavior against step-type input, obtaining performance criteria for the control loop such as the rate of decay, the rise time, overshoot, those based on the IAE, (Smith, 2005; Sahib, 2016). All these criteria work very well for this type of input (step-type), where the output converges to a fixed value over time. The previous does not apply for an oscillatory input since the output will have a sustained oscillatory behavior without reaching a fixed value in time because the nature of the input is different.

Due to the above, an index that seeks to minimize the amplitude of this oscillation is proposed. If the oscillation cannot fade, at least its impact can be decreased by reducing its amplitude. By reducing the amplitude, the output can be kept as close as possible to its average value, which is the setpoint from a control engineering perspective. The standard deviation is an ideal statistic for this function since it quantifies the amount of variation in a data set. A lower value of the standard deviation would indicate that the data tend to be closer to the mean (the setpoint). In contrast, a high value of the standard deviation would show that the data are spread over a wider area farther away from the setpoint. The general structure of the standard deviation of a data sample is:

$$\sigma=\sqrt{\frac{\sum_{i=1}^{N}\left(x_i-\bar{x}\right)^2}{N-1}} \tag{4}$$

On the other hand, the amplitude of the input disturbance, besides being unknown, cannot be modified. Therefore, the index intends to minimize the standard deviation of the output. The previous is possible by recalling that the controller affects the control loop response by being present in the characteristic equation of the loop, as will be seen next. In the event of

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an oscillatory disturbance, the desired behavior of the controller in the control loop will be that of a filter, since although the oscillation cannot fade, it is possible to reduce its impact by designing the controller as a filter. In this way, the attenuation index (*AI*) is defined, which is focused on reducing the amplitude of the controlled variable:

$$AI = \frac{\sigma_{PV}}{\sigma_D} \tag{5}$$

where σ_{PV} is the standard deviation of the controlled variable (Process Variable, PV) and σ_D is the standard deviation of the oscillatory disturbance (disturbance, D).

The impact obtained with the designed re-tuning strategy can be expressed by the ratio of the attenuation index with the proposed tuning versus the attenuation index with the traditional tuning as follows

$$\eta_{AI} = \frac{AI_{re-tunned}}{AI_{original}} \tag{6}$$

It is worth mentioning that this indicator should oscillate between 0 and 1. A zero value would be obtained with a tuning that eliminates the oscillation presented (ideal case not feasible). A value of one would be obtained by remaining with the original tuning (without changing the initial tuning). A better filtering effect of the controller occurs the lower the value of η_{AI}. A value above one in the calculation of η_{AI} indicates that the tuning used worsens the initial situation.

Tuning Equation for an Oscillatory Input

The control system to consider is a Single-Input Single-Output, or commonly called SISO system, operating with a feedback controller, as shown in Fig. 3 $G_P(s)$ is the process transfer function, $G_D(s)$ is the disturbance transfer function, and $G_C(s)$ is the controller transfer function. The performance and stability of the control loop is defined by the components present in its loop, $G_P(s)$, $G_D(s)$ and $G_C(s)$.

$$G_C(s) = \frac{M(s)}{E(s)} = K_C\left(1 + \frac{1}{T_I s} + \frac{T_D s}{\alpha T_D s + 1}\right) \tag{7}$$

The transfer function of a PID controller with derivative filtering mode is shown in (7). Industrial Processes are usually represented with a FOPDT (First-Order-Plus-Dead-Time) transfer function. They can also be modeled using a more complex structure, using differential equations proposed in [24]. However, the FOPDT model has been used in this research:

$$G_P(s) = \frac{C(s)}{M(s)} = \frac{K_P e^{-t_0 s}}{\tau s + 1} \tag{8}$$

The parameters of this model are the process constant K_P, the process dead time t_0 and the process time constant τ. Practice in control engineering applications indicates that controller tunings based on this empirical model result in good control loop performance near the conditions used for process characterization. The non-linear behavior of the process is reflected in changes in some (or all) of these parameters as the real-operating conditions change.

A factorial experiment was designed to obtain tuning equations of the controller to attenuate/filter the effect of an oscillatory disturbance to the control loop. Two experiments were performed: the proportional controller (P) and the other for the Proportional-Integral controller

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(PI). The response variable is lambda λ, which is the parameter that is varied in the range $\lambda = \left[-0.9t_0, 10t_0\right]$ for each experimental condition.

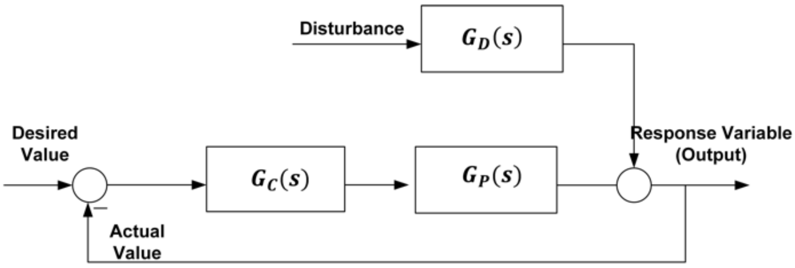

FIGURE 3
SISO FEEDBACK CONTROL LOOP

λ is the parameter that affects the tuning of the controller, as shown in the following equation:

$$K_C = \frac{\tau}{K_P\left(\lambda + t_0\right)} \tag{9}$$

The optimal lambda λ in each experimental condition is the one that leads to the minimization of the index defined previously, the attenuation index AI, which is focused on reducing the amplitude of the controlled variable. Figure 4 shows the scheme of the dynamic model implemented in Simulink^{TM} to carry out the experiment. For the process block, a FOPDT was used to model the process, and for the controller block, the equations corresponding to controller P and PI were used, as described in the previous section.

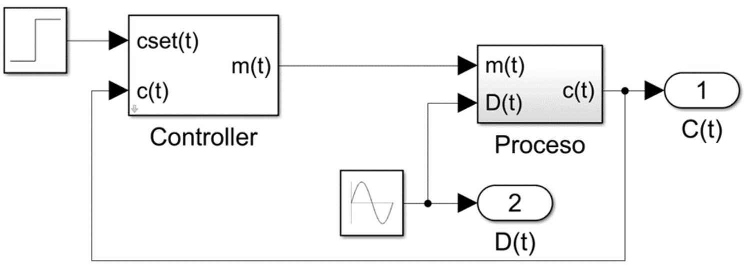

FIGURE 4
BLOCK DIAGRAM IMPLEMENTED IN SIMULINK^{TM} FOR THE EXPERIMENT

A three-level factorial experiment of the form 3^k was carried out to observe the linear and non-linear correlations between the process parameters and the optimal tuning. This experiment includes four factors, and 162 experimental runs were performed for each controller. The factors are ω, K_P, τ and t_0/τ which are the angular frequency of the oscillatory disturbance, the process gain, the process time constant, and relationship between dead time and time constant, respectively. It was unnecessary to carry out replications because this experiment is a deterministic computational test, and the repetition of the factor levels would bring the same results. A fractional design was not carried out to preserve the number of degrees of freedom and, therefore, the robustness and reliability of the equations obtained. Table I shows the levels selected for each experimental factor. The response variable of the experiment is lambda which, as explained previously, is the parameter that provides optimal tuning. The levels of each experimental factor were selected by taking a broader range of dynamic process parameters than other sets of tuning equations (Beltrán, 2018).

TABLE 1

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LEVELS OF EXPERIMENTAL FACTORS OF THE DYNAMIC PARAMETERS OF THE PROCESS FOR THE EXPERIMENT OF OPTIMAL TUNING				
	FACTORS			
	A	**B**	**C**	**D**
LEVELS	ϖ	K_P	τ	t_0/τ
Low	0.1	0.5	1	0.2
medium	0.5	1.5	3	0.6
high	1	2.5	5	1

Tuning Equation for Proportional controller (P)

Table 2 presents the ANOVA of the experiment carried out for the proportional controller. Here it can be seen that the factor t_0/τ does not significantly affect the response variable lambda, while the factors ϖ, K_P, and τ do. The previous is verified by performing a correlation analysis between the factors and the response variable, shown in Table 3, which shows the same trend.

Table 2 ANALYSIS OF VARIANCE FOR THE RESPONSE VARIABLE LAMBDA FOR THE PROPORTIONAL CONTROLLER					
Source	**Sum of Squares**	**DF**	**Mean Square**	**F-test**	**P-value**
MAIN EFFECTS					
Factor A: ϖ	20378. 0	2	10189. 0	128203. 23	0. 0000
Factor B: K_P	1464. 07	2	732. 035	9210. 85	0. 0000
Factor C: τ	2357. 45	2	1178. 72	14831. 33	0. 0000
Factor D: t_0/τ	0. 0581481	2	0. 0290741	0. 37	0. 6948
INTERACTIONS					
AB	5153. 32	4	1288. 33	16210. 46	0. 0000
AC	2740. 67	4	685. 168	8621. 14	0. 0000
AD	0. 0514815	4	0. 0128704	0. 16	0. 9570
BC	10962. 4	4	2740. 6	34483. 63	0. 0000
BD	0. 269259	4	0. 0673148	0. 85	0. 4995
CD	0. 429815	4	0. 107454	1. 35	0. 2580
ABC	37944. 7	8	4743. 08	59679. 98	0. 0000
ABD	0. 473333	8	0. 0591667	0. 74	0. 6521
ACD	0. 925278	8	0. 11566	1. 46	0. 1867
BCD	0. 2575	8	0. 0321875	0. 41	0. 9146
ABCD	0. 454352	16	0. 028397	0. 36	0. 9882
RESIDUALS	6. 4375	81	0. 0794753		
TOTAL (CORRECTED)	81009. 9	161			

After more than 300 iterations in the search for a suitable regression model, the following equation for lambda was obtained

$$\lambda = -0.67938 K_P \tau^{1.014} + 0.012396 \frac{t_0}{\omega} \tag{10}$$

Achieving an adjusted R^2 of 0.99. A p-value of 1.34×10^{-129} for the model. The p-values of the coefficients are shown in Table IV.

Tuning Equation for Proportional-Integral (PI) Controller

Table VII presents the ANOVA of the experiment carried out for the Proportional-Integral controller. Here it can be seen that the factor K_P does not significantly affect the

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response variable lambda, while the factors ω, τ and t_0/τ do. The previous is verified by performing a correlation analysis between the factors and the response variable, shown in Table V, which shows the same trend.

After more than 300 iterations in the search for a suitable regression model, the following equation for lambda was obtained for the PI controller:

$$\lambda = -0.045297\tau t_0^{\ 1.014} - 0.32272\sin\left(\frac{t_0}{\tau}\right) \tag{11}$$

Achieving an adjusted R^2 of 0.932. A p-value of $2.27\text{x}10^{-90}$ for the model. The p-values of the coefficients are shown in Table VI.

Table 3
ANALYSIS OF VARIANCE FOR THE RESPONSE VARIABLE LAMBDA FOR THE PROPORTIONAL-INTEGRAL CONTROLLER

Source	Sum of Squares	DF	Mean Square	F-test	P-value
MAIN EFFECTS					
Factor A: ω	4349. 25	2	2174. 62	308376. 20	0. 0000
Factor B: K_P	0. 00677531	2	0. 00338765	0. 48	0. 6203
Factor C: τ	1910. 53	2	955. 265	135462. 97	0. 0000
Factor D: t_0/τ	1902. 83	2	951. 415	134917. 03	0. 0000
INTERACTIONS					
AB	0. 00289877	4	0. 000724691	0. 10	0. 9812
AC	4735. 85	4	1183. 96	167893. 93	0. 0000
AD	4734. 57	4	1183. 64	167848. 50	0. 0000
BC	0. 0160395	4	0. 00400988	0. 57	0. 6861
BD	0. 0226617	4	0. 00566543	0. 80	0. 5265
CD	467. 454	4	116. 863	16572. 03	0. 0000
ABC	0. 0468642	8	0. 00585802	0. 83	0. 5782
ABD	0. 023042	8	0. 00288025	0. 41	0. 9127
ACD	6454. 87	8	806. 858	114417. 94	0. 0000
BCD	0. 0285235	8	0. 00356543	0. 51	0. 8488
ABCD	0. 107728	16	0. 00673302	0. 95	0. 5125
RESIDUALS	0. 5712	81	0. 00705185		
TOTAL (CORRECTED)	24556. 2	161			

Detection of Oscillations in the Control Loop

The authors decide to use the detection method of oscillations proposed in (Sanjuan, 2006) called the Peak Detection Algorithm. The peak detection algorithm assumes that the oscillatory closed-loop response can be identified as a second-order pattern. The parameters to be determined from the observed oscillatory behavior are the damped natural frequency, ω_D and the damping ratio, ζ, which can be calculated from a dynamic analysis of the closed-loop system step response, as indicated in (Sanjuan, 2006).

In addition to these parameters, the regularity of the oscillation is also calculated to ensure that it is a sustained oscillation and not make a false detection. The regularity of an oscillatory signal is translated into a quantity that represents non-random behavior. If the variation in the signal is due to random disturbances, the period of oscillation will maintain a wider distribution compared to that of a true oscillatory nature. The regularity of the oscillations can be defined as

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$$r = f\left(\frac{\bar{T}_p}{\sigma_{T_p}}\right), \tag{12}$$

where $\bar{T}_P$ is the mean value, and σ_{T_p} the standard deviation of the periods T_{pi}, in adjacent signal intervals.

A regular oscillation will cross the mean of the signal at regular intervals. Therefore, the intervals between zero crossings of an oscillatory time trend can be exploited for on-line detection of oscillations: the deviation of the intervals between zero crossings is compared to the length of the mean interval; a small deviation indicates an oscillation. The threshold selection is independent of the signal, that is, it is not necessary to scale the individual signals. However, noise can cause "false" crossovers, and the derivative and transients will destroy the notion of the mean of the signal. Instead of observing the zero crossings of the trend over time, in [27] is suggested using the zero crossings of the ACF. By following the regularity of the period, an oscillation can be detected. Regularity is evaluated using a statistic, r, called the regularity factor. This statistic is derived from the sequence of ratios between adjacent intervals Δt_i in which the deviations cross the threshold. Therefore, the mean period of the oscillation $\bar{T}_p$ can be determined from

$$\bar{T}_p = \frac{2}{n}\sum_{i=1}^{n}\left(t_i - t_{i-1}\right), \tag{13}$$

and the dimensional regularity factor as [27]:

$$r = \frac{1}{3}\frac{\bar{T}_p}{\sigma_{T_p}}, \tag{14}$$

where σ_{T_p} is the standard deviation of T_{pi}. The regularity factor r can be considered as an index of oscillation. An oscillation is considered regular with a well-defined period if r is greater than unity.

Table 4
CORRELATION ANALYSIS BETWEEN EXPERIMENTAL FACTORS AND LAMBDA RESPONSE VARIABLE FOR THE PROPORTIONAL CONTROLLER

	ω	K_P	τ	t_0/τ	t_0	λ
ω	1					
K_P	0. 0219	1				
τ	-0. 0219	0. 2357	1			
t_0/τ	1. 4025$x10^{-7}$	5. 1522 $x10^{-7}$	-2. 0818 $x10^{-7}$	1		
t_0	-0. 0147	0. 1586	0. 6731	0. 6424	1	
λ	-0. 1177	-0. 7434	-0. 7247	-8. 5285 $x10^{-9}$	-0. 4878	1

Table 5
REGRESSION COEFFICIENT ESTIMATION FOR PROPORTIONAL CONTROLLER

Coefficient	Estimated value	Sum of Squares	T-test	P-value
B1	-0. 67938	0. 021621	-31. 422	4. 52E-57
B2	1. 014	0. 020791	48. 772	8. 27E-77
B3	0. 012396	0. 0020903	5. 9306	3. 48E-08

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Table 6
CORRELATION ANALYSIS BETWEEN EXPERIMENTAL FACTORS AND LAMBDA RESPONSE VARIABLE FOR THE PROPORTIONAL-INTEGRAL CONTROLLER

	ω	K_P	τ	t_0 / τ	t_0	λ
ω	1					
K_P	0. 01710807	1				
τ	-0. 01513448	0. 00411182	1			
t_0 / τ	-0. 03824361	0. 00591568	0. 05721437	1		
t_0	0. 02803798	0. 00595118	0. 67580389	0. 67911174	1	
λ	0. 00338221	-0. 00661915	-0. 66460229	-0. 66998538	-0. 96931082	1

Table 7
REGRESSION COEFFICIENT ESTIMATION FOR PROPORTIONAL-INTEGRAL CONTROLLER

Coefficient	Estimated value	Sum of Squares	T-test	P-value
B1	-0. 045297	0. 0049147	-9. 2168	1. 05E-15
B2	1. 0405	0. 066527	15. 64	5. 03E-31
B3	-0. 32272	0. 029814	-10. 824	1. 37E-19

General Scheme of the Designed Strategy

This section presents a flow chart of the designed strategy. The strategy is to monitor the controlled variable or sensor output signal and the controller's output signal. Using the peak detection algorithm and the regularity index, the existence or not of a sustained oscillation in the controlled variable is detected. Considering the presence of this sustained oscillation, the controller output is forced to the mean value of its signal (since the controlled variable is oscillatory, the controller output is also oscillatory), leaving it fixed for a time equivalent to five times the period of the oscillation detected. Suppose the oscillatory behavior is maintained in the controlled variable. In that case, it is determined that this is the cause of a disturbance (or multiple disturbances), and the controller is re-tuned using the equations obtained in this investigation. Finally, it is verified that the performance of the loop improved, corroborating that the attenuation index (AI) is lower compared to before performing the re-tuning, if indeed the AI is lower, the execution of the strategy is terminated; if not, a notification is sent to the control engineer to take action on this loop. Fig. 8 and Fig. 9 describe the designed method.

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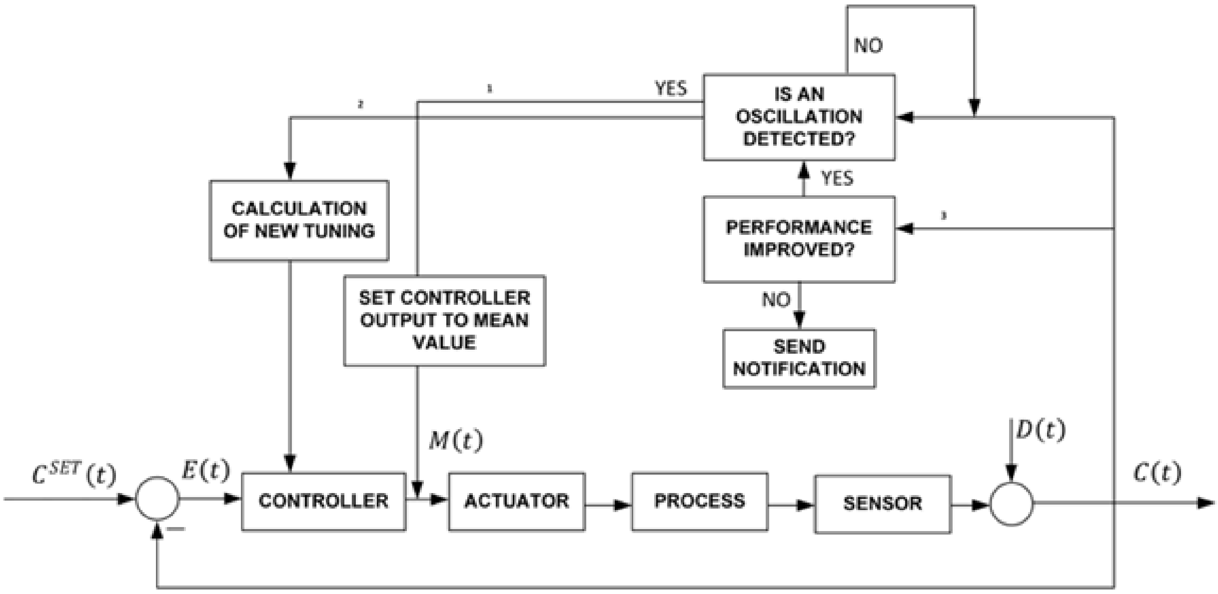

FIGURE 5
BLOCK DIAGRAM OF THE DESIGNED STRATEGY

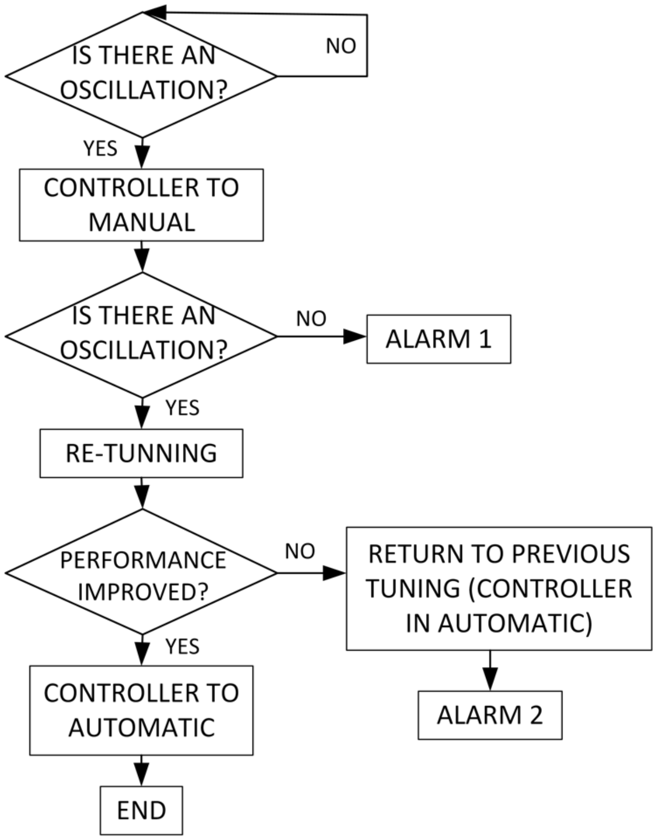

FIGURE 6
FLOW CHART OF THE DESIGNED STRATEGY

RESULTS

In this section, the equations obtained by implementing them are checked to control a general process modeled with a FOPDT and a controller in a closed-loop system under an oscillatory disturbance.

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The case of a steady-state process modeled as a FOPDT is considered, with parameters $K_P = 0.5\frac{\%TO}{\%CO}$, $\tau = 3\text{min}$, $t_0 = 3\text{min}$ (%TO = transmitter output, %CO = controller output). The steady-state value of the sensor output is $\bar{C}(t) = 18.4674\ \%TO$ and the controller output is $\bar{M}(t) = 38.7298\ \%CO$. A noise in the sensor signal of $0.5\ \%TO$ is considered. An oscillatory disturbance is considered, in this case, a sinusoidal with amplitude $A = 5$ and angular frequency $\omega = 0.5\ rad/s$. The programs were developed in Matlab^{TM}, and the simulations were built in Simulink^{TM}. The block diagram of the simulation is shown in Fig. 4. The following table compares the results of the control performance using a traditional tuning vs. that obtained experimentally. The "experimental" row was obtained from the data obtained from the experimental runs carried out during the experiment. In contrast, the "Ex. Experimental" was obtained directly from the equation obtained in equations (10) and (11).

Table 8
SUMMARY OF RESULTS OBTAINED IN THE IMPLEMENTATION OF THE DESIGNED

Controller Type	Tuning Used	AI	% Improvement	η_{AI}
Proportional (P)	Traditional	1. 5261	-	1. 0000
	Experimental Eq.	1. 6381	-7. 34 %	1. 0725
	Experimental	1. 0443	31. 57 %	0. 6843
Proportional-Integral (PI)	Traditional	0. 3994	-	1. 0000
	Experimental Eq.	0. 3293	17. 5 %	0. 8245
	Experimental	0. 1567	60. 77 %	0. 3923

CONCLUSIONS & FUTURE WORK

The design concept of this control strategy is that when an oscillatory disturbance occurs, instead of designing the controller to reach the setpoint, it is re-tuned to act as the best possible filter. Due to this, a performance criterion was defined that sought to minimize the effect of an oscillatory disturbance. The equations developed in this research are limited to self-regulated processes, where proportional (P) or proportional-integral (PI) controllers are implemented. The ranges of the process parameters are those specified in this research.

In thermo-mechanical processes, it is rare for disturbances with a pure oscillatory nature to occur, as it may occur in electrical or mechanical processes. However, in a thermo-mechanical process an oscillation can occur due to factors such as upstream control loops (i.e. poor tuning or non-linearities), interactions between loops, or valve stiction. The controller in its eagerness to execute the control action, induces poles outside the real axis, that is, roots with imaginary components: to stabilize the process quickly, the controller causes poles to appear when running in closed-loop, generating these oscillations.

This technique is not limited to processes with a single control loop because the modification is done on each individual controller. This strategy can be extended to more controllers without additional mathematical developments since this self-tuning technique when operating on each controller individually, seeks to cancel a disturbance that affects each controller independent of the control action adjacent controllers. Each controller perceives a behavior and applies the technique to know if the source of the disturbance comes from itself or a disturbance, remembering that for each controller what happens outside itself is considered as process, if the oscillation is not cause by itself (the controller) then it is due to a disturbance, which, as mentioned, is most likely due to the control action of another control loop.

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How is good or bad is the performance of this technique when the cause of the oscillation is another controller versus when it is an oscillation in the upstream process is a subject for future research. In the case study analyzed in the master's thesis (Borrero Salazar, 2019), it was found that the tuning developed leads the controller to act as a filter against an oscillatory disturbance caused by a poorly tuned controller; however, because the tuning equations were conceived under the scenario of an external oscillatory disturbance and not like the aforementioned scenario, a better performance against an external oscillatory disturbance is to be expected.

This technique is considered for one input and one output systems (SISO), therefore, it is recommended to explore a scenario of two controllers doing this type of compensation simultaneously. A conjecture is that both controllers acts as filters, that is to say, the control loops will be attenuated since they will work as filters, consequently, they will compete as such. The action of this competition between them should lead to the stabilization of the loops. This is a hypothesis that remains to be validated in future works. It is recommended to explore tuning equations to filter out oscillatory disturbances by changing the three controller parameters $K_c, T_I\ y\ T_D$ for further investigation. In this research, a good result was obtained by changing only one parameter for the experimentally developed equations, which helps transmit knowledge to the industry as it is a simple technique. The equations obtained experimentally were constructed based on the optimal results found in the manual search for each experimental condition explored in the execution of the experiment; however, the significant difference in the results shown in Table VIII between the row "Experimental Eq." and "Experimental" is because it is very complex to find a regression model that fits 100% of the data and a difference of only 4% in the value of the approximation results in this difference in the percentage of improvement.

In the primary research carried out (Borrero Salazar, 2019), it was found that the attenuation index was reduced from $AI = 0.9352$ to $AI = 0.7874$ or from $AI = 0.5775$ to $AI = 0.3006$ when comparing between the traditional tuning to the new filtering tuning, obtaining improvements of 15.8% and 47.9%, respectively. As this is an index based on the standard deviation, only by modifying the controller's gain, significant reductions in the variance of the process can be achieved, therefore increasing the profits.

The tuning equations obtained through this investigation are presented in Table IX, where λ is the recommended value for the controller's gain given in Eq. (9) (re-written here):

$$K_C = \frac{\tau}{K_P\left(\lambda + t_0\right)}$$

Table 9 **SUMMARY OF CONTROLLER TUNING EQUATIONS**
Proportional Controller (P)
$\lambda = -0.67938 K_P \tau^{1.014} + 0.012396 \frac{t_0}{\omega}$
Proportional-Integral Controller (PI)
$\lambda = -0.045297 \tau t_0^{1.014} - 0.32272 \sin\left(\frac{t_0}{\tau}\right)$ $T_I = \tau$

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