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Various Controller Design and Tuning Methods for a First Order Plus Dead Time Process

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ABSTRACT

The closed loop system should satisfy a number of performance criteria for desirable dynamic and steady state response characteristics. The closed loop system must be stable and steady state error is to be eliminitated. The effects of disturbances should be minimized to provide good disturbance rejection along with rapid and smooth responses to set-point changes are required for good set-point tracking. Excessive control action is to be avoided and the control system is required to be insensitive to changes in process conditions and to inaccuracies in the process model for the system to be robust. It is not possible to achieve all these goals simultaneously because they involve inherent conflicts and tradeoffs. In the present paper, a simple closed loop system is considered that consists of a first order plus dead time (FOPDT) model and a PI controller. Various controller design methods and tuning relations for PI controllers are determined for an important parameter i.e. consistency in paper industry. In fact consistency is a very important parameter in paper mills in its various stages of operations. Without the knowledge of consistency it is not possible to optimize productivity with optimal quality.

Keywords: FOPDT, Consistency, PI Controller, Tuning Methods, Headbox, Closed Loop Response

1. INTRODUCTION

Many pulp and paper processes are represented by first order plus dead time for tuning purposes. A PID controller can be used to control this type of process if the dead time is less than three times the process time constant. The regulatory control performance of the loop i.e. disturbance rejection, deteriorates rapidly when dead time exceeds time constant of the process model, even though the response to set point changes remains acceptable.

The first order plus dead time transfer function is defined as

$$G_P(s) = \frac{K_P e^{-\theta_D s}}{1 + \tau s}\ ;$$ Where θ_D is the dead time and τ is the time constant.

The integral gain remains constant as dead time increases, but the proportional gain decreases. The proposed model is based on unsteady state material balance or energy balance or combination of both. The consistency control loop can be designed by various configurations such as negative feedback, cascade, feed forward and feedback combination, feed forward and cascaded feedback, ratio control. For simplicity negative feedback control configuration has been considered. Usually, the dilution water from various sources is always added to the thick stock immediately before fan pump and then led to flow to a consistency sensor, and then to the other equipments of approach flow system including Head box. A feedback signal is obtained from the consistency sensor which is transmitted to the consistency controller through transmitter.

A comparator is used in the loop to compare the set point and measured variable to produce an error which goes to the controller to determine an appropriate position of the valve controlling the flow of dilution water to the stock immediately ahead of the pump. The value of the dead time for consistency control depends upon type of the process, loop design and location of sensor.

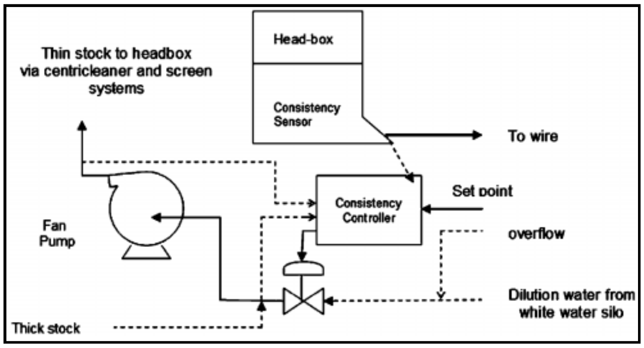

Fig. 1 : Consistency Control for a Head Box

The transfer function of consistency control process can be adequately represented by first order plus dead time as under

$$G_p(s) = K_p[e^{-\theta ds}/(1+ \zeta s)]$$

Carrying out bump test on the approach flow system flow loop, Nancy [1] developed the following dynamics equation with dead time of the order of 5 s due to transmitter location relative to the dilution point. The time constant of 10 s is due to the sensor measurement dynamics.

$$G_p(s) = 0.03e^{-5s}/(1+10s).$$

2. VARIOUS PI CONTROLLER DESIGN TECHNIQUES

PI controller settings can be determined by a number of alternative techniques. Direct Synthesis method and IMC method are based on simple transfer function models. Controller tuning relations are analytical expressions for PID controller settings. Computer simulation technique can provide considerable insight into dynamic behavior and control system performance. The objective for these methods is to provide good controller settings that can subsequently be fine tuned online, if required. It is very useful to have good initial controller settings in order to minimize the required time and effort, as online tuning can be time consuming task.

2.1. Direct Synthesis Method

In this method, the controller design is based on a process model and a desired closed loop transfer function. It provides valuable insight into the relationship between the process model and the resulting controller.

The following are the controller parameters for PI controller using DS Method

$$Kc = 1/K * \tau/(\theta + \Gamma);\ T_i = \tau$$

Where, Γ = desired closed loop time constant = 1

τ = time constant = 10

Therefore, the controller is designed as,

$$Kc = 55.5\ (1 + 1/10s)$$

The consistency transfer function with first order Pade approximation is given as

Transfer function:

$$(-0.03\ s + 0.012)\ /\ (10\ s^2 + 5\ s + 0.4)$$

Thus, the closed loop transfer function is given as

Transfer function:

$$(-0.3\ s^2 + 0.12\ s)\ /\ (100\ s^3 + 33.35\ s^2 + 8.995\ s + 0.666)$$

The plot giving the insight about the dynamic and steady state performance and stability knowledge about the closed loop responses are as follows:

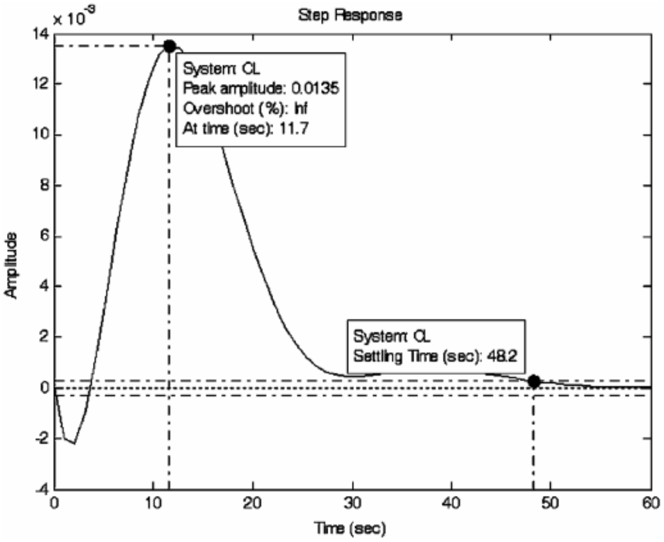

Fig. 2: Step Response in Case of DS Method

2.2. Internal Model Control (IMC) Method

It is based on an assumed process model and leads to analytical expressions for the controller settings. DS method and IMC method are closely related and produce identical controllers if the design parameters are specified in a consistent manner. However, the IMC approach has the advantage that it allows model uncertainty and tradeoffs between performance and robustness to be considered in a more systematic fashion.

It gives the same controller settings as in case of DS method for desired time constant value for closed loop system to be 1.

For log dominant models, the standard IMC controllers for first order and second order models provide sluggish disturbance responses because reset time is very large. As a remedy, Skogestad has proposed limiting the value of reset time as

$$Ti = \min\ [Ti,\ 4(\Gamma + \theta)]$$

$$= \min\ [10,\ 4(1 + 5)] = 10$$

In present case, the PI controllers settings are same. But if delay would have been 1s, which makes the second term smaller than reset time, i.e. 10, the reset time will be 8s and it will give different PI controller settings and thus better responses would have been achieved.

2.3. Hagglund and Astrom Method

It develops PI controller tunings that maximize performance subject to a constraint on the degree of robustness. PI controller settings for a first order with dead time process by this method are given as

$$K_C = (0.14\ /\ K) + (0.28\ \tau\ /\ \theta\ K)$$

$$T_I = 0.33\ \theta + 6.8\ \tau\theta\ /\ (10\ \theta + \tau)$$

Using these expressions for parameters evaluation of PI controller settings, we get

$K_C = 23.3$; $T_I = 7.3$

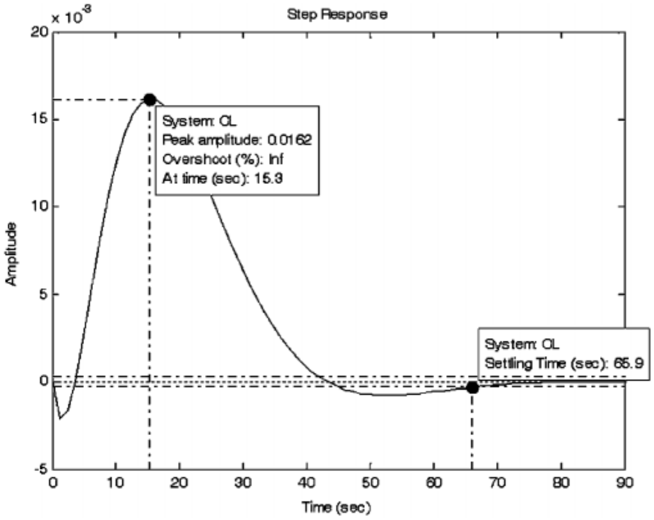

Fig. 4 : Step Response in Case of Hagglund and Astrom Method

Controller Transfer function is given as

(170 s + 23.3) / 7.3 s

2.4. Tuning Relations Based on Integral Error Criteria

To optimize the closed loop response for a simple process model and a specified disturbance or set point change, Controller tuning relations have been developed. The optimum settings minimize an integral error criterion viz. IAE (Integral absolute error), ISE (Integral square error) and ITAE (integral time weighted absolute error).

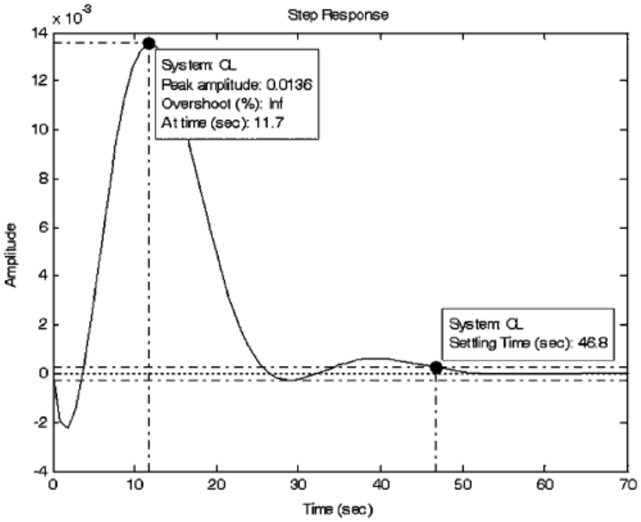

Fig. 6 : Step Response in Case of ITAE (Disturbance) Tuning Method

ITAE is the preferred criteria because it results in the most conservative controller settings. The optimal controller settings are different for set point changes and step disturbances. In general, the controller settings for set point changes are more conservative.

Controller tuning design relations for the ITAE (disturbance) performance index for PI controller parameters are given as

$$K\,K_C = A(\theta/\tau)^B$$

$$\tau/T_I = A(\theta/\tau)^B$$

The values of A and B for a FOPTD model are given by Smith and Corripio as

For Proportional mode, $A = 0.859$; $B = -0.977$

For Integral mode, $A = 0.677$; $B = -0.68$

We get $K_C = 56$; $T_I = 9.2$

Controller tuning design relations for the ITAE (set point) performance index for PI controller parameters are given as

$$K\,K_C = A(\theta/\tau)^B$$

$$\tau/T_I = A + B(\theta/\tau)$$

The values of A and B for a FOPTD model are given by Smith and Corripio as

For Proportional mode, A = 0.586; B = - 0.916

For Integral mode, A = 1.03; B = - 0.165

We get $K_C = 36.3$; $T_I = 10.5$

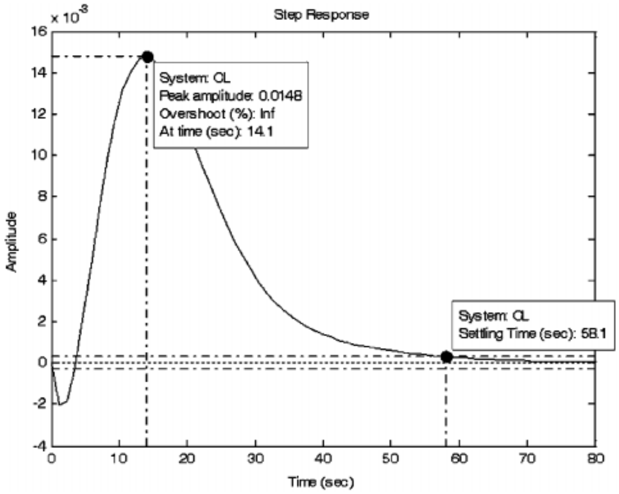

Fig. 7: Step Response in Case of ITAE (Set Point) Tuning Method

2.5. Ziegler Nichol's Method

The tuning relations reported by Ziegler and Nichols [2] were determined empirically to provide closed-loop responses that have a quarter decay ratio the Z- N controller settings have been widely used as a benchmark for evaluating different tuning methods and control strategies. The ultimate gain and ultimate period are determined as

$K_{CU} = 35.54$ and $P_U = 16.97$

Thus, the controller parameters are calculated as

$K_C = 16$; $T_I = 14.1$

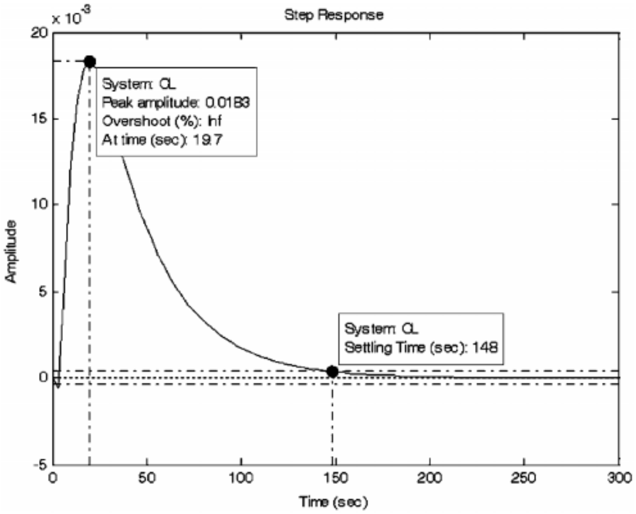

Fig. 8: Step-response in Case of Z-N Tuning Method

2.6. Tyreus Luyben Method

As Z-N settings are based on a quarter decay ratio, the Z- N settings tend to produce oscillatory responses and large overshoots for set point changes. Consequently, more conservative controller settings are preferable such as Tyreus-Luyben settings.

The controller settings based on continuous cycling method, given by Tyreus and Luyben are

$K_C = 0.31\ K_{CU}$; $T_I = 2.2\ P_U$

The ultimate gain and ultimate period are determined as

$K_{CU} = 35.54$ and $P_U = 16.97$

Thus, the controller parameters are calculated as

$K_C = 11$; $T_I = 37$

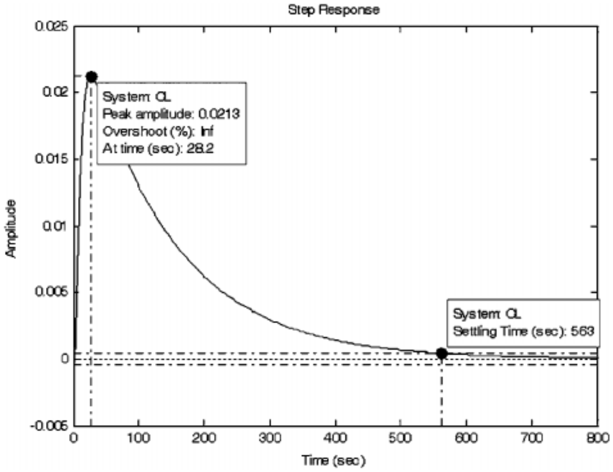

Fig. 9: Step Response in Case of T-L Tuning Method

3. RESULTS AND DISCUSSION

Table 1
Characteristics of Closed Loop Response for Different Methods

	Peak time	*Peak Amplitude*	*Settling time*	*Gain Margin*	*Phase crossover frequency*	*Closed loop stability*	*Peak gain*
DS	11.7	0.0135	48.2	40.1	0.459	Yes	-32.8
IMC	11.7	0.0135	48.2	40.1	0.459	Yes	-32.8
H and A	15.3	0.0162	65.9	42.8	0.473	Yes	-31.8
ITAE (disturbance)	11.7	0.0136	46.8	39.9	0.456	Yes	-32.4
ITAE (set point)	14.1	0.0148	58.1	41.9	0.471	Yes	-33.3
ZN	19.7	0.0183	148	43.4	0.484	Yes	-32.7
TL	28.2	0.0213	563	43.8	0.488	Yes	-32.5

Table 2
Controller Settings for Different Methods

	Controller gain	*Integral time*
DS	55.5	10
IMC	55.5	10
H and A	23.3	7.3
ITAE (disturbance)	56	9.2
ITAE (set point)	36.3	10.5
ZN	16	14.1
TL	11	37

From table 1, it is clear that peak time is same in case of DS method, IMC method and ITAE (disturbance) tuning method and is minimum. It is maximum in case of TL method. Peak amplitude is minimum for Ds method and maximum for TL method. Settling time, an important steady state characteristic is minimum for ITAE (disturbance) method and maximum for TL method. Gain Margin requirement is minimum for ITAE (disturbance) method and maximum for TL method. Phase cross over frequency is min for ITAE (d) method and max for TL method. In all the cases closed loop stability is achieved.

4. CONCLUSION

Different controller design strategies have been attempted for a FOPTD model. Various decisions can be made from the analysis of the results thus obtained. The IMC controller is identical to the DS controller for a FOPTD model. The IMC controller provides an excellent set point response whereas Skogestad based controller have significant overshoots and longer settling times.

The ITAE (disturbance) settings are the most aggressive as it has the maximum value of controller gain. The Tyreus Luyben controller has the minimum value for controller gain and maximum value for reset time, whereas H & A method controller settings have minimum integral time.

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