Comparison of closed loop performance of consistency process dynamics for various PID controller algorithms

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Abstract. In this work, various algorithms of PID (Proportional-Integral-Derivative) controllers such as series, parallel, series together with derivative filter and parallel together with derivative filter factor are implemented for the comparative analysis of the closed loop responses of an important parameter in head box of a paper machine in a paper making process industry called consistency, which has FOPDT (First Order Plus Dead Time) dynamics. Also the comparison is made between the closed loop responses achieved from different values of derivative filter factor for non-ideal situations. The steady state and dynamic characteristics are analyzed and compared and important inferences are derived.

Keywords. PID Controllers; Controller Tuning methods; Consistency control; FOPDT, Derivative Filter

1. Introduction
In The physical limitation of a system is invariably the factors that determine its controllability. Hence, system controllability is affected not only by short coming in the mechanical design of the head box, but also by deficiencies in the equipment used to sense and adjust controlled and manipulated variables.

A PID controller has a great ability of generating an equation with the fuse of the future, past and present control error values [2].
For more than eight decades, the PID controllers are recommended by control experts and designers due to their remarkable capability of eliminating the error of control with integral action. Moreover, PID controllers have been efficient in identifying the trend of the control variable and improve upon their performances with the derivative action. These are also considered to be the significant parts of predictive control or distributed control systems. Fuzzy and neural controls also utilize their coefficients as set by genetic algorithms [3, 4, 5].

Although these controllers are very popular in the process industry, easy to handle and reliable in nature but at the same time their response is average for unstable, integrating and resonant process [6].

In the modern control era, several statistical methods are also practiced frequently for designing the control system, where the information of exact relation among inputs and outputs is not necessary for designing [7], yet for industrial processes, the contribution of classical PID controllers is remarkable. Some demerits of these have also been witnessed over a period of time such as problems in eliminating the disturbance [8].

For specific processes [9], PID, in comparison to modern techniques, has shown poor performance. For further modifying PIDs, proper tuning is an essential step always without which the performance of these is always doubtful.

As per a study [10], more than 90% of all installed industrial controllers are PID but at the same time, only 20% of these are correctly tuned. Moreover these installed controllers are troubled by issues like incorrect synthesis method, unawareness of nonlinearities of actuators, improper selection of sampling frequency.

In a control system, it is practically not possible to completely stop the disturbances caused by the input or output but these can be minimized by using proper control design that reduces the effects of such disturbances before the process is affected. [11].

For higher order complex processes with multiple variables, techniques of reduction of model order have been successful in some cases also that reduce the system order but the essential properties are not altered. [12, 13].

In the pulp and paper industry, consistency is considered to be a very important variable to be controlled as it decides the quality of the paper and also the efficiency of the paper making process [14, 15]. Consistency can be understood as the uniformity of dilution water with the stock for making the paper and is recorded with consistency sensors to be treated as a control variable for consistency controller [16].

Various tuning algorithms are available including series, parallel, series together with derivative filter, parallel with derivative filter etc. But selection of the best suited for a process is the function of the process control requirements and objectives. Performances of different algorithms differ in different circumstances [17].

Moreover other tuning techniques, such as direct synthesis method, Internal model control, Hagglund and Astrom Method, Tuning Relations Based on Integral Error Criteria, Ziegler Nichol’s Method, Tyreus Luyben Method are also available and are found efficient for FOPDT processes each serving different advantages.

Figure 1 shows a schematic sketch of a typical, air loaded head box system. Two flows are of interest in the system - the flow of stock through the system and out the slice and the flow of air to and from the head box air pad. Stock flow originates at a constant speed centrifugal fan pump, the prime mover for the entire whitewater system. From there, it passes to a bank of primary centrifugal cleaners, where approximately 80 per cent of the flow is accepted and sent on through the system. Rejects are recirculated to the silo by way of the secondary and tertiary cleaners and from there to the fan pump again. On the exit side of the cleaners, the accepted stream encounters a pressure regulating valve, which serves to maintain constant pressure on the upstream side of the systems water valve or stream flow valve by recirculating part of the accepts back to the silo.

2. Methodology
A sample flow diagram is shown in figure 2. At first the SOPDT process is selected for which the controller is to be designed. Then controllers are designed sequentially for the process with Zieglar
Nichol’s method, Skogestad method and at last with Tyreus Luyben’s method. This steps involves determination of controller parameters with each method. Then in the next step, for different values of derivative filter factor $\alpha$, the controller is implemented with the use of parallel with derivative PID algorithm and also using series with derivative PID algorithm. Then in the final step, comparison of closed loop responses for controller’s set-point tracking capability is performed.

Figure 1. Wet end system

Figure 2. A sample flow diagram
3. Determination of controller parameters using Ziegler Nichol’s Method

Nancy [1] developed the following dynamics equation for consistency –

\[ G(s) = 0.03 \frac{e^{-5s}}{(1+10s)} \]  

(1)

The ultimate period and gain are determined as follows-

\[ K_{CU} = 127.8 \quad \text{and} \quad P_U = 16.97 \]

Thus, the controller parameters are computed as-

\[ K_C = 0.6 \quad K_{CU} = 76.7; \]
\[ T_I = \frac{P_U}{2} = 8.48 \text{ sec}; \]
\[ T_D = \frac{P_U}{8} = 2.12 \text{ sec}; \]

Performance evaluation is performed next for consistency parameter using Ziegler Nichol’s controller settings for various PID controller algorithms as follows-

3.1 Parallel form

It is also called ideal or additive form. Derivative action mode is combined with proportional and integral action modes while each mode operates in parallel.

The transfer function of PID controller for this type of algorithm is given as:

\[ G_c(s) = K_c \left(1 + \frac{1}{sT_I} + sT_D\right) \]  

(2)

The controller transfer function is mathematically derived as:

\[ G(s) = \frac{1379s^2 + 650.4s + 76.7}{8.48s} \]  

(3)

Therefore, the closed loop transfer function is computed as:

\[ G(s) = \frac{-41.36s^3 - 2.966s^2 + 5.504s + 0.92}{43.44s^3 + 39.43s^2 + 8.896s + 0.92} \]  

(4)

From figure 3, it can be depicted that the peak amplitude is 1.1, peak time is 15 seconds and settling time is 24.7 seconds for closed loop response of consistency process with the use of controller in parallel form.

![Figure 3. Closed loop Step response for PID Parallel form](image-url)
3.2 Series form
It is also called multiplicative or interacting form of PID controller. In principle, it makes no difference whether the PD element or the PI element comes first.

The transfer function of PID controller for this type of algorithm is given as:

\[ G(s) = K_c \frac{(1+T_I s)(1+T_D s)}{T_I s} \tag{5} \]

The Controller transfer function is derived as:

\[ G(s) = \frac{(161.8s^2 + 95.4 s + 9)}{s} \tag{6} \]

Therefore, the closed loop transfer function is computed as:

\[ G(s) = \frac{(-4.854 s^3 - 0.9205 s^2 + 0.8748 s + 0.108)}{5.146 s^3+4.079 s^2+1.275 s + 0.108} \tag{7} \]

From figure 4, it can be depicted that the peak amplitude is 1.08, peak time is 9.8 seconds and settling time is 15 seconds for closed loop response of consistency process with the help of controller in series form.

3.3 Parallel with Derivative filter type PID form
It is also called Realizable or ISA standard form. The derivative mode is usually used with a derivative filter. The transfer function of PID controller for this type of algorithm is given as:

\[ Gc(s) = Kc \left(1 + \frac{1}{sT_I} + \frac{sT_D}{sT_D(\alpha + 1)} \right) \tag{8} \]

The derivative filter factor \( \alpha \) is normally selected in the range of 0.05 and 0.2 and most often it is preset to 0.1.

3.3.1 Derivative filter factor = 0.1
The controller transfer function is mathematically derived as:
\[ G(s) = \frac{178s^2 + 78.23s + 9}{0.212s^2 + s} \]  

(9)

Therefore, the closed loop transfer function is computed as:

\[ G(s) = \frac{-5.339s^3 - 0.2112s^2 + 0.6687s + 0.108}{2.12s^4 + 5.721s^3 + 4.874s^2 + 1.069s + 0.108} \]  

(10)

From figure 5, it can be depicted that the peak amplitude is 1.09, peak time is 15.3 seconds and settling time is 25.7 seconds for closed loop response of consistency process with the use of controller in parallel form together with derivative filter and for value of \( \alpha \) to be 0.1.

**Figure 5.** Closed loop response for PID parallel form together with derivative filter for \( \alpha = 0.1 \)

3.3.2 Derivative filter factor = 0.05

The controller transfer function is mathematically derived as:

\[ G(s) = \frac{170.7s^2 + 77.61s + 9.04}{0.106s^2 + s} \]  

(11)

Therefore, the closed loop transfer function is computed as:

\[ G(s) = \frac{-5.12s^3 - 0.2803s^2 + 0.6601s + 0.1085}{1.06s^4 + 5.41s^3 + 4.762s^2 + 1.06s + 0.1085} \]  

(12)

From figure 6, it can be depicted that the peak amplitude is 1.1, peak time is 15.2 seconds and settling time is 25.3 seconds for closed loop response of consistency process with the use of controller in parallel form together with derivative filter and for value of \( \alpha \) to be 0.05.

3.3.3 Derivative filter factor = 0.2

Controller transfer function is mathematically derived as:

\[ G(s) = \frac{195s^2 + 80.4s + 9.04}{0.106s^2 + s} \]  

(13)
Therefore, the closed loop transfer function is computed as:

$$G(s) = \frac{(-5.85 s^3 - 0.072 s^2 + 0.6936 s + 0.1085)}{1.06 s^4 + 4.68 s^3 + 4.97 s^2 + 1.094 s + 0.1085} \quad (14)$$

From figure 7, it can be depicted that the peak amplitude is 1.08, peak time is 16.3 seconds and settling time is 25 seconds for closed loop response of consistency process with the use of controller in parallel form together with derivative filter and for value of $\alpha$ to be 0.2.

### 3.4 Series together with derivative filter

It is also known as physically realizable form. The transfer function of PID controller for this type algorithm is given as:

$$Gc(s) = Kc\left(\frac{1 + sT_d}{T_i\left(sT_i + \alpha + 1\right)}\right) \quad (15)$$

#### 3.4.1 Derivative filter factor = 0.1

Therefore, the closed loop transfer function is computed as:

$$G(s) = \frac{161.8 s^2 + 95.4 s + 9}{0.212 s^2 + s} \quad (16)$$

Thus, the closed loop transfer function is computed as:

$$G(s) = \frac{-4.854 s^3 - 0.9204 s^2 + 0.8748 s + 0.108}{2.12 s^4 + 6.206 s^3 + 4.164 s^2 + 1.275 s + 0.108} \quad (17)$$

**Figure 6.** Closed loop response for PID parallel form together with derivative filter for $\alpha = 0.05$
Figure 7. Closed loop response for PID parallel form together with derivative filter for $\alpha = 0.2$

From figure 8, it can be depicted that the peak amplitude is 1.13, peak time is 8.94 seconds and settling time is 15.5 seconds for closed loop response of consistency process with the use of controller in series form together with derivative filter and for value of $\alpha$ to be 0.1.

3.4.2 Derivative filter factor $= 0.05$

The controller transfer function is mathematically derived as:

$$G(s) = \frac{(161.8s^2 + 95.4s + 9)}{(0.106s^2 + s)}$$

(18)

Therefore, the closed loop transfer function is computed as:

$$G(s) = -\frac{4.854s^3 - 0.9204s^2 + 0.8748s + 0.108}{1.06s^4 + 5.676s^3 + 4.122s^2 + 1.275s + 0.108}$$

(19)

From figure 9, it can be depicted that the peak amplitude is 1.1, peak time is 9.3 seconds and settling time is 15.4 seconds for closed loop response of consistency process with the use of controller in series form together with derivative filter and for value of $\alpha$ to be 0.05.

3.4.3 Derivative filter factor $= 0.2$

The controller transfer function is mathematically derived as:

$$G(s) = \frac{(161.8s^2 + 95.4s + 9)}{(0.424s^2 + s)}$$

(20)

Therefore, the closed loop transfer function is computed as:

$$G(s) = -\frac{4.854s^3 - 0.9204s^2 + 0.8748s + 0.108}{4.24s^4 + 7.266s^3 + 4.249s^2 + 1.275s + 0.108}$$

(21)

From figure 10, it can be depicted that the peak amplitude is 1.2, peak time is 8.23 seconds and settling time is 15 seconds for closed loop response of consistency process with the use of controller in series form together with derivative filter and for value of $\alpha$ to be 0.2.
Comparison of step responses for PID series form with different values of derivative filter is shown in figure 10 (for parallel form) and figure 11 (for series form). Also the comparison of important steady state and dynamic characteristics for different PID algorithms for consistency process is shown in Table-1.
Figure 10. Comparison of PID parallel form and PID series form

Figure 11. Comparison of step responses for PID series form with derivative filter for $\alpha = 0.1$(CLS1), 0.05(CLS5) and 0.2(CLS2)

From table 1, it is evident that the minimum peak amplitude is 1.08 which is same for PID controller in series form, parallel form together with derivative filter factor 0.2. The peak time achieved is minimum for PID controller in series configuration together with derivative filter factor 0.2. Settling time is minimum for PID controller in series form, series form together with derivative controller with $\alpha$ value of 0.2, which amounts to 15 seconds. These characteristics peak amplitude, peak time and settling time resemble closely in case of standard parallel form and parallel together with derivative
filter for derivative filter factor as 0.05. Settling time is maximum for the case of Parallel form with derivative filter in case when $\alpha$ is 0.1. This value is 25.7, which is much larger than the minimum value of 15 seconds.

**Table 1.** Comparison of important steady state and dynamic characteristics for different PID algorithms for consistency process

|                      | Parallel form | Series form | Parallel with derivative filter | Series with derivative filter |
|----------------------|---------------|-------------|---------------------------------|------------------------------|
| $\alpha = 0.1$       | 1.1           | 1.08        | 1.09                            | 1.13                         |
| $\alpha = 0.05$      | 1.08          | 1.1         | 1.08                            | 1.1                          |
| $\alpha = 0.2$       | 1.09          | 1.1         | 1.08                            | 1.13                         |
| Peak amplitude       | 15            | 9.8         | 15.3                            | 15.2                         |
| Peak time (sec)      |               |             | 16.3                            | 8.94                         |
|                      | 15            | 9.8         | 15.3                            | 9.3                          |
|                      | 24.7          | 15          | 25.7                            | 15.5                         |
| Settling time (sec)  |               |             | 25.3                            | 15.4                         |
|                      | 25            |             | 25                              | 15                           |

4. Conclusion

In this work, a comparative analysis is performed for the consistency variable, an important parameter in paper machine, with the implementation of various PID controller algorithms such as series, parallel, series together with derivative filter and parallel together with derivative filter form. Different closed loop responses are achieved and compared for different values of derivative filter factor.

The analysis suggests that the peak value has the least variation in its value for different PID algorithms. The peak time is lesser for series form or for series form with derivative filter with different cases of $\alpha$ value than any of the parallel configuration dealt with. Peak time is less for series configuration. It is least for series with derivative value of 0.2. Settling time is minimum for series form. It is same for series together with derivative value of 0. Overall steady state and transient characteristics are minimum for the case of series configuration, especially with the highest derivative configuration among selected values of filter coefficients.

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