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Performance Improvement of PID Controls in Tyre Vulcanisation Process

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Today's global competitive business environment challenges tyre-manufacturing industries to implement continuous improvement systems that can reduce cost of production and improve product quality. Proportional-Integral-Derivative (PID) controllers play a key role in deciding the quality of vulcanised tyres. This paper proposes a matrix of performance indices to effectively assess control performance of curing presses with respect to standard benchmarks. The usefulness of λ*-tuning as a uniform method for performance improvement of vulcanisation plant process control is also explored. The tuning method gave satisfactory results when analysed with the help of the performance matrix. The proposed methods were validated through temperature control loop data of a few curing presses using MATLAB simulation.*

Keywords: Tyre vulcanisation, PID control, process control, performance improvement, controller-tuning.

1. Introduction

Process control is a key area in the tyre industry where performance is crucial in maintaining product quality and minimising losses due to wastage of energy and raw materials. Vulcanisation is a key process in the manufacture of tyres. The vulcanisation process, also known as curing, takes place in curing presses where soft, uncured, green tyre is subjected to one or more heating media under specified temperature and pressure to produce cured tyre. A medium tyre plant in India has on an average 80 to 100 tyre-curing presses. Maintaining the press control loops in good performance results in overall performance improvement of the plant.

Performance improvement of control loops involves three vital steps: assessment of the existing performance of the controller with reference to an industry benchmark, detection and diagnosis of performance problems, and corrective actions such as controller-tuning, valve-servicing and sizing. However, a systematic approach to control performance improvement is lacking in the process industry in general and in the tyre segment in particular. A few obvious reasons are:

- The lack of awareness by the plant management and process control team of the crucial role of process control in product quality,
- Too few staff to maintain the relatively large number of control loops, as much as 400-loops/ engineer (**Miller &Desborough, 2001**),
- The lack of supportive environment for the control engineer in decision-making regarding control loop performance and maintenance.

The past decade witnessed active research into performance assessment of control loops; (see **Qin, 1998; Harris *et al.*, 1999; Harris & Seppala, 2001; Jamsa-Jounela *et al* 2002** for review of the methods). Algorithms for the automatic detection of inapt behaviour of control loops such as oscillation, sluggishness etc. were developed and applied (**Hagglund, 1995; 1999; Wallen, 1997**). A variety of

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controller-tuning methods has been developed in the recent past (**Astrom *et al.*, 1993; Ho *et al.*, 1996, Cominos & Munro, 2002**). However, application of these methods to a specific industry setting requires an understanding of the existing needs and challenges of that particular industry.

This paper proposes a matrix of PID performance indices to assess controller performance of tyre vulcanisation plants. In addition, the usefulness of λ -tuning as a uniform method for controller-tuning for all varieties of controllers in the plant is also presented. Validation of the methods is done using temperature controller data from a tyre vulcanisation plant, through simulation.

2. System Requirements for a Tyre Industry

A visit to a tyre industry would prove that multi-vendor, multi-technology, multi-generation controllers co-exist in various floors of process control from banburry mixer to tyre-curing. Continuous change of product and process specifications, expansions of existing facilities and automation of manual processes among others, has resulted in heterogeneity of controllers plant-wide. New generation of controllers and Supervisory Control And Data Acquisition (SCADA) systems come with built-in auto tuning facility. However, not all controllers have the same PID algorithm, not all controllers comply with Object Linking and Embedding (OLE) for Process Control (OPC), not all controllers are digital or electronic and industry still opts for pneumatic controllers (**Staff, 1998**).

Therefore, any system for performance-monitoring and controller-tuning should be able to work with offline data as well, serving as a uniform solution provider for any kind of controller.

Approximately 97% of process control is handled by PID controllers (**Ender, 1993; Astrom & Hagglund, 2001; Miller & Desborough, 2001; Paulonis & Cox, 2003**); the tyre industry is no exception to this. Thus, PID specific assessment and tuning techniques for Single Input Single Output (SISO) control loops, which are more relevant to tyre industry, are considered in this work. In addition, Proportional Integral (PI) control structure is proposed for the temperature control loops of the curing presses as derivative action in the controller, in the presence of measurement noise, leads to 'jerky' effects, which affect control quality and increase valve running costs (**Buckbee, 2002**).

Now, a short tutorial on PI control structure is presented before analysing the available techniques for performance assessment of this type of controllers.

2.1 Functional Description of a PI Control

The block diagram representation of a PI control loop is given in **Figure 1**.

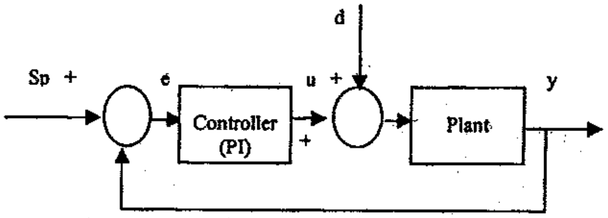


FIGURE 1: *The Block Diagram Representation of a PI Control Loop*

A Pi-controller consists of two elements: P for Proportional control and I for Integral control (**Wilkie *et al.*, 2002**). The PI control can be implemented to meet various design specifications of the closed loop system. For proper understanding of the operation of a PI feedback controller, the above two terms are required to be considered separately.

i) ***Proportional Control:***
Proportional control is pure gain adjustment acting on the error signal to provide the driving input to the process. The P term in the PI controller is used to adjust the *speed* of the system.

ii) ***Integral Control:***
Integral control is implemented through the introduction of an integrator. Integral control is used to provide the required accuracy for the control system.

The input/output relationship of a closed loop PI control system in discrete form could be expressed by:

$$u(t) = u(t-1) + K_c[e(t) - e(t-1)] + \frac{KcTs}{T_i} e(t) \qquad ....(1)$$

where:

K_c is the proportional gain,
T_i is the integral time and
T_s the sampling time

Tuning of a PI controller is the task of assigning optimal values for K_c and T_i depending on the control objectives. In a regulatory control, the parameters are adjusted to minimise error due to disturbance occurring at the process. This disturbance gets added to the controller output (u). In servo control, parameters are assigned for tracking setpoint (Sp) changes.

The existing methods for control performance are now reviewed in some detail in order to assess the suitability of the methods for tyre-curing process control.

3. Performance Assessment of PID Loops

Harris **(1989)** compared the existing variance of a controller to that of a Minimum Variance Controller (MVC). The Harris definition of performance index of a controller is given by:

$$I_h = \frac{\sigma_y^2}{\sigma_{mv}^2} \qquad \text{........(2)}$$

Here σ_y^2 is the variance of the process variable with the given controller and is the variance that would be produced by an MVC controller. The value of the index will ideally be one and values closer to one for a control loop implies good performance. Calculation of the Harris index involved time series modelling of process variable and the knowledge of process deadtime.

Empirical studies based on industry data by **Eriksson & Isaksson (1994)** and **Isaksson (1996)** resulted in the definition of a few alternate PID specific performance indices. **Eriksson & Isaksson (1994)** proposed an optimal performance index and a PID best performance index. The former is given by:

$$I_{opt} = \frac{\sigma_y^2}{\sigma_{opt}^2} \qquad \text{........(3)}$$

Here, the calculation of σ_y^2 requires the determination of closed loop transfer function of the control loop based on a setpoint or process disturbance model. For a step disturbance at the setpoint, variance of the control error e_t, is used in performance assessment because y_t is non-stationary for servo control. Therefore, σ_e^2 is given by:

$$\sigma^2{}_e = \frac{1}{2\pi}\int_{-\pi}^{\pi} \left|H(e^{jw})\right|^2 \Phi_{Sp-d}(\omega)\,d\omega, \qquad \text{........(4)}$$

where $\Phi_{Sp-d}(\omega)$ represents the spectrum of Sp_t-d_t (dt, a load disturbance acting at the process output). The "sensitivity function" $H(z^{-1})$ represents the closed loop transfer function from Sp_t-d_t to the control error e_t. The optimal performance variance σ_{opt}^2 is determined from the disturbance model using pulse response up to the instant before deadtime of the process.

For a controller with PI control structure, the PI best performance index is given by:

$$J_{PI} = \frac{\sigma_y^2}{\sigma_{PI}^2} \qquad \text{........(5)}$$

Here σ_{PI}^2 is calculated by minimising (4) with respect to the controller gain (K_c) and integral time (T_i). This latter index has the advantage of providing information about the scope of improvement of performance for a given control structure. However, PI controller design by minimisation of (4) could also result in oscillatory response, though performance might show values close to 1.

Works of **Thornhill *et al.* (1999)** and **Ko & Edgar (2003)** also enhanced PID specific performance indices. Process model identification is required in the computation of the above indices, which could be automated using MATLAB functions. However, determination of process model requires the process to be disturbed in order to collect process response data to pre-determined inputs.

3.1 A Performance Matrix for Tyre Vulcanisation Process

Based on the above indices, a performance matrix may be formed to give overall insight about controller performance. Stability parameters gain margin (G_m) and phase margin (P_m) have been included in the matrix in addition to the performance benchmarks discussed previously.

TABLE 1: *Performance Matrix for Curing Process Control*

Tuning Trial	K_c	T_i	I_{opt}	I_{PI}	G_m	P_m
I						
II						

3.1.1 Discussion

Based on the discussion in Section 3, two PID specific performance indices are used; I_{opt}, which compares the existing variance of the control with an ideal controller having no output variance after deadtime and I_{PI} which makes a comparison to an ideal PI controller with parameters that produce minimum output variance. These two values, along with stability parameters provide sufficient data to assess the performance of the controller. Alarm limits could be set for each index for monitoring purposes. The monitoring of these two characteristics, output variance, as well as stability, ensures a reliable assessment of control performance. The matrix has been designed to aid the control engineer during tuning of controllers.

4. λ-Tuning for Process Industry

A λ-tuned loop is one with one-degree-of-freedom controller whose set point response is of First Order Plus Dead Time (FOPDT) (**Rivera et al, 1986**). This tuning rule is very popular for PI controllers in the Pulp and

Paper industry. λ is the time constant of the set-point response. **Olsen & Bialkowski (2002)** applied λ-tuning to refinery process and demonstrated the effectiveness of this tuning method over the conventional Zeigler-Nichol's method for a blending

process. The suitability of λ-tuning method for industry applications was also analysed by **Gerry (2000)**. Analytical studies for regulatory and servo applications showed that the method could be appropriate for regulatory control for processes with deadtime up to 10. If λ is chosen much less than the process time constant, setpoint response becomes fast, but the load response of the loop becomes poor. However, when λ is chosen in the range of $[\tau, 3\tau]$, the tuning has been found to be effective based on empirical studies on loop data (**Ingimundarson, 2003; Gerry, 2000**).

In the tyre-manufacturing process, especially in vulcanisation, the intended control is mostly regulatory. However, in case of size changes in a cavity with a change in temperature specifications, servo control also gets involved. Two case studies conducted in curing presses are presented in the next section.

5. The Case of a 45" Bag O Matic (BOM) Curing Press

A performance study of temperature control loop was conducted on a 45" BOM press. The curing press is designed for vulcanising radial tires. The vulcanising machine is a two-piece metal mold. A bladder forces the tyre against the mold, forming the sidewall patterns and tread pattern. The molding is accomplished using steam pressure and hot water inside the bladder. The rubber components of the tyre are vulcanised by steam-generated heat in the mold, platen and bladder at pressures as high as 400 psi and temperatures of approximately 200°C for approximately 10 mins. This heat results in chemical and physical changes in the rubber compounds. The rubber components are transformed from plastic consistency to the consistency found in a finished tyre (**Blow *et al.*, 1975**). The front view of a tyre-curing press in open condition is given in **Figure 2.**

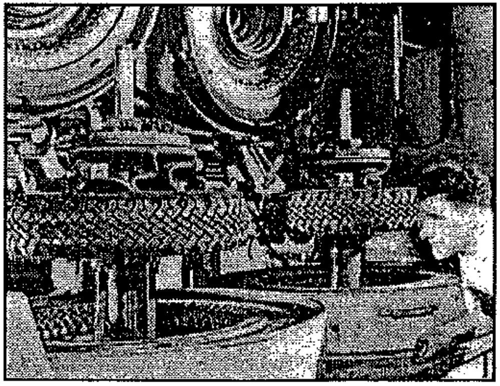


FIGURE 2: *A Tyre-Curing Press in Open Condition*

in **Figure 2**.

The operations of the curing press, bearing the equipment no. 9103 are automated hydraulically and controlled by a *Siemens S7 315-2DP* PLC. PID controller is programmed in the PLC to control the platen temperature of the press. The temperature is controlled by regulating flow of steam to the platen by a Samson control valve. A Pt-100 RTD senses the temperature of the platen at the return steam line. A transmitter converts the resistance variation of the RTD into a standard 4-20 ma calibrated over the range of 0–275 °C.

A data logger with a sampling interval of 100ms was used for data collection. The sampling interval is high enough to represent first order, as well as oscillatory responses (**Stephanopoulos, 1984**). A very high sampling rate, though undesirable for online monitoring and automaton due to explosive amounts of data, does not pose any problem in offline analysis, as is the case under study.

The PLC documentation gives only a block diagram representation of the PID structure and requires, apart from the P, I and D values, inputs such as dead band width (DEADB_W), time lag of derivative action (TM_LAG) etc. As how these parameters exactly affect the control algorithm is not known, controller-tuning is difficult and, therefore, we implemented a PI controller in MATLAB for simulation of the control loop.

5.1 Performance and Tuning Analysis

A series of bump tests were conducted and 6000 input/output data were collected. An ARX model of the process was estimated from the data using MATLAB 6p5. System identification toolbox functions were used in data pre-processing, model order selection and model parameter determination of the process. First, an optimal order ARX model was estimated *arxstruc*, *selstruc* and *arx* functions as follows:

$$y(t) - 0.7315\,y(t-1) - 0.1234\,y(t-2) - 0.05711\,y(t-3) - 0.05115\,y(t-4) + 0.01654\,y(t-5) - 0.00613\,y(t-6) - 0.03065\,y(t-7) + 0.02507\,y(t-8) + 0.005027\,y(t-9) - 0.04655\,y(t-10)$$

$$= 0.0007952\,u(t-3) \qquad \text{........(6)}$$

In addition, a FOPDT model was also estimated as:

$$G(s) = \frac{3.97e^{-0.3s}}{869s+1} \qquad \text{........(7)}$$

Based on the FOPDT model parameters, first, the controller was tuned for robust control ($\lambda = 3\tau$, where τ is the process time constant). Now the closed loop transfer function of the control loop was determined using the PI structure and the optimal order process model as:

$$\frac{0.00079z^8 - 0.000795z^7}{z^{11} - 1.73z^{10} + 0.61z^9 + 0.06z^8 + 0.0058z^7 + 0.067z^6 - 0.02z^5 - 0.024z^4 + 0.05z^3 - 0.02z^2 - 0.05z + 0.046}$$

${\sigma_y}^2$ and ${\sigma_{opt}}^2$ were computed using *filternorm* and *impz* functions respectively resulting in the following values:

$${\sigma_y}^2 = 6.97*10^{-4}$$

$${\sigma_{opt}}^2 = 3.79*10^{-6}$$

$$I_{opt} = {\sigma_y}^2/{\sigma_{opt}}^2 = 183.84$$

A similar calculation by minimising (4) yielded:

$${\sigma_{PI}}^2 = 2.11*10^{-4}$$

$$I_{PI} = {\sigma_y}^2/{\sigma_{PI}}^2 = 3.29$$

Gain margin (G_m) and Phase margin (P_m) were also computed and found to be $1.2*10^4$ and 89.36 respectively. Similarly, computation was carried out for tight control (good speed of response) by assigning $\lambda = \tau$. All the results are given in **Table 2**.

TABLE 2: *Performance Analysis of 9103 Platen Temperature Control Loop during λ-Tuning*

Tuning Trial	K_c	T_i	I_{opt}	I_{PI}	G_m	P_m
$\lambda = 3\tau$	0.0839	869	184	3.29	$1.2*10^4$	89.36
$\lambda = \tau$	0.252	869	122	2.17	4294	88.97

. All the results are given in **Table 2**.

5.2 Discussion

Row 2 and 3 of **Table 2** displays the values obtained for the gain K_c and integral time T_i after performing λ-tuning calculation for robust and tight control respectively. The performance matrix for robust control, i.e., $\lambda = 3\tau$, shows excellent stability as indicated by gain and phase margins, much above the normal minimum specification of 1.7 and 30° (**Coughanowr, 1991**). This is because the time delay in this case is very short (0.3 sec) compared to the dominant time constant (869 sec) and as such, the process is practically inherently stable under PI control. However, the loop exhibits inferior performance in terms of output variance $(I_{opt} = 184)$. The value of $I_{PI} = 3.29$ is suggestive of scope for better performance within the given PI control structure.

The second trial of λ-tuning for fast response $(\lambda = \tau)$ shows again very good stability margins, and much improved performance indices. The PI best performance index and the optimal index show better performance. However, the value of $I_{PI} = 2.17$ indicates that performance can be further improved until it is closer to 1 as stability also shows good margins. The corresponding load response of the loop, for a unit step acting at the *d* input of **Figure 1**, is given in **Figure 3**.

6. The Case of a Bladder-Curing Press

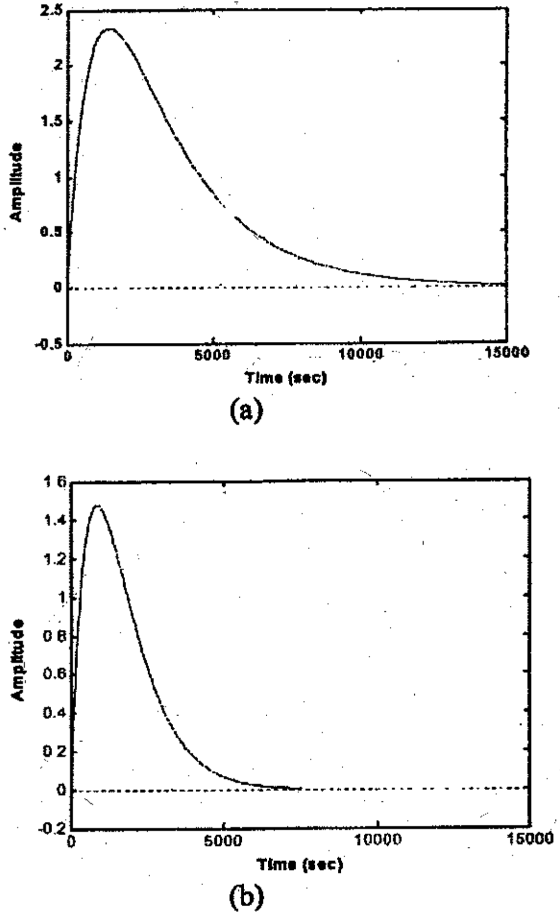
The bladder used in the vulcanisation of tyre is cured in bladder-curing presses through a similar process to that described in Section 5. A similar study was conducted at the platen temperature control loop of a bladder-curing press with equipment no. 3701. ARX model of the process was estimated as:

$$y(t) - 0.4915\,y(t-1) - 0.1622\,y(t-2) - 0.006551\,y(t-3) - 0.07669\,y(t-4) - 0.06323\,y(t-5) - 0.04829\,y(t-6) - 0.04223\,y(t-7) - 0.03617\,y(t-8) - 0.05061\,y(t-9) - 0.02226\,y(t-10)$$

$$= 0.0007594\,u(t-7) \qquad \text{........(8)}$$

The following FOPDT model of process was identified:

$$G(s) = \frac{2.36e^{-0.7s}}{938s + 1} \qquad \text{........(9)}$$



(a)

(b)

FIGURE 3: *Step Response of the 9103 Platen Temperature Loop for Load Disturbance (a) Controller with Robust Response* $(\lambda = 3\tau)$*, (b) Controller with Fast Response* $(\lambda = \tau)$

The performance marix of the loop for robust and tight control is given in **Table 3**.

TABLE 3: *Performance Analysis of 3701 Press Platen Temperature Control Loop during λ-Tuning*

Tuning Trial	K_c	T_i	I_{opt}	I_{PI}	G_m	P_m
$\lambda = 3\tau$	0.1407	938	66.86	1.69	7017	89.2
$\lambda = \tau$	0.421	938	44.24	1.12	2345	88.7

6.1 Discussion

Step responses for the results given in **Table 3** are plotted in **Figure 4**. This control loop shows excellent

stability for the reasons discussed in Section 5.2.

For $\lambda = 3\tau$, $I_{opt} = 44.24$ and $I_{PI} = 1.69$ suggest scope for better performance within the given control structure. The second trial for tight control gives PI best performance index very close to 1 with very good margin for stability. The load response of the loop, for a unit step acting at the *d* input of **Figure 1**, is given in **Figure 4**.

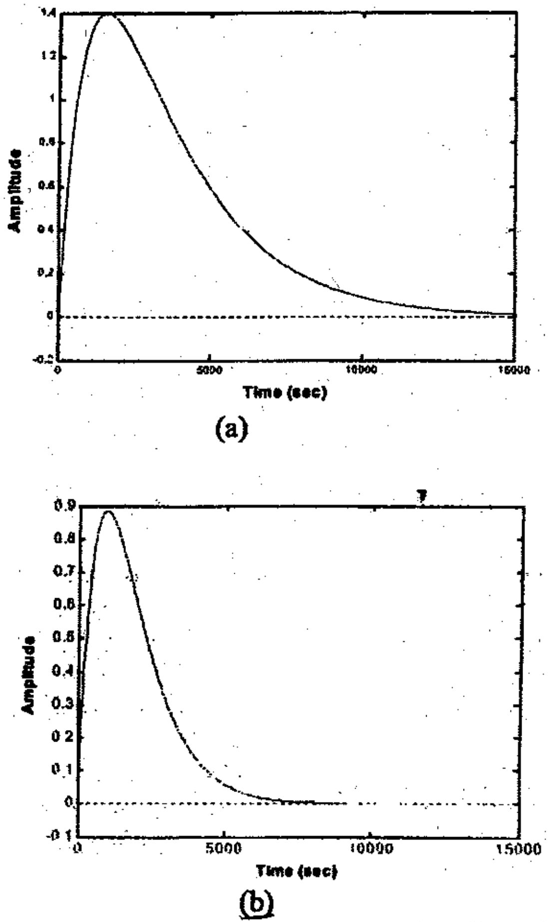


FIGURE 4: *Step Response of the 3701 Platen Temperature Loop for Load Disturbance (a) Controller with Robust Response* $(\lambda = 3\tau)$, *(b) Controller with Fast Response* $(\lambda = \tau)$

7. Conclusion

A performance matrix for assessing performance of PI control loops in tyre vulcanisation process was developed. The suitability of λ-tuning method for controller-tuning in the tyre-curing process was analysed using this matrix. This analysis, which used MATLAB simulation, showed that the λ-tuned controller gives excellent stability to control and moderate performance values for $\lambda = \tau$. However, there is still scope for increasing the speed of response, but at the cost of stability. This further fine-tuning could be performed with the values of K_c and T_i from λ-tuning as the base. Soft computing tools like fuzzy algorighms could be used for fine-tuning, which could also take 'how faster' and 'how robust' inputs in percentile form from the user.

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