# PERFORMANCE MATRIX BASED CONTOLLER TUNING FOR TIRE VULCANIZATION PROCESS

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**Abstract:** Global competition today is forcing tire-manufacturing industries to implement continuous improvement systems that can reduce cost and improve product quality. Proportional-Integral-Derivative (PID) controllers play a key role in the quality of vulcanized tire. This paper presents a novel method for the performance assessment and controller tuning of temperature control loops in a tire vulcanization process. A matrix of performance indices is used in understanding the performance of the controller during controller tuning. A generic approach is employed whereby performance of single loop controllers employing conventional as well as new generation controllers can be assessed and fine-tuned. The case study conducted on a 45” bag o matic curing press is also presented.

Key Words: tire vulcanization, PID control, process control, performance improvement, performance index, controller tuning

## 1. INTRODUCTION

Vulcanization plays a vital role in the manufacturing process of tire. The vulcanization process, also known as curing, takes place in curing presses where soft uncured green tire is subjected to one or more heating medium under specified temperature and pressure. Carefully tuned PID controllers regulate the temperature of the heating surfaces of the curing press, the platen and mould. A medium tire plant in India has on an average 80 to 100 tire curing presses. Maintaining the press control loops in good performance results in overall performance improvement of the plant. Unfortunately, performance monitoring and controller tuning in this area of the industry are overlooked due to one or more of the reasons cited below:

1. In the absence of an international standard, PID algorithms vary among various manufacturers due to historic reasons of development from pneumatic to analog and to digital (Tan *et al.*, 2001). Therefore, control parameters that work well in one controller may not give the same performance in controllers manufactured by other vendors.
2. Commercial Control Loop Performance Monitoring (CLPM) tools demand compliance to OPC standards (Miller and Desborough, 2001) for connectivity to gather online data. Thus, this is not compatible to earlier generation controllers like pneumatic, analog or non-OPC compliant digital controllers. In contrast the demand for pneumatic controllers is still high in the industry (staff, 2003), especially in the tire sector
3. Today most of the digital controllers, especially the

embedded controllers and SCADA systems, come with built-in auto tuning facility. However, this is limited to new generation of systems. Where there is a collection of old and new technology controllers, as is the case in most of the tire industries, controller tuning is difficult to automate.

4. Lack of staff availability and poor training and support environment for loop monitoring and decision-making further deteriorates controller performance (Ingimundarson, 2003).

Surveys show that PID type of control constitutes more than 90% of process control loops (Tan *et al.*, 2001; Astrom and Hagglund, 2001; Ender, 1993). PID controllers have gained widespread acceptance in the tire manufacturing industries because of its simplicity (having only three parameters to tune!) and robustness. Applications of PID control can be found extensively in this entire segment. Despite their lion share in the industry, the three term controllers, as they are often called, do not perform well, as evidenced by numerous investigations (Ender, 1993). At the same time it has been shown that 1-4% of savings in energy consumption of an industry can be saved by performance improvement of control loops (Miller and Desborough, 2001).

This paper proposes a modified λ-tuning method refined by a soft computing technique to tune PID controllers. The control structure will be limited to PI, which is the structure used in more than 90% of PID loops (Ingimundarson, 2003). Presently λ-tuning is limited to pulp and paper industry and refinery processes (Ingimundarson, 2003; Olsen and Bialkowski, 2002). As any single index of performance cannot give insight into all aspects of controller performance (say, stability and output variance cannot be assessed by one index) a matrix of indices is employed to check controller performance and scope for improvement. The temperature loop of a curing press is studied in detail to validate the proposed method for the vulcanization process.

## 2. PERFORMANCE MONITORING OF PID LOOPS

The major steps involved in the performance improvement of PID loops in a tire industry are the assessment of existing performance with reference to a standard or industry benchmark and then doing iterative tuning of control loops to obtain optimal performance. The landmark achievement in the performance assessment of control loops was Harris' definition of a relative index of performance (Harris, 1989). This compared the existing variance of the controller to that of a Minimum Variance Controller (MVC).

The Harris definition of performance index of a controller is given by:

$$I_h = \frac{\sigma^2{}_y}{\sigma^2{}_{mv}} \qquad (1)$$

Here $\sigma^2{}_y$ is the variance of the process variable with the given controller and $\sigma^2{}_{mv}$ is the variance that would be produced by an MVC controller. An MVC produces zero variance after process deadtime is over and is as such the ideal controller theoretically. The value of the index will ideally be one and values closer to one for a control loop implies good performance.

The computation of the index only required the time series modeling of the process data and was easy to automate. Since MVC performance is practically not achievable, the comparison to MVC is overly optimistic and many different variants of the approach followed; see surveys by Harris and Seppala (Harris and Seppala, 2001; Harris *et al.*, 1999;Qin, 1998).

Performance indices specific to PID control were proposed following the work of Eriksson and Isaksson (1994) who showed that Harris index, which applied to stochastic control, could lead to erratic conclusions about control loop performance when applied to regulatory or servo control systems. An optimal performance index and a PID best performance index were proposed in this work. The optimal index is given by:

$$I_{opt} = \frac{\sigma^2 y}{\sigma^2_{opt}} \qquad (2)$$

Here the calculation of $\sigma^2 y$ requires 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, $\sigma^2 y$ is given by:

$$\sigma^2_y = \frac{1}{2\pi}\int_{-\pi}^{\pi} | He^{iw} |^2 \ dw \qquad (3)$$

Here $H$ is the closed loop disturbance model of the control loop from setpoint to process output. The optimal performance variance $\sigma^2_{opt}$ is determined from the disturbance model using pulse response upto the deadtime of the process.

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

$$I_{PI} = \frac{\sigma^2 y}{\sigma^2_{PI}} \qquad (4)$$

Here $\sigma^2_{PI}$ is calculated by minimizing (3) for Kc and Ti. 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 minimization of (3) could also result in oscillatory response, though performance might show values close to 1.

### *3.1 A Performance Matrix for Tire Vulcanization Process*

Based on the above indices, a performance matrix may be formed to give overall insight about controller performance.

**Table 1: Performance Matrix for Curing Process Control**

| Tuning Trial | Kc | Ti | $I_{opt}$ | $I_{PI}$ | Gm | Pm |
|---|---|---|---|---|---|---|
| I | | | | | | |
| II | | | | | | |

Here Gm and Pm are the gain margin and phase margin of the loop and Kc and Ti are the controller gain and integral time respectively.

## 3. λ-TUNING

Tuning of controllers using conservative methods may lead to oscillatory or sluggish controller behavoiur both of which can result in loss of energy, raw materials and other resources. Therefore, PID controller tuning to suit control objective and performance specification is very important. Also different approaches are to be employed for regulatory and servo control. In the present study, λ-tune method, which is based on the Internal Model Control (IMC), is used. This method requires the First Order Plus Delay Time (FOPDT) identification of the process and then controller gain Kc and integral time Ti are calculated from the model parameters.

### *3.1 Model Identification and Controller Parameters*

The FOPDT model is identified from the controller input output data. The model is then determined as the transfer function G(s), given by:

$$G(s) = Ke^{-Tds} / \tau s+1 \qquad (5)$$

Here, K is the process gain, $T_d$ is the process time delay and $\tau$ is the time constant.

Based on this model, tuning parameters can be determined using λ-tuning method (Ingimundarson, 2003) as follows:

$$Kc = \tau / K (T_d+\lambda), \quad Ti = \tau, \quad \lambda \in (\tau, 3\tau) \qquad (6)$$

This is an Internal Model Control (IMC) design obtained by approximating the dead time with a first order Taylor approximation,

$$\exp(-T_d) \approx 1- T_d \qquad (7)$$

The disturbance is assumed a step disturbance. Parameter λ is typically chosen to be between τ and 3τ. If λ = τ the tuning is considered tight while λ = 3τ is referred to as robust. MATLAB functions could be can be used in the determination of the above parametric model and tuning parameters.

## 4. THE CASE OF A 45" BAG O MATIC (BOM) PRESS

A case study was conducted on a 45" BOM press. The given curing press, with equipment no. 9103, is designed for vulcanizing radial tires. The operations of the curing press are done hydraulically and is controlled by a 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.

### *4.1 Performance and Tuning Analysis*

A few bump tests were conducted and 6000 input output data were collected by a data logger at a sampling interval of 100ms. Estimation of the FOPDT model was done using MATLAB 6p5. The following model resulted:

$$G(s) = 3.972e^{-0..3s} / (869s+1) \qquad (8)$$

First the controller was tuned for good robustness by assigning λ = 3τ and controller structure based performance index ($I_{PI}$), controller optimal performance index (Iopt), Integrated Time multiplied Squared Error (ITSE), Gain margin (Gm), Phase margin (Pm) etc. were computed. Similar computation was carried out for tight (λ = τ) control and for the optimal values for Kc and Ti obtained by evaluating (6). The values are given in Table 1.

Row 2 and 3 of Table 1 displays the values obtained for PI control gain and integral time after performing λ-tuning calculation for robust as well as tight control. The results show that λ-tuning provides robust control and excellent stability as indicated by the gain and phase margins. However, the performance indices calculated for these controller tunings show that there is still scope for improvement at a lesser moderate gain and phase margin values.

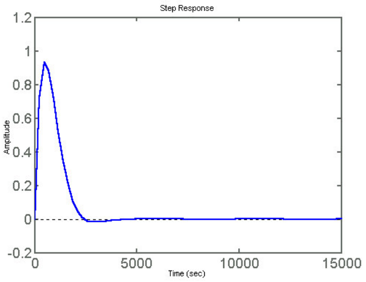
Table 2 shows the values of the performance parameters of the controller for optimal values of Kc and Ti obtained by minimizing (3). The performance indices have substantially improved at the cost of stability as evidenced by the fall of phase margin to 4.37. The trade off between stability and performance is a subjective decision depending on the application requirement. Therefore, a fuzzy logic based fine tuner was developed to determine optimum values for Kc and Ti, which would reduce process variance and retain the process stable. The results are shown Table 2. The Fine Tuner was developed in MATLAB to enable the control engineer to express his percentile preference of stability and performance. The loop was simulated with values obtained for 'moderate' performance and 'moderate' stability. The step response tallies with this performance specification and is the best among the four sets of values for curing temperature control.

**Table 1: Performance Analysis of 9103 Platen Temperature Control Loop for λ-Tuning**

| Tuning Rule | Kc | Ti | ITSE | $I_{opt}$ | $I_{PI}$ | Gm | Pm |
|---|---|---|---|---|---|---|---|
| Optimal | 1 | 1 | 1.125e8 | 55.8 | 1.001 | 981 | 4.37 |
| Fuzzy fine tuner | 0.474 | 499 | 1.114e8 | 83.9 | 1.5 | 2280 | 75.29 |

**Table 2: Performance Analysis for Best PID Performance and Fuzzy Fine Tuning**

| Tuning Rule | Kc | Ti | ITSE | $I_{opt}$ | $I_{PI}$ | Gm | Pm |
|---|---|---|---|---|---|---|---|
| λ=3τ | 0.0839 | 869 | 8.1e7 | 184 | 3.29 | 1.2e4 | 89.36 |
| λ=τ | 0.251 | 869 | 1.05e8 | 122 | 2.17 | 4294 | 88.97 |



(b)

**Fig 2.: Step Response of the Platen Temperature Loop for Load Disturbance. Controller was tuned by fuzzy fine tuner**

## 5. CONCLUSION

Study of performance parameters of temperature control loop of tire vulcanization process was carried out to determine a tuning and performance monitoring method for tire vulcanization process. The study focused only on regulatory response as setpoint changes are not very frequent in tire curing unless in case of mould change when the loop gets sufficient time to stabilize. Though λ-tuning provides sets the controller for robust performance, there remains scope for further improvement as evidenced by the performance indices. The fuzzy fine tuner further improved controller performance by helping the control engineer to strike a balance between stability and performance. The study shows that this modified approach can be used for performance monitoring and fine-tuning of tire vulcanization process control loops.

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