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RESEARCH ARTICLE

Dead Time compensators for Stable Processes

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Abstract

Dead time is often present in control systems as computational or informational delay but in most cases it is very small and is neglected. Dead time is widely found in the process industries when transporting materials or energy. Generally stable processes are represented by first-order-plus-dead-time or second order-plus-dead-time models for analysis. The problem of control design for processes with dead time is quite crucial and long-standing. The advent of the Smith Predictor (SP) provided the industrial control community with another tool to tackle the control of processes where the presence of dead time was impairing closed-loop performance. In this paper, analysis of stable processes with dead time is done. Here PI controller and Smith Predictor are used as dead time compensators. The comparative study with respect to reference tracking and disturbance rejection of PI controller and Smith Predictor for the considered processes has been covered in this paper.

Keywords: Process dead time, informational delay, Smith Predictor, PI controller, stable processes.

Introduction

All the feedback systems are generally represented by the linear lumped parameters mathematical model. This is valid so long as the time taken for energy transmission is negligible i.e. the output begins to appear immediately on application of input. This is not quite true of transmission channel-lines, pipes belts, heat exchangers, conveyors etc. In such cases a definite time elapses after application of input before the output begins to appear. This type of pure time lag is known as transportation lag or dead-time. Dead times or time delays, are found in many processes in industry. Dead time can arise in a control loop for a number of reasons (Nagrath and Gopal, 1997; Normey-Rico and Camacho, 2007). Dead time issues can be addressed by a simple change in design of the process. The process plant is designed such that the sensors are located close to the action. For any process larger the dead time, the quality performance becomes more difficult to achieve.

The major difficulties in controlling dead-time processes are as (Normey-Rico and Camacho, 2007): (i) the effect of the disturbances is not felt until a considerable time has elapsed; (ii) the effect of the control action takes some time to be felt in the controlled variable; (iii) the control action that is applied based on the actual error tries to correct a situation that originated some time before. Delay is unavoidable in many control systems. Most of the classical methods such as root locus and Nyquist criterion that analyze the control system cannot deal with delay. Moreover, systems with delay have infinite dimensions which make it impossible to express the system in state space. But for analysis and to understand the dynamic behavior of the systems, mathematical modeling of processes is important.

In case of dead time processes generally FOPDT and second order plus dead time (SOPDT) models are formed for analysis without losing the characteristics of the process (Abdel Fattab *et al.,* 2004; Rahmat and Sahazati, 2008). It is also done because analysis of higher order processes becomes quite difficult. Generally process identification methods are used to reduce higher order processes into FOPDT and SOPDT models. The FOPDT model is represented by

$$P(s) = \frac{K_p}{1+Ts} e^{-Ls} \tag{1}$$

Where K_p , T and L are real numbers. $T > 0$ is the equivalent time constant of the plant and K_p is the static gain. $L > 0$ is the equivalent dead time (Morari and Zafiriou, 1989; Coughanow, 1991; Seborg, 2004; Singh, 2009). When it is desirable to represent a smoother step response in the first part the transients or an oscillatory step response, a second-order process with a dead time is used.

$$P(s) = \frac{K_p e^{-Ls}}{(1+T_1 s)(1+T_2 s)} = \frac{K_p e^{-Ls}}{1+\frac{2\xi s}{\omega}+\frac{s^2}{\omega^2}} \tag{2}$$

Where, $K_p, T_1, T_2, \xi, \omega_n$ and L are real numbers. As in the FOPDT model K_p is the static gain and $L > 0$ the equivalent dead time. $T_1 > 0$ and $T_2 > 0$ are time constants of the plant in the case of a non-oscillatory response while the damping coefficient, $\xi \varepsilon$ $(0,1)$ and the natural frequency $\omega_n > 0$ are used when the process exhibits an oscillatory step response.

Dead time compensators

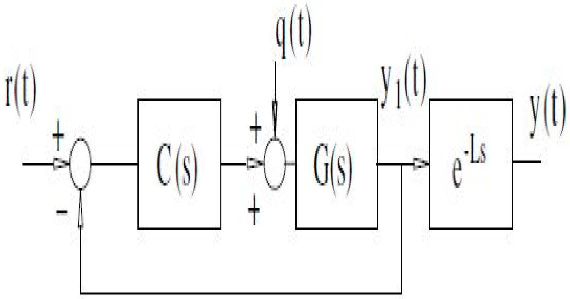
PI Controller: When dead time is very small and for slow variations of the output signal PID control is a better choice but when dead time is long enough the control performance obtained with a proportional-integral-derivative (PID) controller is limited. Predictive control is required to control a process with a long dead time efficiently. Therefore, if a PID controller is applied on this kind of problems, the derivative part is mostly switched off and only a PI controller without prediction is used (Nagrath and Gopal, 1997). In an integral error compensation scheme, the output response depends in some manner upon the integral of the actuating signal. This type of compensation is introduced by using a controller which produces an output signal consisting of two terms, one proportional to the actuating signal and the other is proportional to its integral. Such a controller is called proportional plus integral controller.

A PI controller is a special case of the PID controller in which the derivative (D) of the error is not used. The most famous tuning method for PI controllers is the Ziegler-Nicholas rule (ZN). It was developed using simulations with different systems where the equivalent dead time L and time constant satisfy the condition i.e. $L/T < 1$ or called lag dominant systems. The ZN settings are benchmarks against which the performances of other controller settings are compared in many studies.

The Smith Predictor: The Smith predictor invented by Smith in 1957 is a type of predictive controller for systems with pure time delay (Palmor, 1996). Figure 1 shows this ideal situation in a general case, where the controller C(s) is tuned using only G(s) and the real output y (t) is the output of G(s), y1 delayed L units of time. y(t) = y1(t − L). In this situation the dead time has no effect on the closed loop transients, as the closed-loop transfer function is

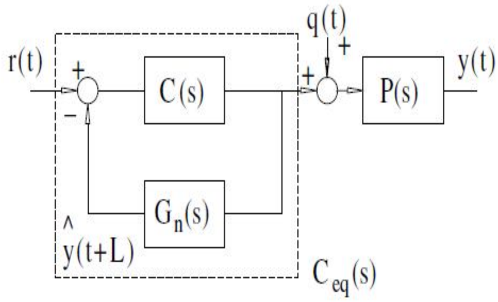
$$\frac{Y(s)}{R(s)} = \frac{C(s)G(s)e^{-Ls}}{1+C(s)G(s)} \tag{3}$$

Fig. 1. Ideal control for dead time processes.



The real implementation of this solution is, in general, not possible in practice mainly because the sensor cannot be installed in the desired position and/or the process dead time is not caused by mass transportation. A simple solution for this problem can be obtained using the idea of prediction and will be applied here to a stable process. If a dead-time-free model $G_n(s)$ of the plant $P(s) = G(s)e^{-Ls}$ is considered, it is possible to feed the output of this model to the controller as shown in figure 2.

Fig. 2. Open loop predictor.

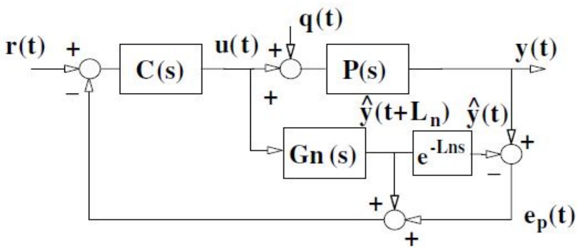


In this structure if $G_n(s) = G(s)$ the primary controller C(s) can be tuned considering only G(s) and the obtained closed- loop performance is the same as in the ideal case as in equation (3).The equivalent controller for this system is

$$C_{eq}(s) = \frac{C(s)}{1+C(s)G_n(s)} \tag{4}$$

This operates in an open-loop manner. This strategy is known as open-loop predictor based control and it is clear that it cannot be used in practice because the controller does not "see" the effect of the disturbances and also model mismatches are not taken into account and, therefore, all the beneficial properties of feedback disappeared. A better solution for this problem was proposed by Smith based on a closed-loop predictor structure of the open-loop-stable process. In this strategy, the prediction at time t is computed by the use of a model of the plant without dead time $G_n(s)$ and, in order to correct the modeling errors, the difference between the output of the process and the model (including the dead time $P_n(s) = G_n(s)e^{-Lns}$ is fed back, as can be seen in figure 3.

Fig. 3. The Smith predictor structure.



With this structure, if there are no modeling errors or disturbances, the error between the current process output and the model output $e_p(t)$ will be null and the controller can be tuned as if the plant had no dead time. Thus, in the nominal case this structure gives the same performance as the ideal solution. To consider the modeling errors, the difference between the output of the process and the model including dead time is added to the open-loop prediction, as can be seen in the scheme of figure 3. If there are no modeling errors or disturbances, the error between the current process output and the model output will be null and the predictor output signal yp(t) will be the dead-time-free output of the plant. A simple solution to this problem is to use a filter $F_r(s)$ with unitary static gain $F_r(0)=1$. The filter should be designed to attenuate oscillations in the plant output especially at the frequency where the uncertainty errors are important. This can be done by low pass filter that increases the robustness of the controller.

Results and discussion

Here simulation results of three processes such as stirred tank heat exchanger; electric oven temperature control and coupled tank process are shown and discussed. PI controller and Smith Predictor are used to control these processes and how the performance of these controllers is influenced by the variation in dead time is also discussed in this section.

Stirred tank heat exchanger: The FOPDT model of stirred tank heat exchanger (Morari and Zafiriou, 1989; Coughanow, 1991) process is considered as

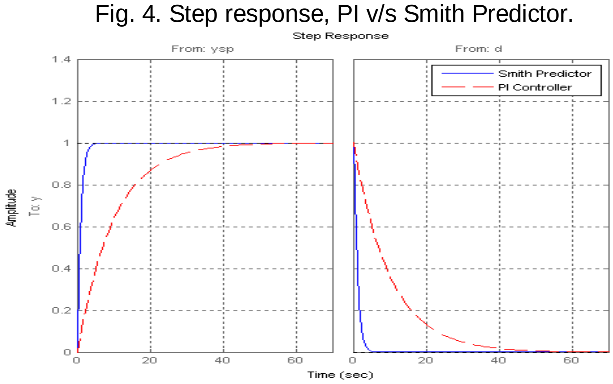
$$G(s) = \frac{e^{-0.0396s}}{0.202s+1}$$

Here in this FOPDT model of stirred tank heat exchanger the dead time is very small and the tuning parameters are taken as $K_p = 0.01$ and $T_i = 0.1$, which are chosen using Cohen and Coon tuning rule. For Smith Predictor, the tuning parameters are considered same as above for PI controller. Actually the control algorithm in a Smith Predictor is usually a PI controller. Here, $F = \frac{1}{0.202s+1}$ is used as a filter to remove dead time estimation errors. Actually the filter which is used to remove dead time dead time estimation errors is in the form

$$F = \frac{1}{1+sT_f} = \frac{1}{1+s\varepsilon L} \quad \text{where} \quad \varepsilon = 0.5 \quad \text{and} \quad T_f = L/2$$

where L is the dead time (Normey-Rico and Camacho, 2007). From figure 4, it is clear that Smith Predictor provides much faster response as compared to PI controller and also Smith Predictor rejects the disturbance earlier as compared to PI controller.

Fig. 4. Step response, PI v/s Smith Predictor.



In the above analysis, the internal model $G_n(s)e^{-L_n s}$ matched the process model $P(s)$ exactly but in practical situations the internal model is only an approximation of the true process dynamics.

Electric oven temperature control system: The FOPDT model of electric oven temperature system (Singh, 2009) is

$$G(s) = \frac{1.63e^{-270s}}{1+3480s}$$

This system has a long dead time. Now when a PI controller is applied on this system with $K_p = 3.5$ and $T_i = 773.63$ using Cohen and Coon tuning rule, the result obtained is shown in figure 5.

Fig. 5. Step response with $K_p = 3.5$ and $T_i = 773.63$.

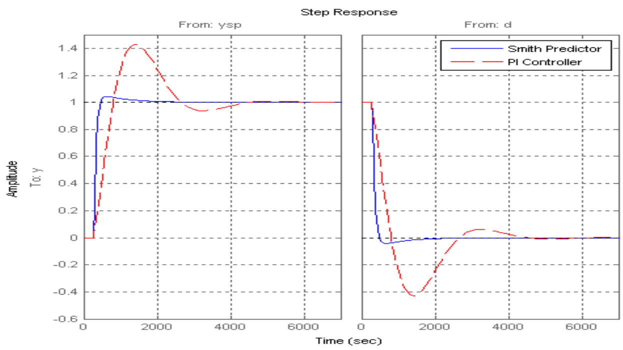
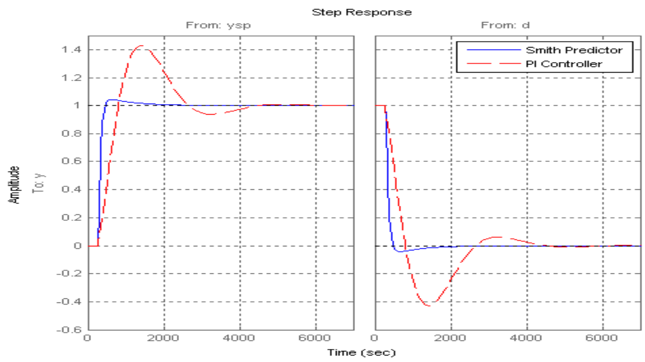


Fig. 6. Step response, PI v/s Smith Predictor.



From figure 6, it is clear that Smith Predictor provides much faster response as compared to PI controller and also Smith Predictor rejects the disturbance earlier as compared to PI controller.

Coupled tank process: The results presented above are for FOPDT models and now a SOPDT model of a coupled tank process (Rahmat and Rozali, 2008) with a small delay is considered as

$$G(s) = \frac{0.0331e^{-0.4s}}{s^2 + 0.0315s + 0.0248}$$

When a PI controller is applied on the above system described by the equation with $K_p = 0.0315$ and $T_i = 30.21$ which are chosen using Zeigler-Nicholas tuning method, the result obtained is shown below in figure 7.

Fig. 7. Step response with $K_p = 0.0315$ and $T_i = 30.21$.

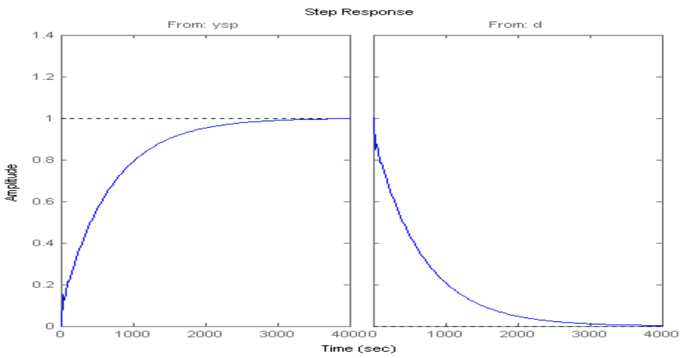


Figure 8 shows how step response is affected by increasing the delay in dead time part. Here four different values of dead time are used. For analysis purposes, SOPDT model with long delay time is used. Therefore the considered model is

$$G(s) = \frac{0.0331e^{-600s}}{s^2 + 0.0315s + 0.0248}$$

Figure 9, shows step response, depicting comparison between PI controller and Smith Predictor. It is clear that Smith Predictor provides much faster response as compared to PI controller and also Smith Predictor rejects the disturbance earlier as compared to PI controller. So, it is important to understand how robust the Smith Predictor to uncertainty on the process dynamics and dead time (Saravanakumar, 2006). Smith predictor is able to control the process having larger value of dead time in a much faster and accurate way as compared to conventional PI controller.

Fig. 8. Step response with different time delays.

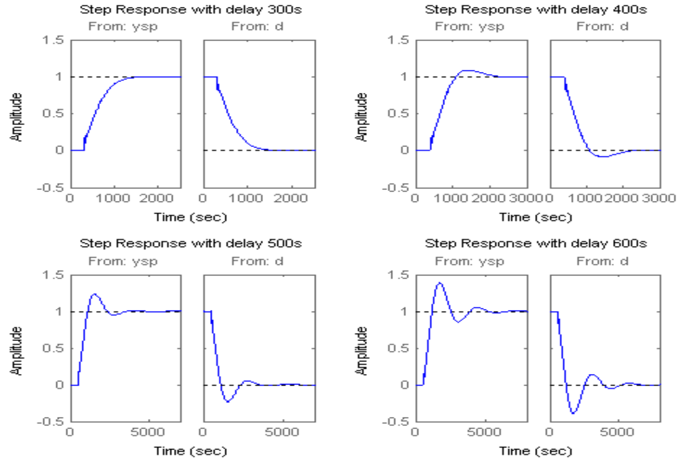
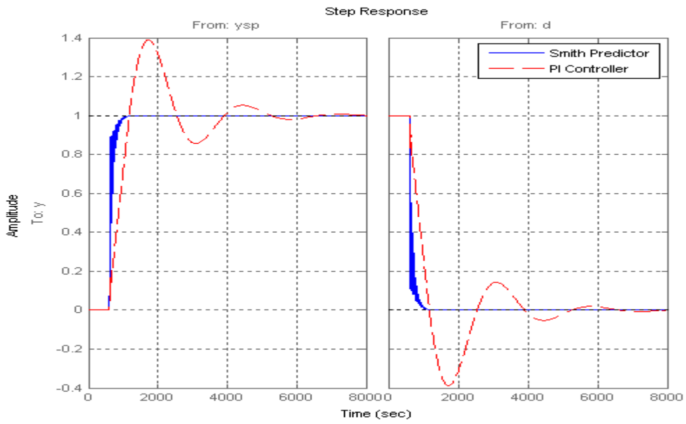


Fig. 9. Step response, PI v/s Smith Predictor.



Conclusion

PI controller and Smith Predictor are good dead time compensators for dead time processes. The control algorithm in a Smith Predictor is a PI controller and it also uses the idea of prediction. When a comparison is made between the performance of PI controller and Smith Predictor for long dead time processes, better results are obtained with Smith Predictor. Smith Predictor eliminates the effect of the dead time in the set point response. A good trade- off between robustness and performance can be obtained by appropriate tuning of primary controller. When the process exhibits integral dynamics, the classical Smith Predictor fails to provide a null steady state error in the presence of a constant load disturbance.

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