Detection and Compensation of Dead Time in Chemical Processes

MASTER OF SCIENCE IN ENGINEERING
(CHEMICAL)

KAWNISH KIRTANIA

DEPARTMENT OF CHEMICAL ENGINEERING
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY, DHAKA

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KAWNISH KIRTANIA

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CERTIFICATION OF THESIS WORK

We the undersigned, are pleased to certify that **Kawnish Kirtania**, a candidate for the degree of **Master of Science in Engineering (Chemical)** has presented his thesis work on the subject **"Detection and Compensation of Dead Time in Chemical Processes"**. The thesis is acceptable in form and content. The student demonstrated a satisfactory knowledge of the field covered by this thesis in an oral examination held on **February, 2011**.

____

Dr. M.A.A. Shoukat Choudhury — Chairman
Associate Professor
Department of Chemical Engineering
BUET, Dhaka-1000

____

Dr. Dil Afroza Begum — Member
Professor and Head
Department of Chemical Engineering
BUET, Dhaka-1000

____

Sirajul Haque Khan — Member
Associate Professor
Department of Chemical Engineering
BUET, Dhaka-1000

____

Dr. Khawza Iftekhar Ahmed — Member (External)
Associate Professor
Department of Electrical and Electronic Engineering
United International University
Dhanmondi, Dhaka-1209

Abstract

Dead time is commonly found in chemical processes. Significant amount of dead time can lead to unsatisfactory and unstable process operation. Therefore, dead time estimation and compensation is very important for processes with long dead time. In this study, a new dead time compensation technique for stable processes has been developed.

The estimation of dead time is developed using a numerical technique. Numerical Integration is used to detect dead time from step response data of a process. The method was evaluated and validated in simulation. Later, this method has been used to detect dead time from step response data of a real process. The dead time estimation technique performs well up to a certain amount of noise present in the system.

The dead time compensation method is developed by modifying the classical dead time compensator structure. Two new filters are introduced in the traditional compensator. New rules for tuning the controller and the parameters of the filters are developed. The performance of the newly proposed dead time compensator has been compared with the most recently appeared dead time compensator in the literature using both simulation and experimental studies. A pilot scale two tank heating system is used for experimental evaluation of the proposed dead time compensator. The dead time compensator outperforms the most recently appeared dead time compensator. The reliability analysis is performed to test the robustness of the proposed method. The reliability analysis shows that the newly developed dead time compensator can handle some uncertainties in the estimation of dead time and process model.

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Abbreviations

2DOF	**T**wo **D**egrees of **F**reedom
ARMA	**A**uto **R**egressive **M**oving **A**verage
DTC	**D**ead **T**ime **C**ompensator
FOPDT	**F**irst **O**rder **P**lus **D**ead **T**ime
FSP	**F**iltered **S**mith **P**redictor
IAE	**I**ntegral of **A**bsolute **E**rror
IMC	**I**nternal **M**odel **C**ontrol
IPDT	**I**ntegrating **P**rocess with **D**ead **T**ime
ISE	**I**ntegral of **S**quared **E**rror
LHP	**L**eft **H**alf **P**lane
MSP	**M**odified **S**mith **P**redictor
PI	**P**roportional **I**ntegral
PID	**P**roportional **I**ntegral **D**erivative
PPI	**P**redictive **P**roportional **I**ntegral
RHP	**R**ight **H**alf **P**lane
SP	**S**mith **P**redictor
TCV	**T**emperature **C**ontrol **V**alve
TT	**T**emperature **T**ransmitter

Symbols

C	controller	
$C^{'},\ C_{eq}$	equivalent controller	
$\hat{D}$	delayed disturbance	
F	disturbance Estimator	
F_1	filter for set-point tracking	
F_2	filter for disturbance rejection	
f_1, f_2	functions	
$G_1,\ G_n$	process model without time delay	
G_C	auxiliary controller	
$H_{Y_{sp}}$	set-point response	
H_D	disturbance rejection response	
$K,\ K_P$	process gain	
K_V	time constant of integrating process	
K_C	proportional controller gain	
L	actual dead time	second
L_n	estimated dead time	second
N	low pass filter parameter	
N_e	Polynomial	
P	actual process	
P_n	estimated process	
Q	transfer function of inner loop of smith predictor	
s	Laplace domain variable	
T	process time constant	second

T_1, T_2	filter parameters	
T_I	integral time constant	second
T_0, T_V	tuning parameter	
T_r	closed loop pole	
u	input	
V	filer for disturbance observer approach	
W	performance weight	
y, Y	process output	
Y_{sp}	set-point	
Z	filter parameter of modified Smith predictor	

GREEK SYMBOLS

α	constant
β_1	tuning parameter
δ	differential value
Δ	small value
κ	constant
τ	constant
τ_c	parameter related to IMC tuning
λ	part of disturbance rejection response expression

Chapter 1

Introduction

1.1 Background

Whenever material or energy is physically moved in a process or plant, there is time delay associated with the movement. For example, if a fluid is transported through a pipe in plug flow as shown in Figure 1.1 [7] , then the transportation time between points 1 and 2 is given by

$$L = \frac{\text{length of pipe}}{\text{fluid velocity}} = \frac{\text{volume of pipe}}{\text{volumetric flow rate}} \tag{1.1}$$

where length and volume both refer to the pipe segment between 1 and 2.

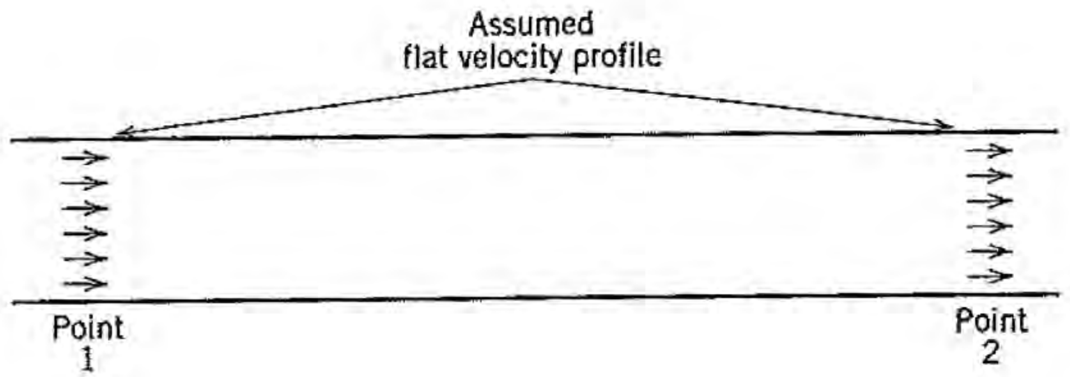


FIGURE 1.1: Transportation of fluid in a pipe for turbulent flow

Besides the physical movement of liquid and solid materials, there are other sources of dead time. For example, the use of a chromatograph to measure concentration in liquid or gas stream samples taken from a process introduces a time delay, the analysis time. One distinctive characteristic of chemical processes is the common occurrence of dead times. The effect of dead time can be illustrated by an example. A process with time constant 5 seconds and gain 1 will be

$$Process = \frac{1}{5s+1} \tag{1.2}$$

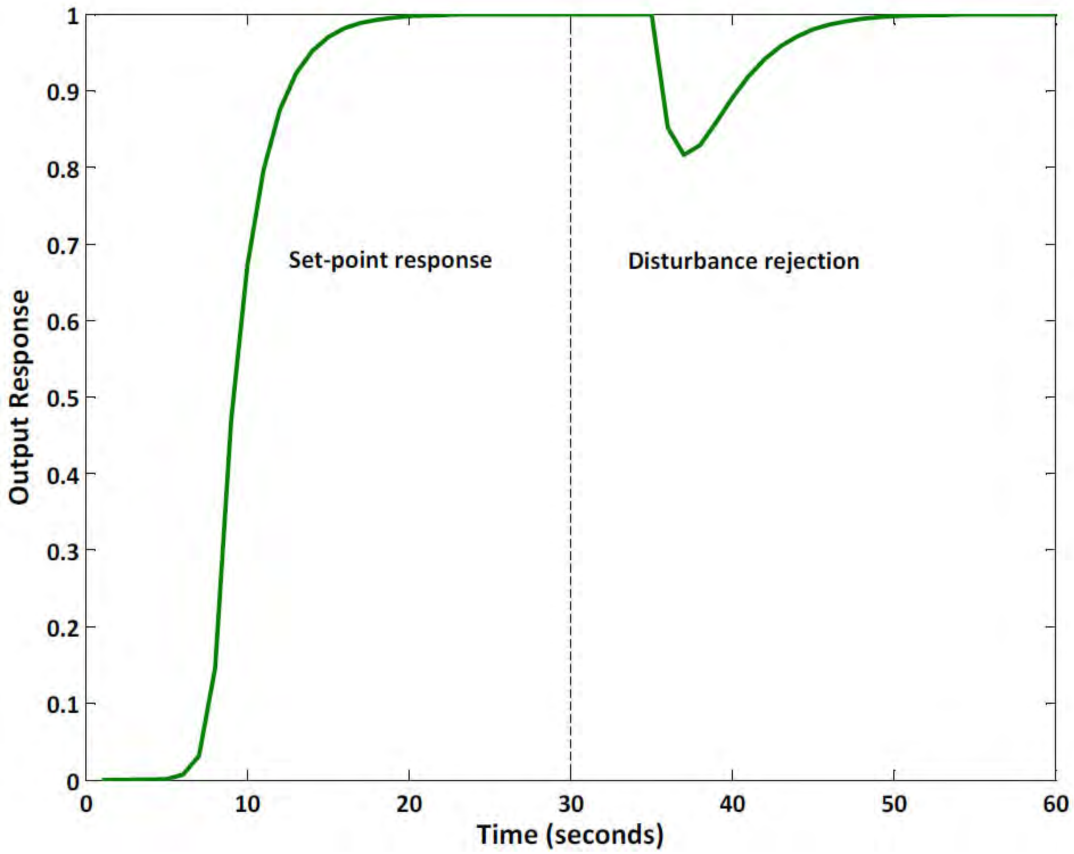


FIGURE 1.2: Process response without dead time

This process can be easily controlled by a PI controller designed by Internal Model Control (IMC) method. As per the IMC method, the controller gain will be 1 and

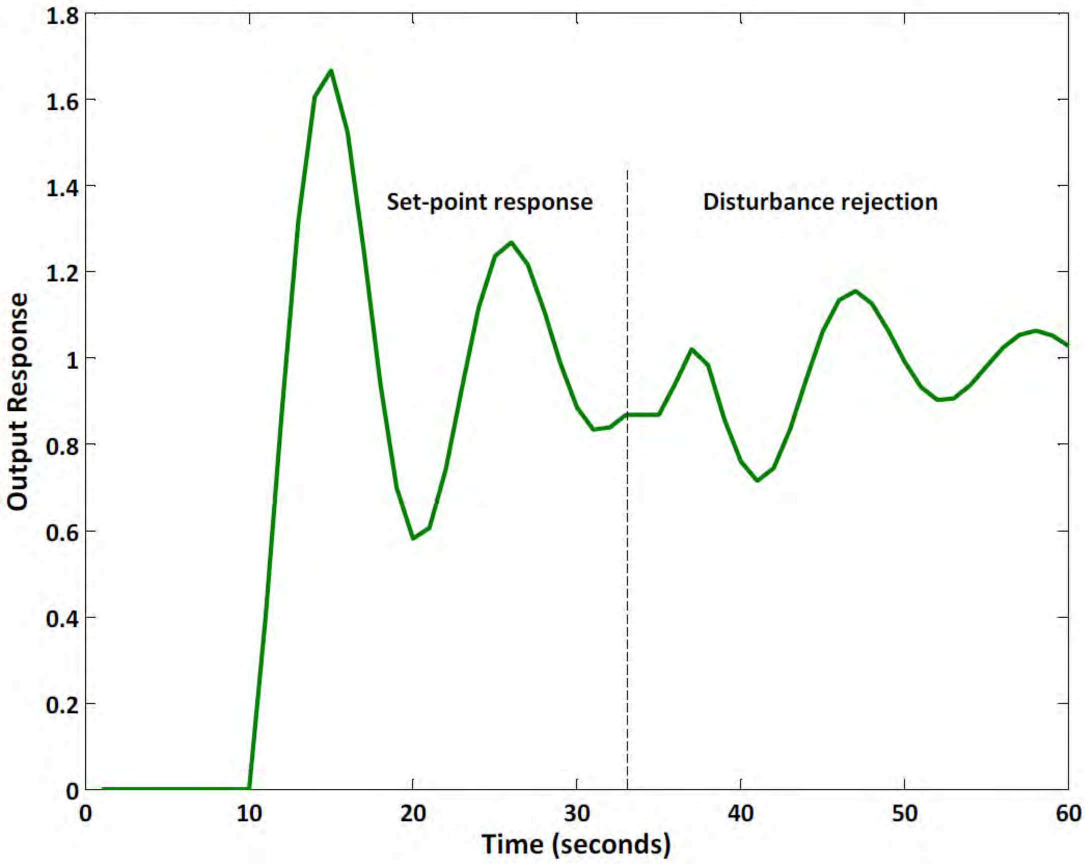


Figure 1.3: Process response with dead time

integral time constant will be 5 seconds. The set-point and disturbance rejection response can be presented as shown in Figure 1.2. The response is very smooth and satisfactory. But if a dead time of 6 seconds is introduced into the process, the process response becomes really oscillatory. Figure 1.3 shows the response with dead time. Any further increase in dead time will make the process unstable.

The product quality is greatly affected by dead time. To retain the product quality and make the process stable, control engineers have been working hard to compensate the dead time. But before compensating, dead time is to be estimated. The detection and compensation were always a challenge for the control engineers. So several works have been attempted to detect and compensate the dead time [1–25]. Numerical and statistical techniques are applied on the process data from step or relay tests to detect dead time.

A dead time compensator was first proposed by Smith [1].This classical compensator has some limitations. It requires accurate estimation of dead time and process model. If there are estimation errors in dead time and process model, it does not work properly. To overcome the limitations, several modifications of Smith Predictor have been proposed in this study.

1.2 Objective and Scope of the Study

The objective of the study is to device a method to determine the dead time from step test data of any stable process. Also emphasis of this study will be on formulating a new dead time compensator to compensate the dead time effectively for stable processes.

The scope of the study can be listed as follows

- Dead time estimation: A new method would be developed to determine the dead time from a step test data. The method would be based on numerical integration which can take into account the maximum amount of noise.
- Dead time compensation: Dead time compensation will be done by modifying the Smith predictor. New rules for tuning will be established for the proposed modification. Also the robustness of the dead time compensation technique will be analyzed.
- Evaluation in a simulation: The dead time estimation will be done for a process with known dead time in simulation. Also the method will be evaluated by introducing gaussian noise into the process. Simulation study will be done on the dead time compensator to assess its capability to compensate the dead time.
- Evaluation in pilot plant set-up: Both the dead time estimation and compensation technique will be implemented on a pilot scale two tank heating system to evaluate the performance of the proposed methods.

The experimental setup in the Process Control Laboratory of Department of Chemical Engineering, BUET has been used to introduce dead time for experimenting on dead time detection and compensation.

1.3 Thesis Organization

Chapter 1 is the introduction to this thesis. Summary of the background and thesis organization are also included in this chapter.

Chapter 2 provides an overview of dead time compensation along with some detection techniques. It provides the insight into the first dead time compensator named as Smith Predictor [1] and then its evolution by several dedicated workers to make it usable for many different kinds of processes.

Chapter 3 describes a new method for estimating the dead time. The method has been evaluated using extensive simulation.

Chapter 4 includes the dead time compensation methodology. With the theoretical evaluation, this chapter provides the simulation results with uncertainty analysis.

Chapter 5 provides the description of the experimental rig along with the results of the experimental studies on both dead time detection and compensation. The results are quantified to draw the conclusion.

Chapter 6 states the conclusions drawn from the current work and suggests possible directions for future research.

Chapter 2

Literature Review

Dead time is a common phenomenon in chemical industries. In chemical processes, a certain amount of time is needed for the material, energy and information flow through the system. That is why; the signal passing through the process needs some time to reach the signal transmitter. Whenever, the time needed to pass the signal through the system is more than the time constant of the process, there is predicted to be some dead time. Also the accumulation of time lags in a great number of low order system connected in series or complicated control strategy may introduce some dead time in the system. Whenever material or energy is physically moved in a process or plant, there is a dead time associated with it. Sometimes, it is called time delay, transport delay or transportation lag.It can be represented as

$$y(t) = \begin{cases} 0 & t < L \\ x(t-L) & t \geq L \end{cases} \tag{2.1}$$

where, y(t) is the output and x(t) is the input to the process which changes along with time, t. L is dead time for the system. Whenever the process overcomes the dead time, the process begins to respond. Before that, the process output remains at static state. This dead time not only slows down a process response but also make a process oscillatory and sensitive sometimes. This happens because dead time introduces nonlinearity to linear process. So this dead time can be a big issue when this phenomenon occurs in the production line or quality control section of a chemical industry. Thus it can cause a million dollar loss for an industry. Now a days, it has become an issue to detect and compensate satisfactorily wherever a tight control strategy is needed. For processes with large dead time, the traditional feedback controllers cannot be used. The reasons are -

- The effect of the perturbations is not felt until a considerable time has elapsed
- The effect of the control action takes time to be reflected in the controlled variable
- The control action that is applied based on the actual error, tries to correct a situation that originated some time before

When the process has a significant dead time, the performance of the closed-loop system can be improved by using a predictor structure. These predictor based controllers are known as dead-time compensators (DTC) and have been applied to many engineering fields, mainly in the process industry [23]. The first DTC structure, the Smith predictor (SP), was presented at the end of the 1950s [1] to improve the performance of classical controllers (PI or PID controllers) for plants with dead time. It is one of the most popular dead-time compensating methods and most widely used algorithm for dead-time compensation in industry. To use this compensator, it is important to estimate the dead time in a process correctly. To detect dead time, Wang [10] suggested a method which uses the step test response to detect the dead time. Another method proposed by Majhi [18] detects the dead time by relay based identification. Both of these methods requires some excitation of the process to detect dead time.

Over the past 25 years, numerous extensions and modifications of the SP have been proposed in order to: (a) improve the regulatory capabilities of the SP for measurable or unmeasurable disturbances; (b) to allow its use with unstable plants; (c) to improve the robustness or (d) to facilitate the tuning in industrial applications. Practical stability of SPs was analyzed in Palmor [12] and Palmor and Halevi [11] showing that if the primary controller is not properly tuned, the SP could be unstable when a small mismatch in the delay is considered, in spite of having high gain and phase margins for the ideal system.

The properties of the SP were analysed in Jerome and Ray [20], Garcia and Morari [25] and Morari and Zafiriou [17] using some ideas derived from internal model control (IMC). An analysis of the asymmetry of the dead time estimation error effect on performance and stability is made in Ingimunderson and H*ä*gglund [17]. Simple tuning rules for the SP are given in Hägglund [24] while two degree of freedom (2DOF) structures has been introduced in Normey-Rico and Camacho [15] and Zhang [9]. A SP with a modified model is presented in Wantanabe and Ito [2] to improve the disturbance rejection capabilities. This structure can also be used to control unstable plants. A modified structure including a disturbance observer in the DTC, are presented in Zhong and Normey-Rico [8]. The control strategy to control the unstable plants with dead time was presented in Tan [4] and Liu [19]. The unified approach for controlling the processes with dead time was presented in Normey-Rico and Camacho [6] in 2009. They proposed a method which took all the discrepancies of Smith predictor in one design.

2.1 Smith Predictor

The most well known approach to compensate the dead time was the Smith Predictor [1]. It can eliminate the dead time containing term from the characteristic equation of a control loop. This predictor is shown in Figure 2.1. For simplification, it is assumed that $G_d(s) = G(s)$. The simplified Smith predictor is shown in Figure 2.2.

The structure of the SP shown in Figure 2.2 can be divided into two parts: the primary controller $C(s)$ and the predictor structure. The predictor is composed of a model of the plant without dead time ($G_1(s)$), also known in literature as the fast model, and a model of the dead time e^{-Ls}. Thus, the complete process model is $G(s)e^{-Ls} = G_1(s)e^{-Ls}$. The fast model $G_1(s)$ is used to compute an open-loop

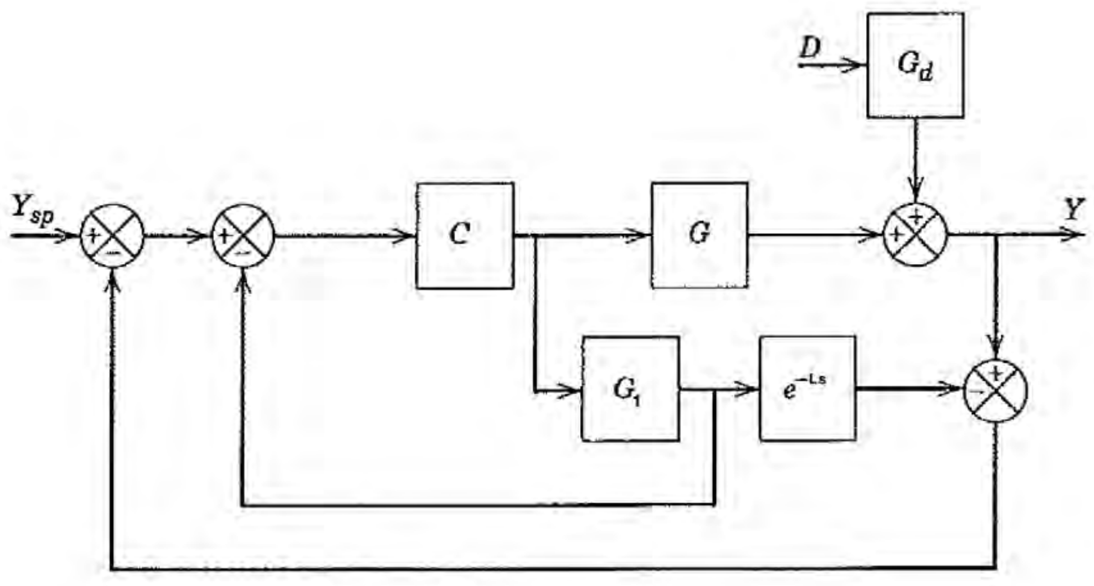


FIGURE 2.1: Classical Smith Predictor [1]

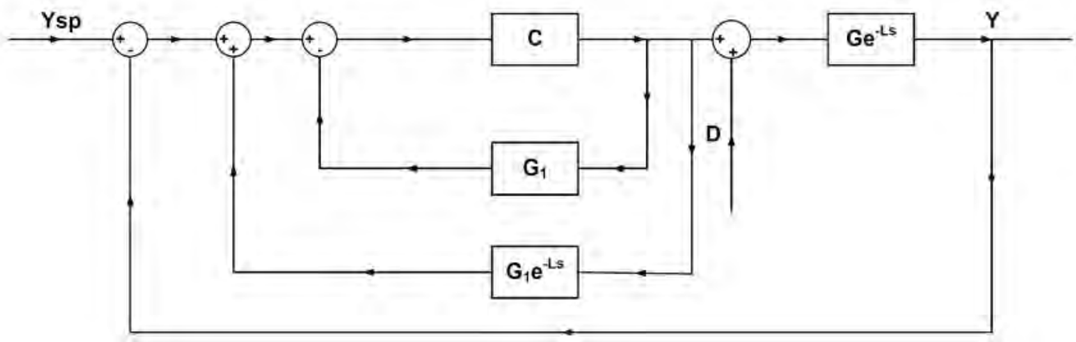


FIGURE 2.2: Classical Smith Predictor (Simplified)

prediction. 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 $Y(s)$ will be the dead-time-free output of the plant. Under these conditions, $C(s)$ can be tuned, at least in the nominal case, as if the plant had no dead time. Some fundamental characteristics of the SP must be analyzed when considering perfect modeling.

2.1.1 Nominal Properties of SP

The SP structure for the nominal case has the following fundamental properties [13]-

Dead time compensation and prediction: The dead time is eliminated from the closed-loop characteristic equation. From Figure 2.2, it is easy to see that if disturbance is zero and $G(s)e^{-Ls} = G_1(s)e^{-Ls}$, the error signal is zero. Under this condition, the characteristic equation is -

$$1 + C(s)G_1(s) = 0 \tag{2.2}$$

Performance limitation: The structure of the SP implicitly factorizes the plant into two parts: $G_1(s)$ that, in some cases, can be invertible and e^{-Ls} that is non-invertible due to the dead time. Using this idea and considering that an ideal controller could be applied which follows -

$$C^{'}(s) = \frac{C(s)}{1 + C(s)G_1(s)} = (G_1(s))^{-1} \tag{2.3}$$

Although this ideal controller cannot be used in practice, it shows what could be achieved with the SP and gives an upper limit of performance for the closed-loop.

2.1.2 Reference tracking and disturbance rejection

When the model of the plant is perfect, the following responses can be derived -

$$H_{Ysp}(s) = \frac{Y(s)}{Y_{sp}(s)} = \frac{C(s)G_1(s)e^{-Ls}}{1 + C(s)G_1(s)} \tag{2.4}$$

$$H_D(s) = \frac{Y(s)}{D(s)} = G_1(s)e^{-Ls}\left[1 - \frac{C(s)G_1(s)e^{-Ls}}{1 + C(s)G_1(s)}\right] \tag{2.5}$$

It is notable that -

- If $C(s)$ is tuned to define the disturbance rejection dynamics then it is not possible to attain a desired set point response. This is a common problem of all one degree of freedom structures, not just a drawback of the SP. $C(s)$ is the only degree of freedom, it is not possible to arbitrarily define $Y(s)/D(s)$ and $Y(s)/Y_{sp}(s)$.

- The poles of $G(s)e^{-Ls}$ cannot be eliminated from the disturbance rejection transfer function, except for a pole at $s = 0$. Even in the ideal case ($C(s) \rightarrow inf$), $G_1(s)e^{-Ls}$ appears in the expression of $y(t)$, but when $G_1(s)e^{-Ls}$ has a pole at $s = 0$, $G_1(s)e^{-Ls}[1 - e^{-Ls}]$ has not. $[1 - e^{-Ls}]$ is zero for $s = 0$, thus the root of the numerator cancels the roots of the denominator. In the non-ideal case, $G_1(s)e^{-Ls}$ is a factor in the disturbance rejection response and its denominator will appear in the denominator of $Y(s)/D(s)$ even when $C(s)$ cancels the plant poles. This has a fundamental consequence: if the poles of $G(s)e^{-Ls}$ are slower than the defined closed loop poles of $H_{Ysp}(s)$, they will dominate the disturbance rejection response, and thus, the slow transients cannot be canceled. In practice, this is only a problem when the dead time is small, because in other cases the closed loop poles are, in general, very close to the open loop ones.

2.1.3 Robustness

In the real case there are modeling errors. Consider a family of plants $G(s)e^{-Ls}$ such that [13]-

$$G(s)e^{-Ls} = G_1(s)e^{-Ls}[1 + \delta(G(s)e^{-Ls})] = G_1(s)e^{-Ls} + \Delta(G(s)e^{-Ls}) \qquad (2.6)$$

and

$$|\delta(G(j\omega)e^{-Lj\omega})| \leq \bar{d}(G(\omega)e^{-L\omega}) \qquad (2.7)$$

for all plants in the family. If $C(s)$ stabilizes $G_1(s)$, the condition for the robust stability of the SP closed loop is that, for all frequencies -

$$\bar{d}(G(\omega)e^{-L\omega}) < d(G(\omega)e^{-L\omega}) = \frac{|1 + C(j\omega)G_1(jw)|}{|C(j\omega)G_1(j\omega)|} \tag{2.8}$$

Function $d(G(\omega)e^{-L\omega})$ is the upper bound of the multiplicative modeling error of the plant to guarantee stability and it can be used as a measure of the controller robustness. $dP(\omega)$ is a rational function because the predictor has eliminated dead time. This, in general, allows a better trade-off between robustness and performance to be achieved than in the PID case where $dP(\omega)$ is dead time dependent. If C(s) is not appropriately chosen, small uncertainties could drive the system to instability.

2.1.4 Shortcomings of SP

The shortcomings of SP are different for different classes of plants -

SP for general unstable plants: The poles of the process cannot be eliminated from the disturbance rejection transfer function except for a pole at $s = 0$. This has a very important consequence: the SP cannot be used with general unstable plants that posses right hand side pole(s). Reference tracking is possible for even in the unstable case, as $C(s)$ can be chosen to stabilize $G_1(s)$. However, the transfer function $Y(s)/D(s)$ always has unstable poles.

SP for integrative processes: Integrative processes are a special case of unstable plants. In this case, the SP gives a stable closed loop if the controller is properly implemented. Let $C(s)$ stabilizes $G_1(s)$ and gives closed loop with unitary gain, thus -

$$\frac{C(s)G_1(s)}{1 + C(s)G_1(s)} = \frac{N_e(s)}{D_e(s)} \qquad (Let) \tag{2.9}$$

where $D_e(s)$ has all negative roots. The disturbance to the output transfer function is then -

$$H_D(s) = G_1(s)e^{-Ls}\left[1 - \frac{N_e(s)e^{-Ls}}{D_e(s)}\right] \tag{2.10}$$

which has a root at $s = 0$ both in the numerator and denominator. The pole at $s = 0$ does not appear in $H_D(s)$ when properly implemented, avoiding closed loop instability. To reject a step disturbance, the gain of $Y(s)/D(s)$ must be zero. This gain cannot be computed directly because the cancelation causes an indetermination. This analysis can be made using the Figure 2.3. The internal model principle states that in order to reject a step disturbance,

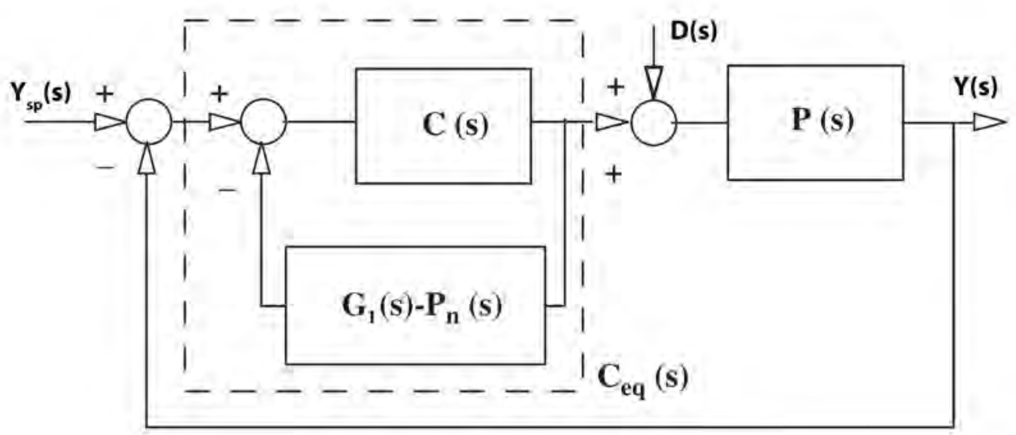


FIGURE 2.3: Equivalent structure of the Smith predictor

the equivalent cascade controller, $C_{eq}(s)$ in Figure 2.3, must have integral action (a pole at $s = 0$) and the closed loop system must be stable. In this case $C_{eq}(s)$ is -

$$C_{eq}(s) = \frac{C(s)}{1 + C(s)(G_1(s) - P_n(s))} \tag{2.11}$$

that is, the primary controller has a feedback block $H(s) = G_1(s) - P_n(s)$. Computing the static gain of $H(s)$ for the SP. It follows -

$$\lim_{s\to 0} H(s) = L_n(s)G_e(0) \neq 0 \tag{2.12}$$

that is, even if $C(s)$ has integral action, the equivalent controller $C_{eq}(s)$ will not have a pole at $s = 0$ as desired and in consequence, will not reject the step disturbances. Because of these problems, over the last twenty years several authors have proposed special tuning procedures or modified versions of the SP.

2.1.5 Dead Time Compensator (DTC)

Dead time compensator is the structure which has the provision to compensate the dead time in a process. Dead time compensator is an advanced technique to compensate the dead time because it does not modify the process physically. It compensates the dead time by modifying the closed loop configuration for controlling a process. Smith predictor was the first dead time compensator proposed by Smith.

2.1.6 When to use a DTC

DTC structures are more complex and require more knowledge for tuning than traditional PIDs. There is a tendency to think that DTC should be used when the dead time of the process is dominant, (i.e. when the normalized dead time, $\frac{L}{L+T} > 0.5$). In Ingimunderson and Hägglund [21], the integrated absolute error (IAE) is compared for PI, PID and simple DTC for stable and integrative processes when an input imposed. The conclusions of the analysis are that DTC offers better performance than PI for the ratio of time constant and dead time (T/L) in the interval [0.1, 5] while the performance of a PID is better than a DTC for T/L on [1, 10]. However, these results were obtained for a fixed value of delay margin and the performance of the DTC improves when smaller values of delay margin are considered. The analysis concludes that the advantages of the DTC are more significant for integrative processes.

A different analysis is presented in Normey-Rico and Camacho [14] where it is shown that the improvement obtained with a DTC has more to do with the error in the estimation of the dead time than with the absolute value of the dead time. The PID is considered as an SP with a dead time model computed using a Pade approximation. The conclusion is that the PID can be tuned to offer almost the same trade off between performance and robustness as the SP when the maximum relative dead time estimation error is greater than 80%. Finally, for small modeling errors, the advantages of the DTC are more appreciable when the dead time is dominant. The SP performs better than the PID controller when the dead time is dominant and well known. In general, the improvement in the set point tracking is more noticeable than in the disturbance rejection. In the last 60 years,immense work had been done on dead time compensation. During this period, Smith predictor has undergone numerous modification. Different modifications are valid for different process models.

2.2 Predictive Proportional Integral(PPI) Controller

H*ä*gglund [24] tried to simplify the Dead Time Compensator (DTC) tuning procedure by introducing Predictive Proportional Integral(PPI) Controller. This DTC contains only three parameters like a PID controller. The structure of the PPI controller is the same as the Smith Predictor, but with the exception that two of the process model parameters are determined automatically, based on the PI controller parameters. In the PPI controller, parameters K, T_i, and L are provided by the user. Parameters K_p and T are calculated as functions of K, T_i, and L -

$$K_p = f_1(K, T_i, L) \qquad and \qquad T = f_2(K, T_i, L) \tag{2.13}$$

Ideally, the PI controller in a dead-time compensating controller can be tuned as if no dead time were present. Therefore, it is reasonable to let the functions f_1 and f_2 be independent of L. Furthermore, the controller gain K is independent of the process time constant T, and the integral time T_i is independent of the process gain K_p. Eq 2.13 then reduces to -

$$K_p = f_1(K) \qquad and \qquad T = f_2(K) \tag{2.14}$$

To ensure that the close loop gain is reasonable for all values of the process gain, the controller gain is chosen inversely proportional to the process gain. Furthermore, the integral time is chosen to be proportional to the process time constant,i.e.

$$K_p = \frac{\kappa}{K} \qquad and \qquad T = \tau T_i \tag{2.15}$$

where κ and τ are constants. For a critically damped system, the optimum value of κ and τ is found to be 1 by Hägglund [24]. This was crosschecked by the integral of absolute error criterion which also provides the same result. Also it was found that PPI controller was better than the PI controller when dead time is greater than the time constant of the process. But it has the same problem as Smith Predictor because it cannot handle significant error in process model estimation.

2.3 Optimal Dead Time Compensator

To make it usable for the processes with an integrator, Wantanabe and Ito [2] proposed a small modification. With this modification, Smith Predictor is able to control the process with an integrator. Figure 2.4 shows the modified structure of Smith Predictor.

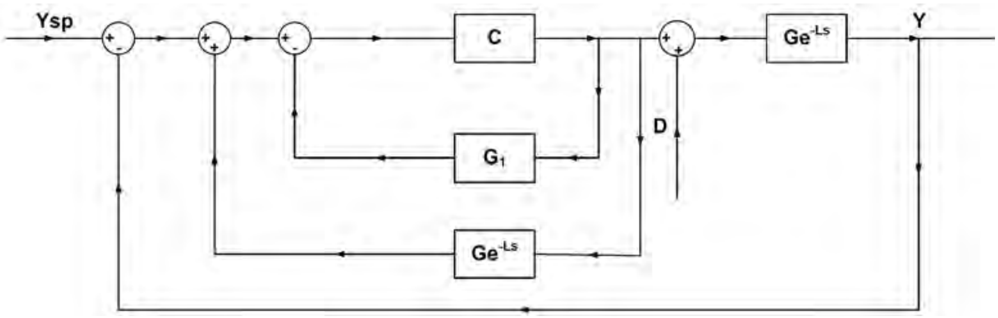


FIGURE 2.4: Modified Smith Predictor by Wantanabe and Ito [2]

Here, G_1 is the fast model of the plant. If the plant contains an integrator and the dead time is L, then the fast plant model will be $\frac{k(1-Ls)}{s}$. Definitely, $(1 - Ls)$ is the approximation of the dead time for removing the steady state offset from the output response. G is the plant model of the plant, which may be accurate or approximate. But if the estimation error in time delay or process parameters is large, the robustness of the closed loop is decreased. The modified Smith predictor suggested by Wantanabe and Ito [2] had undergone several improvements. With these improvements, the dead time compensator became a very powerful tool to control the processes with integrator or long dead time. Normey-Rico and Camacho [3] proposed to include a filter along with the modification of Wantanabe and Ito [2]. The work highlighted on the better performance and increasing the robustness of the control loop. They mainly focussed on the integrating unstable plants with long time delay. The block diagram structure of the loop suggested by Normey-Rico and Camacho [3] is shown in Figure 2.5.

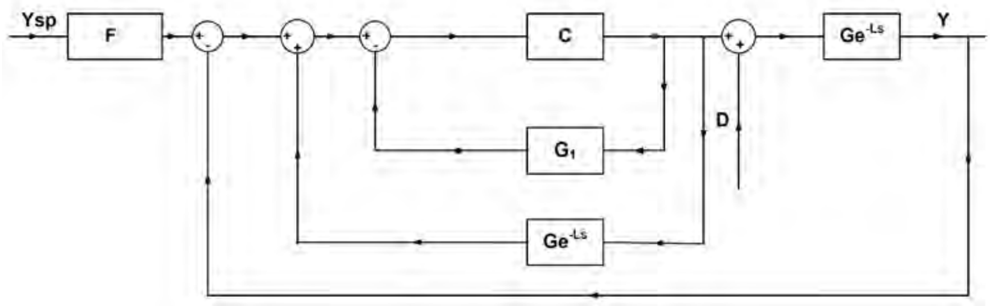


FIGURE 2.5: Modified Smith Predictor with a filter by Normey-Rico and Camacho [3]

From Figure 2.5, the set-point response is -

$$\frac{Y}{Y_{sp}} = \frac{F(s)C(s)G(s)}{1 + C(s)G_1(s)} \tag{2.16}$$

Also the disturbance response is -

$$\frac{Y}{D} = \frac{G(s)e^{-Ls}}{1 + C(s)G_1(s)} + \frac{C(s)G(s)e^{-Ls}}{1 + C(s)G_1(s)}(G(s) - G(s)e^{-Ls}) \tag{2.17}$$

It is noteworthy that the filter dose not affect the disturbance response. So the filter can be tuned to give the best set point response. The PI controller was tuned to get the best disturbance response from the closed loop. The structure of the filter was found to be like this -

$$F = \frac{1 + \alpha T_i s}{1 + T_i s} \tag{2.18}$$

The optimum value of α was found to be 0.4 after extensive simulation. To obtain the values of the parameters of the controller, the closed loop poles was computed as a function of T_i and K_c. As the process model and the controller were assumed to be first order systems, the closed loop transfer function was a second order function. The most common design goal in process control is to obtain a critically damped closed loop system, which is as fast as possible. To meet this specification with a double pole in $s = \frac{-1}{T_0}$ the following relations were to be verified -

$$T_i = 2T_0 + 1, \qquad k_c = \frac{2T_0 + L}{K_P(T_0 + L)^2} \tag{2.19}$$

T_0 is directly related to the time constant of the closed loop system. When controlling processes with long dead times, a general rule used in the process industry is that the closed loop time constant is chosen near the open loop time constant. This idea also used in [16] to tune the controller. Although this choice gives very good results, but in some cases it could produce undesirable oscillatory behavior when dead time uncertainties are large. For long dead times, the compensator proposed by [3] is better than the compensator in [16].

Normey-Rico and Camacho [15] proposed a 2DOF structure for the dead time compensator which is stable for both stable and integrative plants. The previously given filter by Normey-Rico and Camacho [3] in 1999 was modified from one parameter to two parameter model. The block diagram of the dead time compensator is same as Figure 2.5. The only difference is that the modified filter has two parameters to tune.

They had given two different tuning rules for the stable case and the integrating case. For stable case, the controller and the filter is -

$$C(s) = k_c \left(1 + \frac{1}{T_i s}\right) \qquad and \qquad F(s) = \frac{1 + sT_0}{1 + sT_1} \tag{2.20}$$

where, $T_i = T$, $k_c = \frac{T_i}{K_p T_0}$ and T_0, T_1 are tuning parameters. With this choice the closed loop relations are given by -

$$\frac{Y}{Y_{sp}} = \frac{e^{-Ls}}{1 + T_1 s} \tag{2.21}$$

$$\frac{Y}{D} = \frac{K_p e^{-Ls}}{1 + Ts}\left(1 - \frac{e^{-Ls}}{1 + T_0 s}\right) \tag{2.22}$$

which shows that the nominal set-point response is decoupled from the disturbance response. Set point response is tuned by T_1 and disturbance response is tuned by T_0. The proposed controller has five parameters in the stable case and four parameters in the integrative case. But if the process model is obtained experimentally, only two parameters (T_0 and T_1) are to be tuned.

This model was analyzed from a different view point by Zhang and coworkers [9]. They proposed an optimization based method which allows not only optimal but also analytical design of the controller and the filter.

The filters suggested by [9] for the first order and integrating plant are the same as the filters proposed by Normey-Rico and Camacho [15] in 2002. But Zhang and coworkers [9] applied their method for processes with double integrator. Also, for the higher order process, they used the full model of the plant rather than using an approximated model as Normey-Rico and Camacho [15]. So a better and improved response is observed.

2.4 Adaptive Control Strategy

Mihai Huzmezan and coworkers [23] developed an adaptive control strategy for controlling the batch processes mainly. The algorithm learns from the process and takes action. ARMA modeling proved to be sensitive to plant model input and output scaling. The new idea used was the replacement of ARMA (Auto-Regressive Moving Average) model with the Laguerre model. This model increased the estimation accuracy to design the controller. As this model needs some data to start, the data is generated from a First Order Plus Dead Time (FOPDT) model stored previously. Then the algorithm converges with the online data. The model was optimized by quadratic programming. This model was tested on batch processes on pulp bleaching and Claus Sulfur recovery method. For continuous processes, it was not verified.

2.5 DTC Design for Unstable Processes

In 2003 Wen Tan and Chen [4] suggested a IMC based method which is very important from a different viewpoint as it is applicable to unstable processes. Modified IMC structure which can be used for unstable processes is shown by the block diagram -

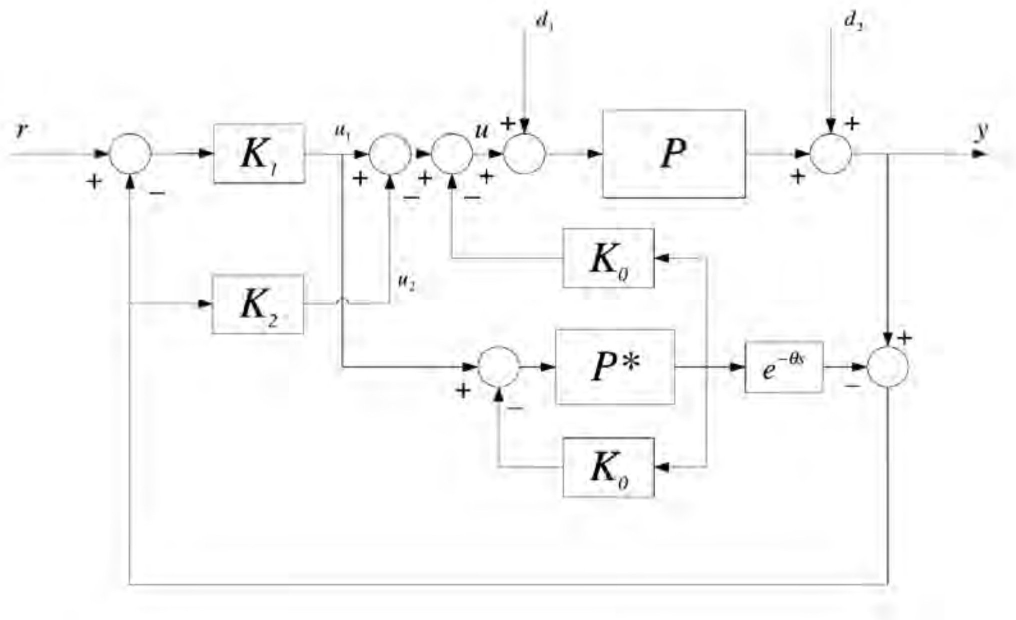


Figure 2.6: Modified IMC structure by Tan and Chen [4]

Here, $P(s)$ and $P^*(s)$ are the actual process and the process model respectively. K_0, K_1 and K_2 are the new notations used here. K_0 is used here for the stabilization of the delay part of the process where K_1 is used to stabilize the model with time delay by IMC method. For load disturbance rejection, K_2 is used to stabilize the original unstable system. The controller has two degree of freedom and usable up to 10 % of delay estimation error.

Another 2DOF control scheme for controlling the unstable processes with dead time was proposed by Liu and Zhang [19] in 2005. The proposed structure is shown in Figure 2.7 -

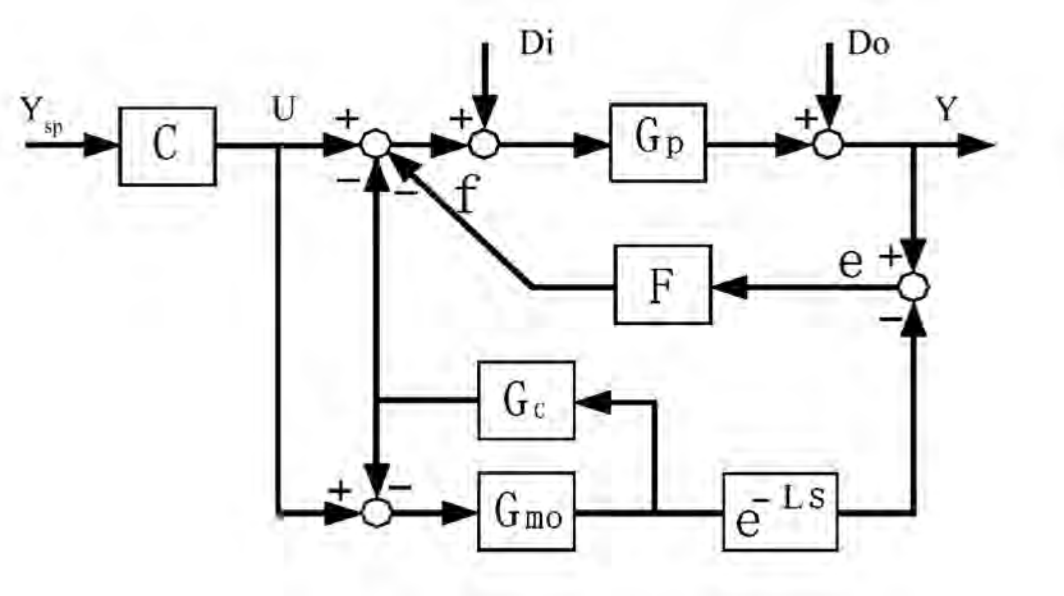


FIGURE 2.7: Two degree of freedom structure for dead time compensation

where, G_{m0} is the delay free part of the model, C is set point tracking controller, F is disturbance estimator, G_c auxiliary controller to stabilize the set point response.Both C and F was designed based on H_2 optimal performance objective which is equivalent to ISE performance criterion. The model holds good up to 10% error in dead time estimation.

The main drawback of the design is so many parameters to tune three parameters of the PID controller and extra two parameters.

2.6 Disturbance Observer Approach

Another method which is called 'Disturbance Observer Approach' was suggested by Zhong and Normey-Rico in 2002 [8].The block diagram of the proposed approach is shown as -

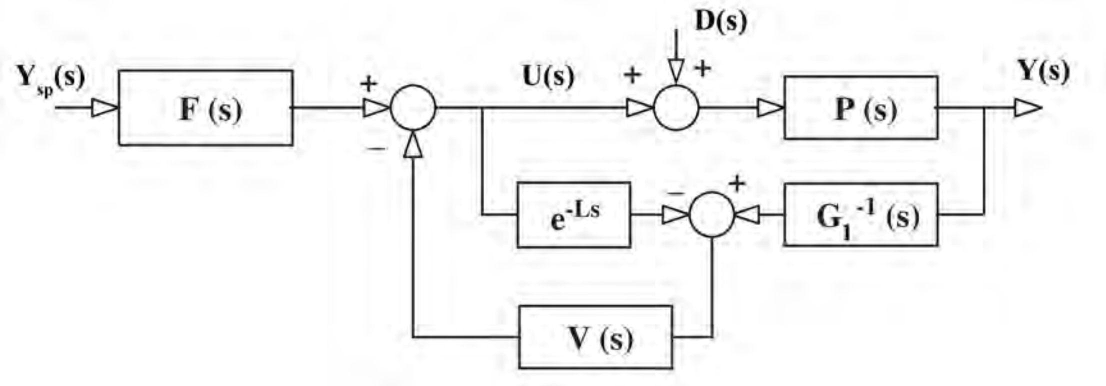


FIGURE 2.8: Disturbance observer approach

The disturbance can be computed ideally as -

$$D(s) = P^{-1}(s)Y(s) - U(s) \tag{2.23}$$

and then used in a feed forward controller. This ideal solution is not realizable as P^{-1} contains a term e^{-Ls}, thus a delayed disturbance is computed -

$$e^{-Ls}D(s) = G^{-s}(s)Y(s) - e^{-Ls}U(s) \tag{2.24}$$

The estimated delayed disturbance $\hat{D}(s)$ can be computed using the model $G_1(s)$ and a filter $V(s)$ that gives a proper and stable $V(s)G_1^{-1}(s)$ -

$$\hat{D}(s) = V(s)[G_1^{-1}(s)Y(s) - e^{-Ls}U(s)] \tag{2.25}$$

and allows a feed forward action to be implemented to design the disturbance rejection characteristics of the closed loop system. The complete controller must also include another degree of freedom to define the set point response, giving the 2DOF DTC based on a disturbance observer as shown in Figure 2.8.

The nominal transfer functions between the reference, the disturbance and the output of this system are given by -

$$\frac{Y(s)}{Y_{sp}(s)} = F(s)G_1(s)e^{-Ls} \tag{2.26}$$

$$\frac{Y(s)}{D(s)} = G_1(s)e^{-Ls}(1 - V(s)e^{-Ls}) \tag{2.27}$$

The controller has decoupled the set point tracking and the disturbance rejection responses and that only $V(s)$ defines the robust stability. Thus, $V(s)$ is tuned for a compromise between robustness and disturbance rejection response and $F(s)$ for a desired set point tracking behavior. To reject the disturbances in the steady state $V(0) = 1$.

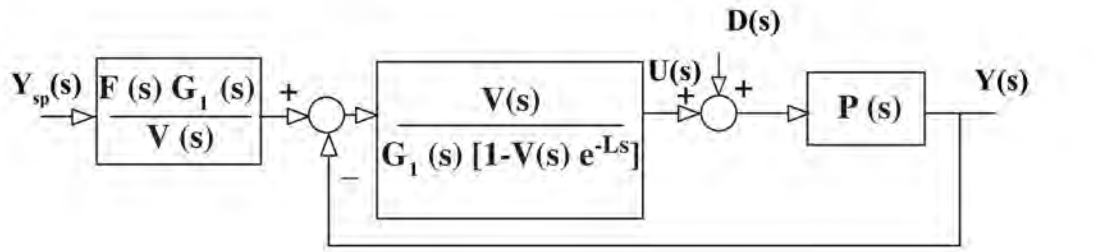


FIGURE 2.9: Equivalent structure of disturbance observer approach for implementation

The structure in Figure 2.8 is not appropriate for implementation. So a modified scheme must be used as is shown in Figure 2.9. This is a very versatile method for dead time compensation. But it needs some prior knowledge about the disturbance.

2.7 Unified Approach for Dead Time Compensator

This approach suggested by Normey-Rico and Camacho [6] in 2009, is based on a modified structure of the Smith predictor that allows to decouple the disturbance and set point responses in order to tune the controller for a compromise between performance and robustness and is able to cope with the unstable process. The proposed controller is shown in Figure 2.10.

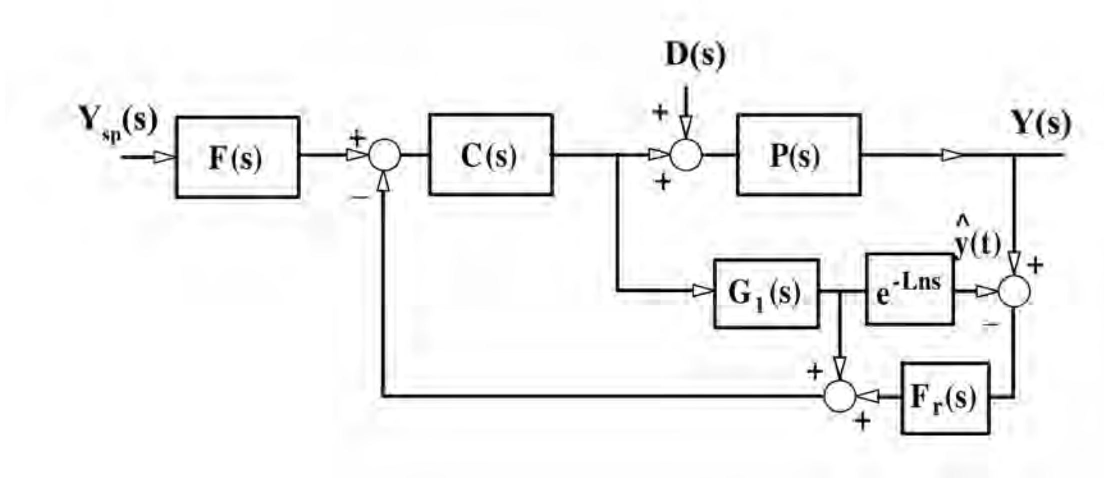


FIGURE 2.10: Unified approach for dead time compensator (Filtered Smith Predictor)

As can be seen the structure is the same as in the SP with two additional filters. $F(s)$ is a traditional reference filter to improve the set-point response and $F_r(s)$ is a predictor filter used to improve the predictor properties. Because of its characteristics, the filtered Smith predictor (FSP) can be used to compute a controller taking into account the robustness, coping with unstable plants, improving the disturbance rejection properties, and decoupling the set-point and disturbance responses. Therefore, all the drawbacks of the SP are considered in the design, using only one structure and a unified design procedure.

In the structure $P_1(s) = G_1(s)e^{-Ls}$ is a model of the process, $G_1(s)$ is the dead-time-free model and $C(s)$ is the primary controller. In this structure that is used for analysis the nominal closed-loop transfer functions (when the model of the plant is perfect, $P(s) = P_1(s)$) are -

$$H_{Ysp}(s) = \frac{Y(s)}{Y_{sp}(s)} = \frac{F(s)C(s)P_1(s)}{1 + C(s)G_1(s)}, \tag{2.28}$$

$$H_D(s) = \frac{Y(s)}{D(s)} = P_1(s)\left[1 - \frac{C(s)P_1(s)F_r(s)}{1 + C(s)G_1(s)}\right] \tag{2.29}$$

In the stable case the tuning of the FSP by this method is simple and intuitive as the correct tuning of $C(s)$ gives an internally stable closed-loop system. $F_r(s)$ is used only to improve the robustness or disturbance rejection performance of the system. These two specifications cannot be achieved simultaneously in the same range of frequencies; that is, there is a trade-off between robustness and performance. The tuning procedure for the FOPDT model can be summarized as -

- C(s) is to be computed as a PI controller with $T_i = T$, $K_c = T/(T_r K_p)$, where T_r defines the closed loop pole and K_P is the process gain.
- $F_r(s)$ has the following structure -

  $$F_r(s) = \frac{(1+sT_r)(1+\beta_1 s)}{(1+sT_0)^2} \tag{2.30}$$

  where, the parameter β_1 is given by $\beta_1 = T[1-(1-T_0/T)^2 e^{-L/T}]$. T_0 is the parameter to be tuned.
- The uncertainties of the plant are to be estimated, and T_0 is to be tuned in order to obtain the best trade off between robustness and performance.

This compensator shows the best performance in comparison with the recently developed compensators.

2.8 Robust Control Design for Long Dead Time

This control scheme is proposed by Albertos and Garcia [5] in 2009. They proposed the following structure -

where, $F_1(z)$ and $F_2(z)$ are the stable predictor, $F_k(z)$ is the additional stable filter, n is the measurement noise. The controller $K(z)$ can be designed to achieve some desired performances on the closed-loop disturbance response, whereas the

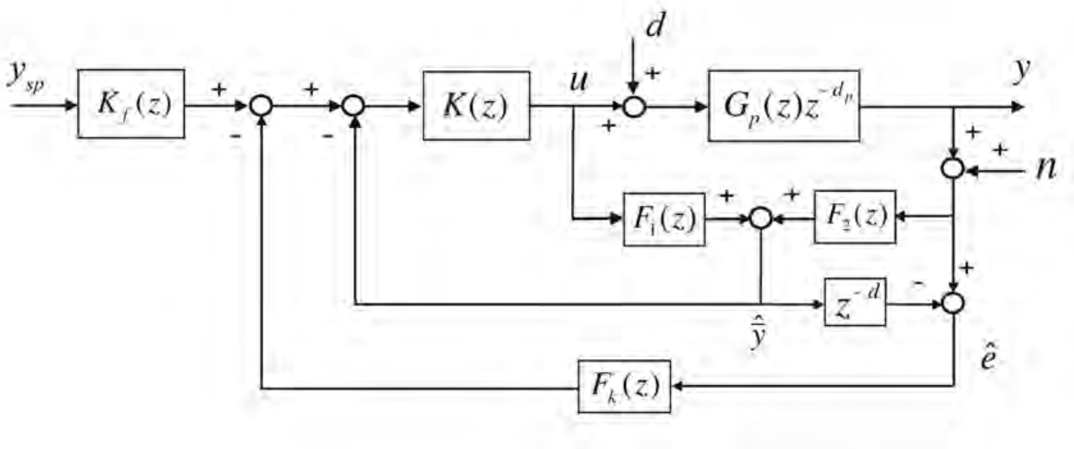


FIGURE 2.11: Robust control design by Albertos and Garcia [5]

filter $K_f(z)$ can be designed to fulfil the tracking performance. If $K(z)$ is properly designed, the system is proved to be internally stable.

The design contribution of the method can be summarized as -

- stable estimation of the undelayed output for any kind of process
- control design for a delay free system
- tuning of the filter in the external loop to cancel the steady-state disturbance error and balance the robustness/performance trade off, based on the uncertainty and measurement noise characteristics.

No proper guideline was given in the proposed method for the third contribution. The performance of the controller is same as the unified approach by Normey-Rico and Camacho [6].

Chapter 3

Dead Time Estimation Technique

3.1 Theory

Dead time estimation is a challenging task. Without giving a perturbation to the systems, dead time cannot be detected. Many methods have been developed till now for detecting dead time. But all dead time estimation methods have some limitations. No general method available which can detect dead time for all kind of processes. The presence of noise in process data is another problem that may lead to erroneous estimations of dead time. This is generally true for all processes.

A simple statistical and numerical signal processing method is used to detect dead time. A perturbation in the process is necessary for understanding the process dynamics and its response characteristics. After the process is excited, when the process begins to respond, the area under its output curve start to increase. Numerical integration is done to evaluate the area under the curve generated by the output response data in the time domain. The time at which the area begins to increase is determined. The difference between this starting time and the time when the input has been changed is the dead time. A sustained increase in area is detected by the newly developed technique and thus the starting point is identified. The technique requires process output data and sampling interval information.

This can be explained by the Figure 3.1 where a step response of a First Order Plus Dead Time (FOPDT) process is shown. Here the shaded area shows the area under the curve. As long as the area is null the process does not begin to respond. Whenever the area begins to increase continuously, then it is to be understood that the process has begun to respond. So the dead can be detected from this concept by estimating the area under the curve.

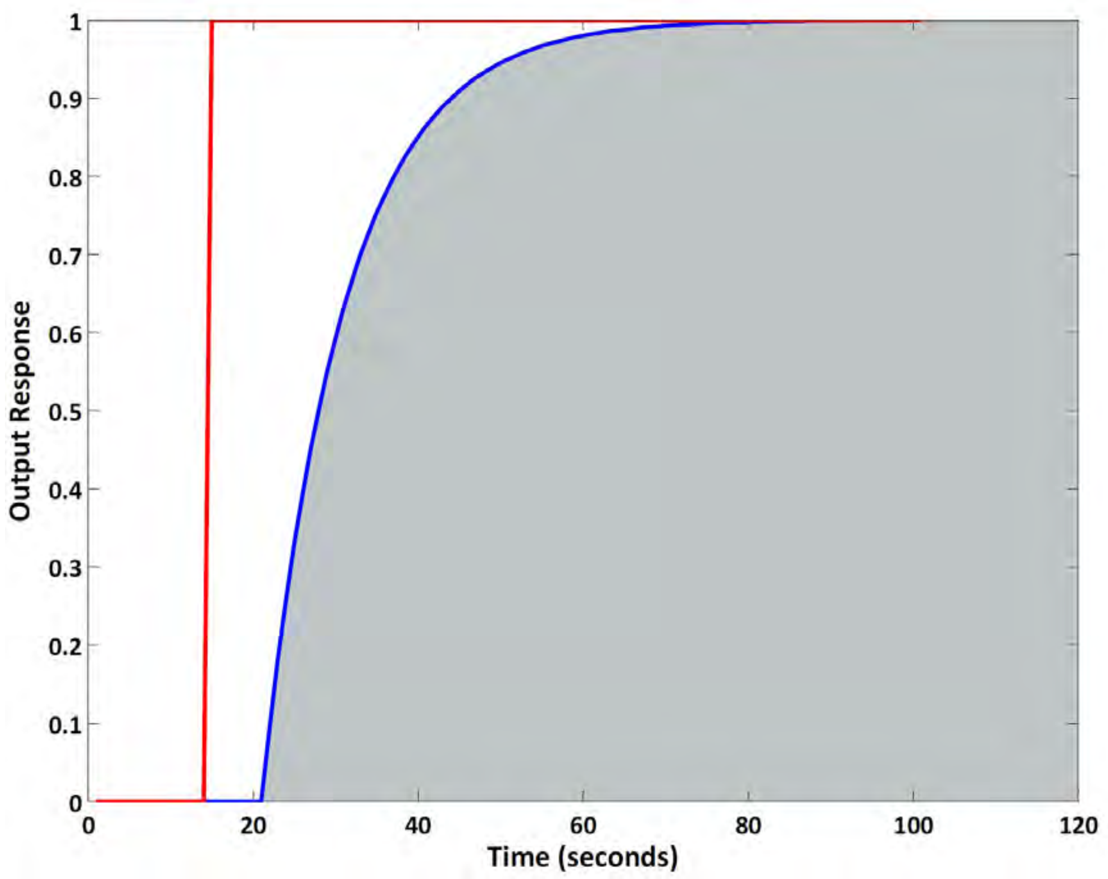


Figure 3.1: Set-point response of a FOPDT process with dead time

When the area under the curve is greater than zero, the point is detected as the starting point. Then the difference between the starting and the step or perturbation point is the dead time. This concept can be simplified by constructing a flow chart which shows the basic procedure to estimate the dead time. This is shown in Figure 3.2.

The area under the curve is determined for each time interval by the trapezoidal integration rule. Then the cumulative area is determined by summing up all the

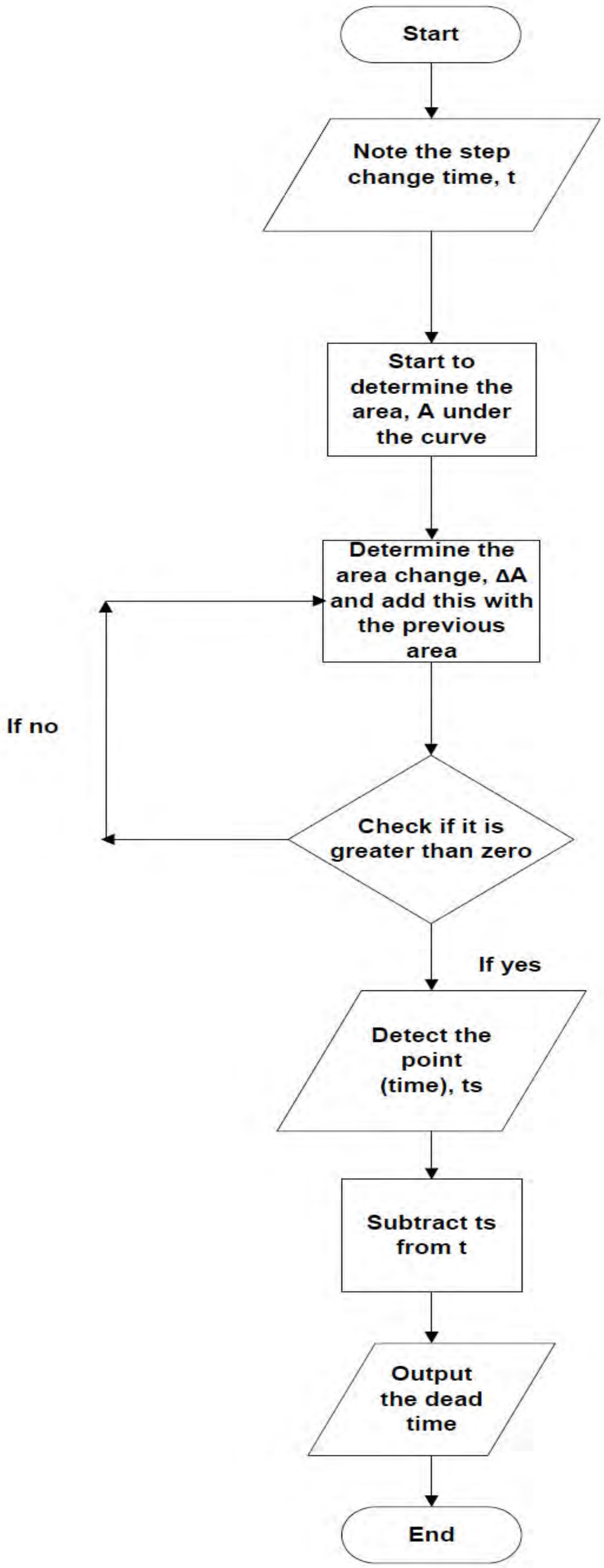


FIGURE 3.2: Algorithm of Dead time estimation

successive area determined by trapezoidal rule. The cumulative area is checked for its nonzero value and the algorithm is stopped accordingly.

If there is significant noise in the process output data, the dead time estimation will be erroneous. The proposed dead time estimation procedure is robust for the presence of small amount of noise as the algorithm checks up to 7 sampling intervals for a sustained increase in area. If the area is continuously increasing for 7 sampling points, then the first of the 7 points is identified as the correct point and dead time estimation calculation is performed as described early. But in case of significant noise, a low pass filter has to be used for filtering the noise. In most cases, this strategy results in an accurate measurement of dead time.

3.2 Simulation

This algorithm is evaluated by simulating a process with known dead time. For a system with zero noise, the dead time estimation is very good and the algorithm detects the actual dead time correctly. A first order plus dead time (FOPDT) model is considered for this. The process has a dead time of 3 seconds and model of the process is given by

$$\frac{1}{5s+1}e^{-3s} \tag{3.1}$$

The block diagram used in Matlab Simulink is shown in Figure 3.3.

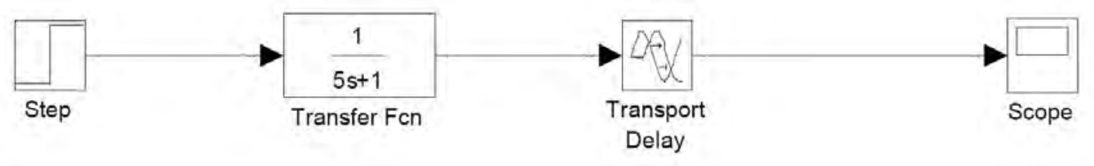


FIGURE 3.3: Matlab Simulink block diagram

The algorithm was applied on the model to evaluate the performance. The result was satisfactory and the algorithm can determine the dead time correctly. But the algorithm has its limitations if the process is too much noisy. The applicability of the algorithm has been tested by introducing gaussian noise into the system. Random number with a variance of 0.001 with 0 mean was introduced into the process. The process output is shown in Figure 3.4

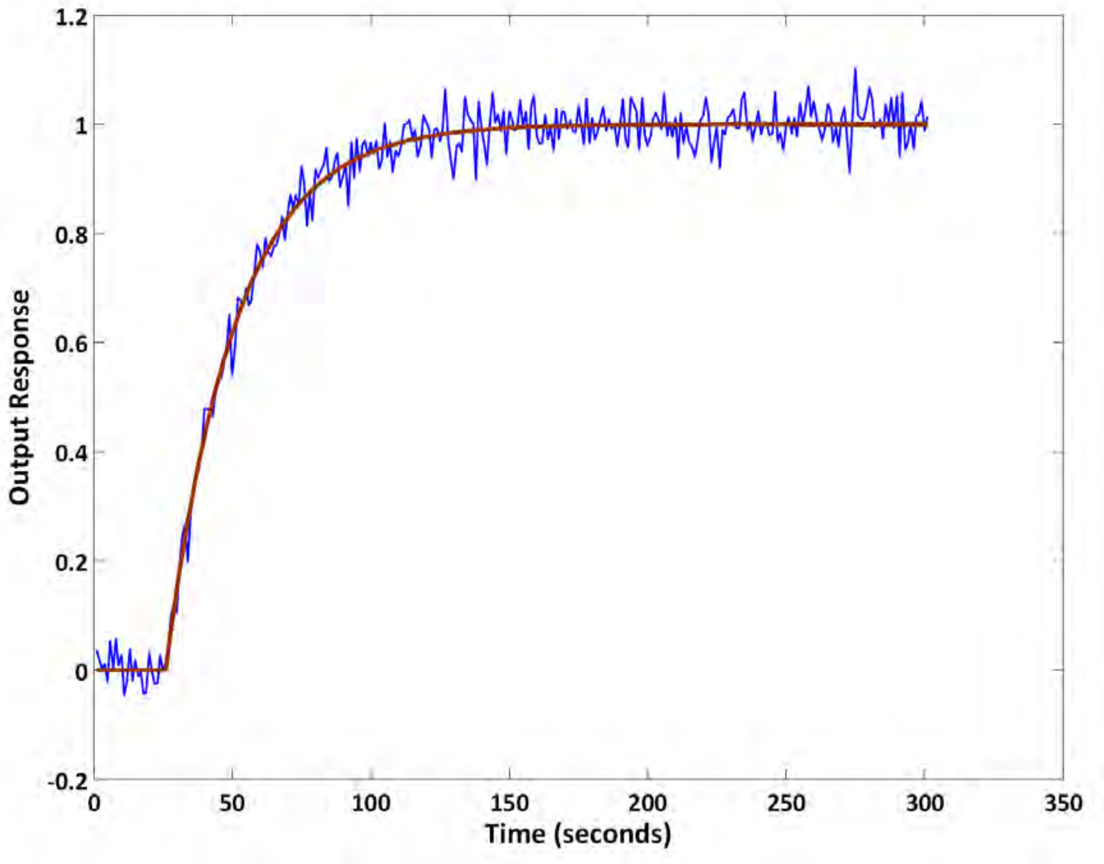


FIGURE 3.4: Response of the process in presence of noise and the model response (thick solid line)

Now it is hard to determine the actual dead time because the point from which the response begun is hard to identify. Still, the algorithm results in an estimated dead time of 2.8 seconds which is close but not exact. But this limitation can be compensated by introducing a low pass filter. In this case, a first order low pass filter is used

$$\text{Low pass filter} = \frac{1}{Ns+1} \tag{3.2}$$

Here, the value of N for the filter is to be chosen. By simulation with several values, the value is chosen as 0.5. After introducing the filter, the response of the process is shown in Figure 3.5. For this response, the algorithm can detect the dead time accurately.

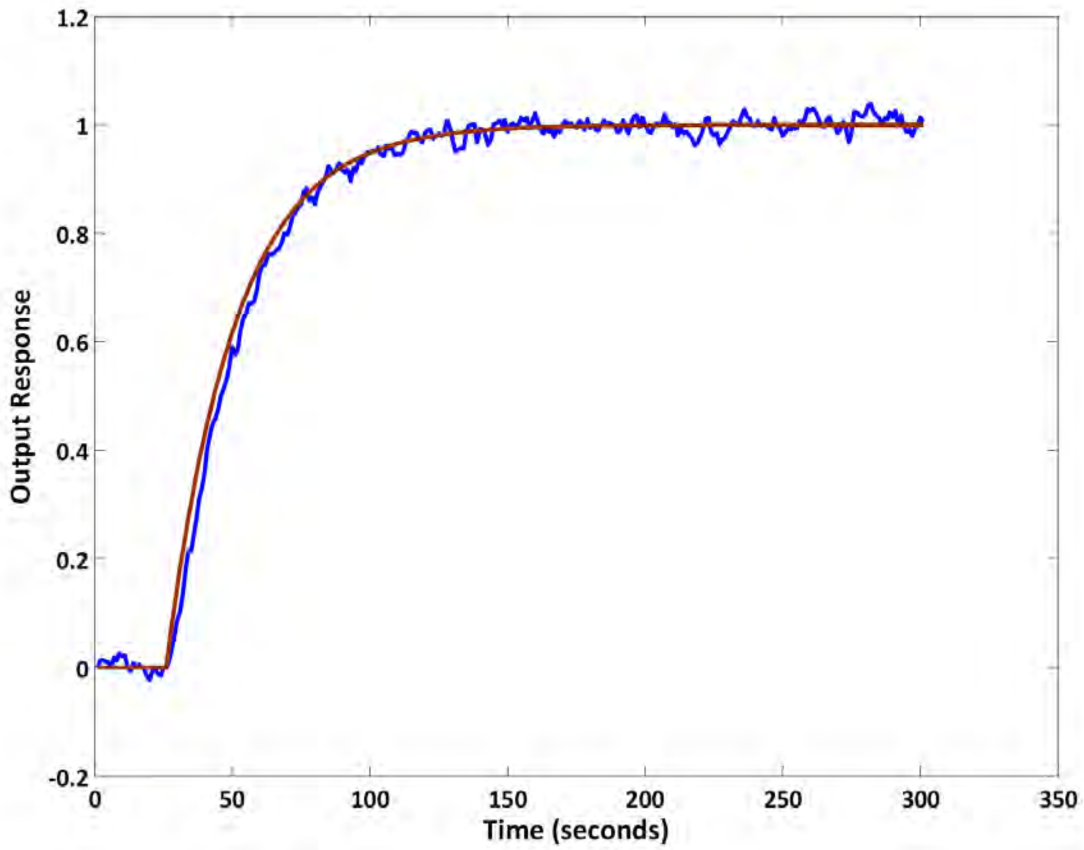


FIGURE 3.5: Filtered response of the process in presence of noise and the model response (thick solid line)

But choosing a filter for a process is not easy. The filter parameter should be chosen in such way that it should not filter out required information. The best way to choose a filter is visual inspection of the processed data by changing the value of N. The lowest value of N which can help getting rid of significant noise should be chosen.

Chapter 4

Dead Time Compensation Technique

As described in Chapter 1, the first dead time compensator is proposed by Smith [1] in 1957 and is known as Smith Predictor. Smith predictor has several limitations. The main limitation is the requirement of identifying the accurate process model along with correct dead time. In reality, it is almost never possible to identify exact process model and dead time as well. Therefore, many researchers [2, 3, 5, 6, 8, 9, 11, 13, 15, 16, 19, 24] have worked to improve the performance of Smith Predictor by modifying its structure and they were discussed in Chapter 2. The following section describes a modification of Smith Predictor proposed in this study.

4.1 Proposed Modified Smith Predictor (MSP)

The proposed modified Smith predictor control structure is shown in Figure 4.1. As can be seen, the structure is same as the Smith Predictor but with two additional filters. F_1(s) is a traditional filter which improves the set point response and F_2(s) is a predictor filter that improves the disturbance rejection response. The proposed modified Smith predictor (MSP) can be tuned to take into account the robustness of the loop, improve disturbance rejection properties, and decouple the set-point

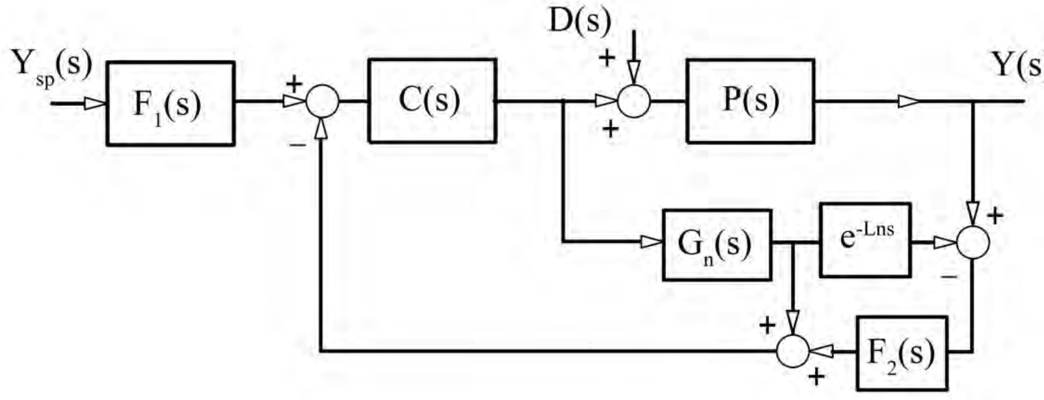


FIGURE 4.1: Block diagram of proposed modified Smith predictor (MSP)

response and disturbance rejection response. Therefore, the main drawback of the SP is considered in this design.

In the proposed structure, $P_n(s) = G_n(s)e^{-L_n s}$ is the process model, $G_n(s)$ is the delay free part of the model, L_n is the estimated time delay and C(s) is the controller. Here, the assumed process model is a FOPDT model. The FOPDT model can be written as

$$P_n(s) = G_n(s)e^{-L_n s} = \frac{K_p}{Ts+1}e^{-L_n s} \tag{4.1}$$

4.1.1 Set-point Tracking Response

When the actual process P(s) is same as the process model $P_n(s)$, the closed loop transfer function of the process for set-point tracking is given by:

$$\frac{Y(s)}{Y_{sp}(s)} = \frac{F_1(s)C(s)P_n(s)}{1 + C(s)G_n(s)} = R(s), (Let) \tag{4.2}$$

(4.3)

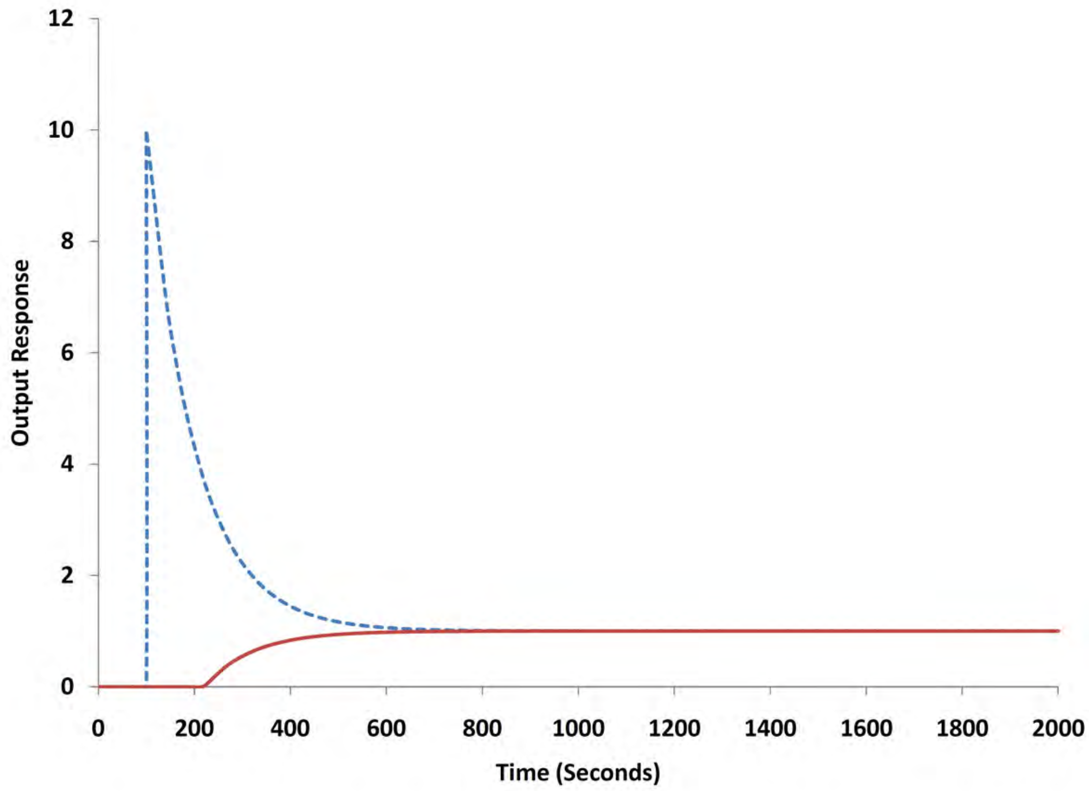


FIGURE 4.2: The effect of the pseudo-set-point (dashed line) on output response (solid line)

The proposed model is based on the theory that the process can be made faster and robust by setting a pseudo set-point which will vary with time and remains stable when the process reaches the desired output. The set point passes through the filter $F_1(s)$ and varies with time so that the process responses very fast to reach the desired value. With the proposed structure, a first order process with 0.2 gain and 1000 seconds of time constant along with a delay of 120 seconds was simulated. The response can be represented as the solid line shown in Figure 4.2. The output response reached the desired value within 600 seconds. To attain this response, the proposed structure of the filter $F_1(s)$ is

$$F_1(s) = \frac{Zs + 1}{T_1 s + 1} \tag{4.4}$$

The parameters Z and T_1 are to be tuned. A simple tuning rule is described in the next section for this filter.

4.1.2 Disturbance Rejection Response

The closed loop transfer function for disturbance rejection is expressed as

$$\frac{Y(s)}{D(s)} = P_n(s)\left[1 - \frac{C(s)P_n(s)F_2(s)}{1 + C(s)G_n(s)}\right] = P_n(s)\lambda(s) \tag{4.5}$$

$$where, \lambda(s) = 1 - \frac{C(s)P_n(s)F_2(s)}{1 + C(s)G_n(s)} \tag{4.6}$$

From the above equation, it can be seen that if the term $\lambda(s)$ is close to zero, the response will be better and improved. The second filter has the following structure

$$F_2(s) = \frac{Zs + 1}{T_2 s + 1} \tag{4.7}$$

Z has the same parameter value as in the previous filter. But the parameter T_2 is to be tuned to have a robust closed loop response as well as the best disturbance rejection response. This filter refines the signal in both feedback loops. It only affects the disturbance rejection response and robustness of the loop but not the set-point response. The parameter T_2 is responsible for the robustness of the loop. Its tuning procedures and properties are discussed in more detail in Section 4.2.

4.2 Filter Parameter Tuning Procedure

The proposed dead time compensator has three parameters to tune, namely, Z, T_1 and T_2. The controller for the proposed structure is a PI controller. So the controller has two more parameters to tune. Tuning rules for the compensator filter parameters and the controller parameters are described in this section.

4.2.1 PI Controller Parameters

The PI controller needs to be tuned to have a stable closed loop response. The controller can be tuned to have the best response by using the predictive structure. The rule suggested by Hägglund [24] is used to calculate the controller parameters. If the controller gain cancels out the process gain and the time constant of the controller is equal to the process time constant, the controller and the process will converge to a first order transfer function of gain 1 and time constant T provided there is no dead time. Therefore, controller parameters are tuned using Internal Model Control (IMC) rules.

4.2.2 Set-point Tracking Filter ($F_1(s)$) Parameters

The filter for the set point tracking is tuned by setting the parameters Z and T_1. The transfer function between the process output and set-point change is given by

$$R(s) = \frac{Y(s)}{Y_{sp}(s)} = \frac{F_1(s)C(s)P_n(s)}{1 + C(s)G_n(s)} = \frac{F_1(s)C(s)G_n(s)e^{-L_n s}}{1 + C(s)G_n(s)} \tag{4.8}$$

The denominator of Eq. 4.8 is called characteristic equation of the process. It is clear that Filter F_1 does not affect the characteristic equation. Therefore, it does not affect the stability of the process. Let, set-point response without the filter be denoted as $G_1(s)$. Therefore,

$$G_1(s) = \frac{C(s)G_n(s)e^{-Ls}}{1 + C(s)G_n(s)} \tag{4.9}$$

If $G_n(s) = \left(\frac{Ke^{-Ls}}{Ts+1}\right)$, the controller designed using IMC rules is $C(s) = K_c\left(1 + \frac{1}{T_I s}\right)$ where, $K_c = \frac{1}{K}$ and $T_I = T$. Therefore, Eq. 4.9 can be rewritten as

$$G_1(s) = \frac{(\frac{Ke^{-Ls}}{Ts+1})K_c(1+\frac{1}{T_I s})}{1+(\frac{K}{Ts+1})K_c(1+\frac{1}{T_I s})} \tag{4.10}$$

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

$$= \left[\frac{e^{-Ls}}{Ts+1}\right] \quad (since,\ K_c = \frac{1}{K}\ and\ T_I = T) \tag{4.11}$$

From Eq. 4.11, it is found that with the proposed controller, the process has the same time constant as for the open loop case but the gain changes to 1 so that the set point can be tracked properly. By combining the Eq. 4.11 and Eq. 4.8, the set-point response can be found as

$$R(s) = F_1(s)\left(\frac{e^{-Ls}}{Ts+1}\right) \tag{4.12}$$

Now, the filter is to be designed in a way so that it cancels the time constant of the process and converts it to a faster process. Therefore, the filter which will serve the purpose can be designed as

$$F_1(s) = \frac{Zs+1}{T_1 s+1} \tag{4.13}$$

The parameter Z is chosen to be equal to the time constant T. So the transfer function becomes

$$R(s) = \frac{e^{-Ls}}{T_1 s+1} \tag{4.14}$$

It will essentially cancel out the long time constant (T) from the system and respond quickly. Now the set point tracking monotonically depends on the value of T_1. The parameter T_1 can be chosen on the basis of the desired set point response. From the experience of the authors, the value of T_1 can be initially chosen as $T/7$, i. e., 7 times faster than the original process time constant.

4.2.3 Disturbance Rejection Filter Tuning

The filter used for disturbance rejection has two parameters Z and T_2. Z is the same as the set point tracking filter. Therefore, the only parameter to be tuned is T_2. The disturbance rejection response of the system can be characterized from the term $\lambda(s)$ of Eq. (4.3). Ideally, $\lambda(s)$ should be derived equal to zero. Therefore

$$\lambda(s) = 1 - \frac{C(s)P_n(s)F_2(s)}{1 + C(s)G_n(s)} \tag{4.15}$$

If C(s) is tuned as proposed, the resultant value of $\lambda(s)$ becomes

$$\lambda(s) = 1 - \left(\frac{e^{-Ls}}{1 + Ts}\right) F_2(s) \tag{4.16}$$

The second term is to be made close to 1 so that the response to disturbance change becomes zero and essentially the disturbance rejection becomes perfect. Therefore, the filter structure for F_2 can be chosen as $F_2(s) = \frac{Zs+1}{T_2s+1}$. Now

$$\left(\frac{e^{-Ls}}{Ts + 1}\right) F_2(s) = \frac{e^{-Ls}}{Ts + 1} \times \frac{Zs + 1}{T_2s + 1} = \frac{e^{-Ls}}{T_2s + 1} \tag{4.17}$$

Asymptotically, Eq. 4.17 is equal to 1. As the time propagates, the disturbance will be nullified. This is interesting to note that with the change of T_2, only the disturbance response will be affected. The parameter T_2 can be chosen on the basis of how fast the disturbance rejection is desired. From the author's experience, a value of $T/14$ is a good choice to start with. Then it can be tuned as required by robustness and stability.

4.3 Robustness and Stability Analysis

4.3.1 Robustness Analysis

The effect of the changes in filter parameters on the robustness and the stability of the process needs to be investigated to choose proper values of these parameters. Stability of the FOPDT process is not affected but the robustness is greatly influenced with the change of filter parameters.The family of plants P(s) having the following relationship are under consideration

$$P(s) = P_n(s)[1 + \delta P(s)]$$
$$P_n(s)\delta P(s) = P(s) - P_n(s) \tag{4.18}$$

The multiplicative norm-bound uncertainty which is used to describe the uncertainty involved in SISO systems with single perturbation [17]. The nature of the uncertainty in process is shown in Figure 4.3. The multiplicative norm-bound

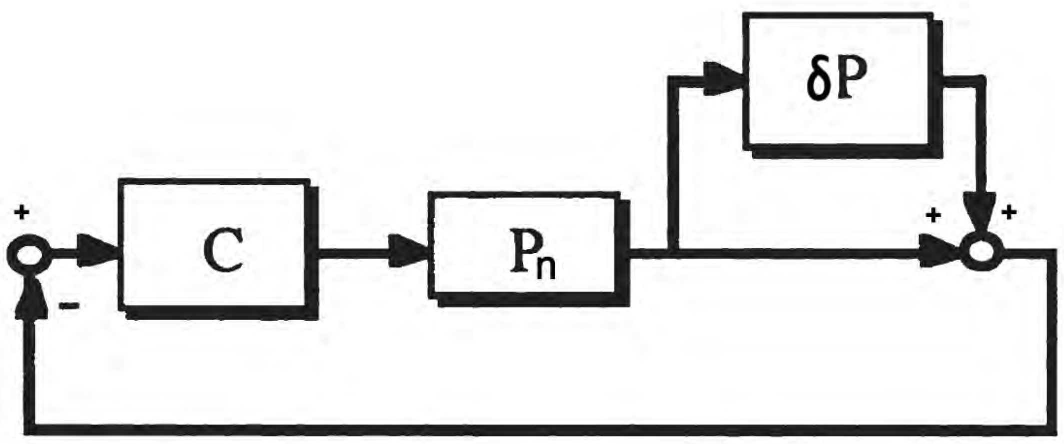


FIGURE 4.3: Multiplicative norm-bound uncertainty

uncertainty, $\overline{\delta P}(\omega)$, can be interpreted as [17]

$$|\delta P(\omega)| \leq \overline{\delta P}(\omega) \qquad \forall \omega > 0 \tag{4.19}$$

From the above consideration the characteristic equation for the system presented in Figure 4.1 becomes

$$1 + C(s)G_n(s) + C(s)G_n(s)F_2(s)(P(s) - P_n(s)) = 0 \tag{4.20}$$

From Eq. 4.18, the characteristic equation can be expressed as

$$1 + C(s)G_n(s) + C(s)G_n(s)P_n(s)F_2(s)\delta P(s) = 0 \tag{4.21}$$

As the nominal system is stable, robust stability condition can be found for the proposed compensator by rearranging Eq. 4.21 and putting $s = j\omega$.

$$\overline{\delta P}(\omega) < dP(\omega) = \left| \frac{1 + C(j\omega)G_n(j\omega)}{C(j\omega)G_n(j\omega)F_2(j\omega)} \right|, \qquad \forall\omega > 0 \tag{4.22}$$

It is notable that the filter only affects the disturbance rejection response and the robustness of the loop. Substituting the transfer function elements into the Eq. 4.22

$$\overline{\delta P}(\omega) < dP(\omega) = \left| \frac{1 + K_c(1 + \frac{1}{T_I jw})(\frac{K}{Tjw+1})}{K_c(1 + \frac{1}{T_I jw})(\frac{K}{Tjw+1})(\frac{Zjw+1}{T_2 jw+1})} \right| \tag{4.23}$$

Based on tuning rules suggested in Section 4.2, $K_c = \frac{1}{K}$, $T_I = T$, Eq. 4.23 simplifies to

$$\overline{\delta P}(\omega) < dP(\omega) = \left| \frac{1 + \frac{1}{T_I jw}}{\frac{1}{T_I jw}(\frac{Zjw+1}{T_2 jw+1})} \right| \tag{4.24}$$

$$= |T_2 j\omega + 1| \tag{4.25}$$

Therefore, the robustness of the loop can be increased by increasing the value of T_2. However, by increasing T_2, the disturbance rejection response will become slower. This is the classical trade off between robustness and performance. For plants that can be approximated by a stable FOPDT model, the value of T_2 can be increased gradually until a satisfactory regulatory and robustness trade-off is achieved. The robustness 'margin' desired would depend on the level of uncertainty in the plant. The greater the uncertainty, larger the value of T_2 and therefore slower the regulatory performance.

4.3.2 Uncertainty Analysis

By introducing some errors in the model parameters, this uncertainty analysis is carried out. The analysis covers the uncertainty in dead time, gain and time constant estimation. As the dead time compensator depends on the model of the process, the uncertainties will affect the performance. But as long as the system is stable, no major problem occurs. By measuring the gain margin, the stability limit of a process can be understood. At the value of gain margin 1 the process becomes marginally stable. On further decreasing the gain margin value, the system becomes unstable. The analysis takes into account both set-point change and disturbance rejection responses.

4.3.2.1 Set-point responses

- Uncertainty in dead time estimation: At first, the process was examined with some errors in dead time estimation for the set-point change. For this, a new equation was derived with an estimation error of ΔL for the delay L. Thus the transfer function between the set-point and output becomes

$$\frac{Y(s)}{Y_{sp}(s)} = \frac{Zs+1}{T_1 s+1} \times \frac{e^{-Ls}}{(Ts+1)+e^{-Ls}(1-e^{-\Delta Ls})} \tag{4.26}$$

To analyze it further, the delay term is approximated by 1/1 Pade approximation. After some simplifications, Eq. 4.26 becomes

$$\frac{Y(s)}{Y_{sp}(s)} = \frac{Zs+1}{T_1 s+1} \times \left(\frac{1-(L/2)s}{(\frac{TL\Delta Ls^3}{4}) + \frac{T(L+\Delta L)s^2}{2} + s(T+\frac{L}{2}+\Delta L)+1} \right) \tag{4.27}$$

Positive and negative value of ΔL will indicate the positive and negative error in estimation of dead time respectively. $\pm 20\%$ error in estimating dead time was considered for a process and then the gain margins were investigated. For this case the following model used by [6] was considered -

$$P(s) = \frac{0.12}{6s+1} e^{-3s} \tag{4.28}$$

Now with an error of 20%, the estimated delay becomes 3.6 seconds. As the filter parameters depend on the process time constant, the filter parameters are not affected. The value of Z was equal to the time constant and the other parameter T_1 was taken as $\frac{6}{8}$. So according to the Eq. 4.27, the transfer function for set-point change becomes

$$\frac{Y(s)}{Y_{sp}(s)} = \frac{6s+1}{0.8s+1} \times \left(\frac{1-1.5s}{2.7s^3 + 10.8s^2 + 8.1s + 1} \right) \tag{4.29}$$

From the Bode plot, gain margin of the transfer function was determined to see whether it crosses the stability limit. The crossover frequency for this process was found to be 1.158 rad/sec and the gain margin was 1.4 which is away from instability. However, the standard value of gain margin is in between 1.7 and 4.0. To achieve the limit, the parameter T_1 is increased to 1.4 while other parameters remaining the same. In this case the transfer function for set-point change is

$$\frac{Y(s)}{Y_{sp}(s)} = \frac{6s+1}{1.4s+1} \times \left(\frac{1-1.5s}{2.7s^3 + 10.8s^2 + 8.1s + 1} \right) \tag{4.30}$$

For this case, the crossover frequency from Bode plot was 0.9862 and gain margin was 1.74. So the value of the gain margin has reached to its practical limit by increasing the parameter T_1. The uncertainty in estimating the dead time is also compensated by a higher value of T_1. The Bode plots for the two cases are shown in Figure 4.4.

Again, for an error of -20% in estimation will result in an estimated dead time of 2.4 seconds. The value of 1.4 is considered for T_1 for this case also. The transfer function of the set-point response with this error is

$$\frac{Y(s)}{Y_{sp}(s)} = \frac{6s+1}{1.4s+1} \times \left(\frac{1-1.5s}{-2.7s^3+7.2s^2+6.9s+1}\right) \tag{4.31}$$

The Bode plot of this set-point change response is shown in Figure 4.5. The crossover frequency and gain margin for this case are 1.711 rad/sec and 2.95 respectively. So the value of gain margin indicates the stability of system with the error.

- Uncertainty in process gain estimation: For set point change, the transfer function with an error in gain estimation becomes

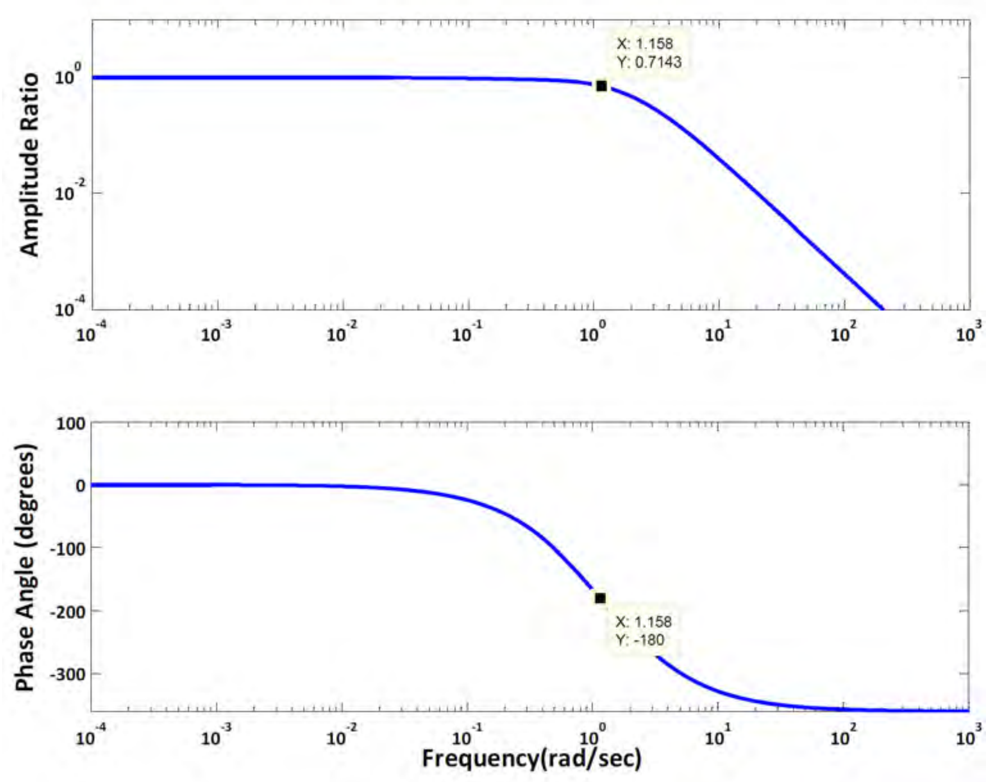
$$\frac{Y(s)}{Y_{sp}(s)} = \frac{(1-Ls/2)}{(1+Ls/2)(\frac{T}{KK_c}s+1)} \times \left(\frac{Zs+1}{T_1s+1}\right) \tag{4.32}$$

As there is an error in estimation of K, the value of K_c will be different from K. So the value of K_c would be equal to $K+\Delta K$ where ΔK is the error in estimation

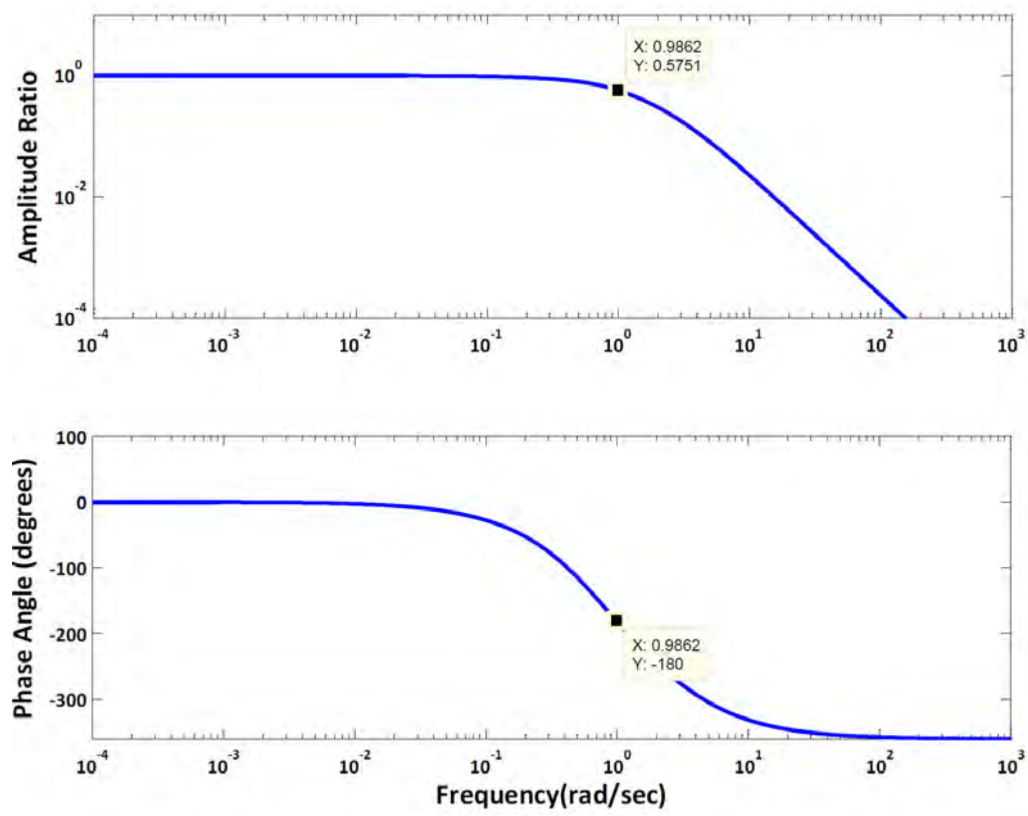
$$\frac{Y(s)}{Y_{sp}(s)} = \frac{(1-Ls/2)}{(1+Ls/2)(\frac{T}{K(K+\Delta K)}s+1)} \times \left(\frac{Zs+1}{T_1s+1}\right) \tag{4.33}$$

Again $\pm 20\%$ error was considered in process gain estimation. To understand the effect quantitatively, for 20% estimation error, the transfer function of the set-point change for the process under consideration is found to be

$$\frac{Y(s)}{Y_{sp}(s)} = \frac{(1-1.5s)}{(1+1.5s)(\frac{6}{0.12(0.12+0.024)}s+1)} \times \left(\frac{6s+1}{0.8s+1}\right) \tag{4.34}$$



(a) For filter parameter $T_1 = 0.8$



(b) For filter parameter $T_1 = 1.4$

FIGURE 4.4: Bode plots for positive error in dead time estimation (servo)

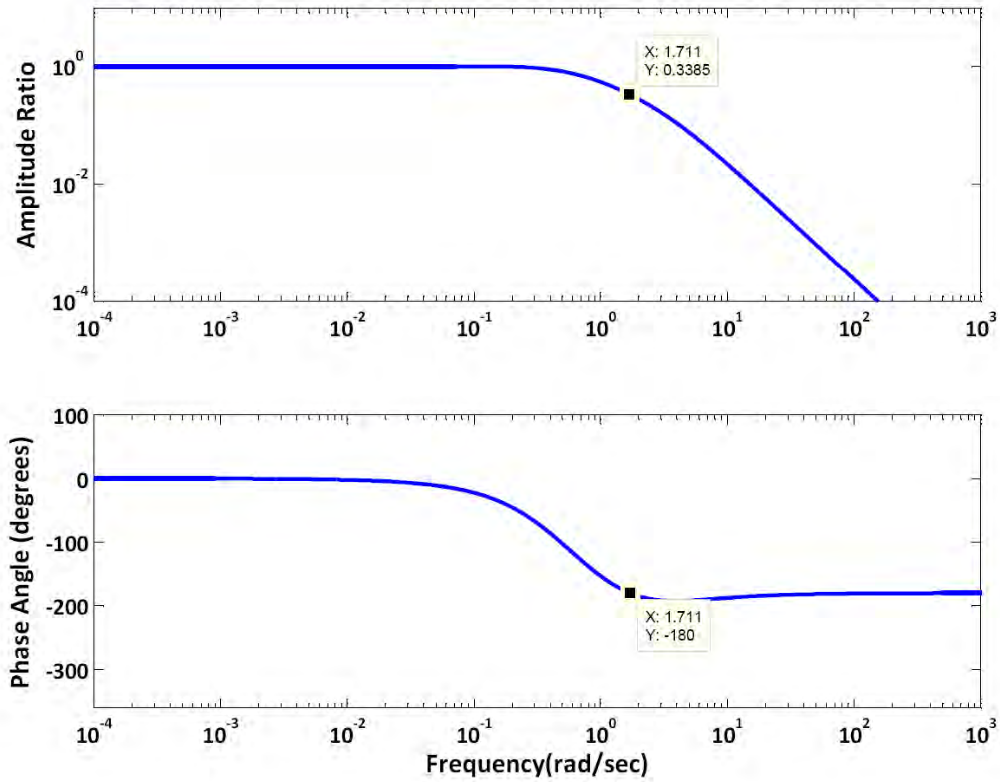


FIGURE 4.5: Bode plots for negative error in dead time estimation (servo)

The Bode plot for the above transfer function is shown in Figure 4.6. The crossover frequency was found to be 1.32 and the corresponding gain margin was 1/0.01198 = 83.47 which is quite high and away from instability.

For an error of −20% in estimation of process gain, the transfer function for set-point change becomes

$$\frac{Y(s)}{Y_{sp}(s)} = \frac{(1-1.5s)}{(1+1.5s)(\frac{6}{0.12(0.12-0.024)}s+1)} \times \left(\frac{6s+1}{0.8s+1}\right) \tag{4.35}$$

The crossover frequency for this system was found 3.052 rad/sec and corresponding gain margin was 131.63. This is shown in Figure 4.7. It is high enough for any process to work in a stable condition. So further change in parameter was not needed.

- Uncertainty in the estimation of process time constant: For this error, the parameters Z of the filter and T_I of the controller would not be right. With

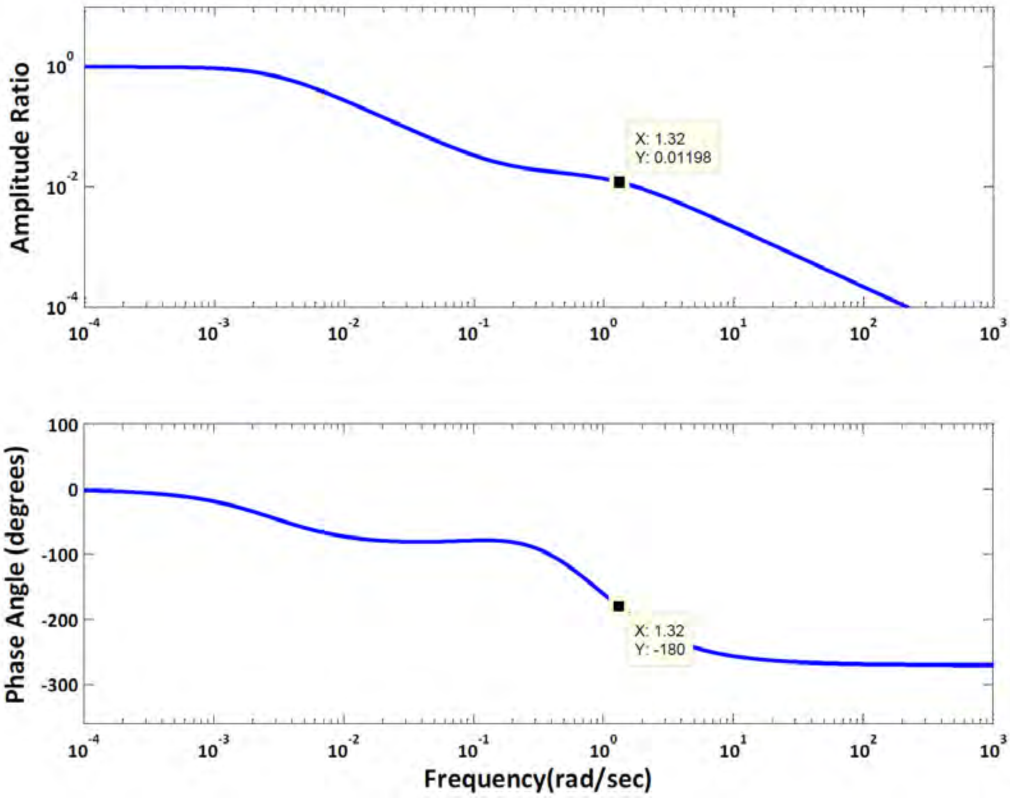


FIGURE 4.6: Bode plot for the positive estimation error in process gain (servo)

a deviation of ΔT from the time constant T is considered. So the resulting transfer function for set-point change

$$\frac{Y(s)}{Y_{sp}(s)} = \frac{(Ts+1)(1-Ls/2)}{((T^2+T\Delta T)s^2+2Ts+1)(1+Ls/2)} \times \left(\frac{Zs+1}{T_1s+1}\right) \quad (4.36)$$

For a 20% estimation error, the process model under consideration provides the following transfer function

$$\frac{Y(s)}{Y_{sp}(s)} = \frac{(6s+1)(1-1.5s)}{(43.2s^2+12s+1)(1+1.5s)} \times \left(\frac{6s+1}{0.8s+1}\right) \quad (4.37)$$

Figure 4.8 shows the Bode plot of the transfer function which clearly shows that for the crossover frequency 1.408, the gain margin is 1.8. So the system is stable.

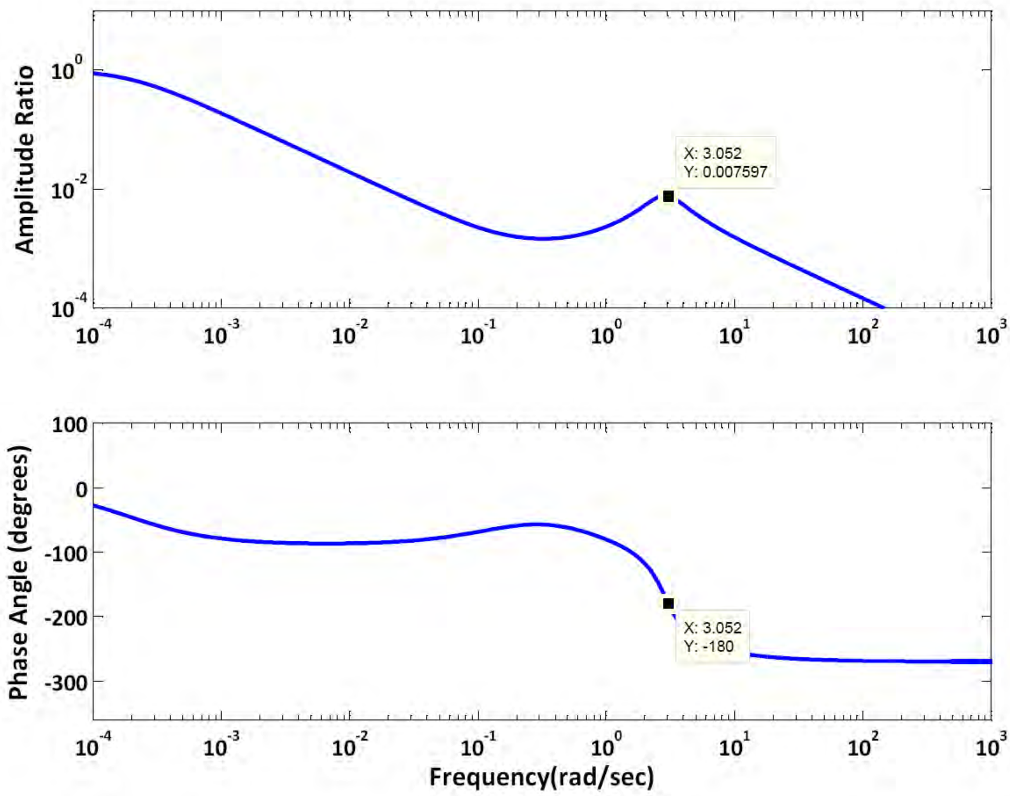


FIGURE 4.7: Bode plot for the negative estimation error in process gain (servo)

If there is −20% error in time constant estimation, the set-point change results in the following transfer function

$$\frac{Y(s)}{Y_{sp}(s)} = \frac{(6s+1)(1-1.5s)}{(28.8s^2+12s+1)(1+1.5s)} \times \left(\frac{6s+1}{0.8s+1}\right) \tag{4.38}$$

For this case, the Bode plot provides a crossover frequency of 1.517 rad/sec and gain margin of 1.27. The gain margin is greater than 1 but not in between the standard limit which is 1.7 and 4.0. For this, the value of T_1 is changed to 1.4 for increasing the stability. Then the transfer function for set-point change becomes

$$\frac{Y(s)}{Y_{sp}(s)} = \frac{(6s+1)(1-1.5s)}{(28.8s^2+12s+1)(1+1.5s)} \times \left(\frac{6s+1}{1.4s+1}\right) \tag{4.39}$$

In this case, the gain margin was found to be 1.724 for the crossover frequency of 1.342 rad/sec from the Bode plot. Now the gain margin is in the standard limit. Both the Bode plots for negative error in estimating time constant are shown in

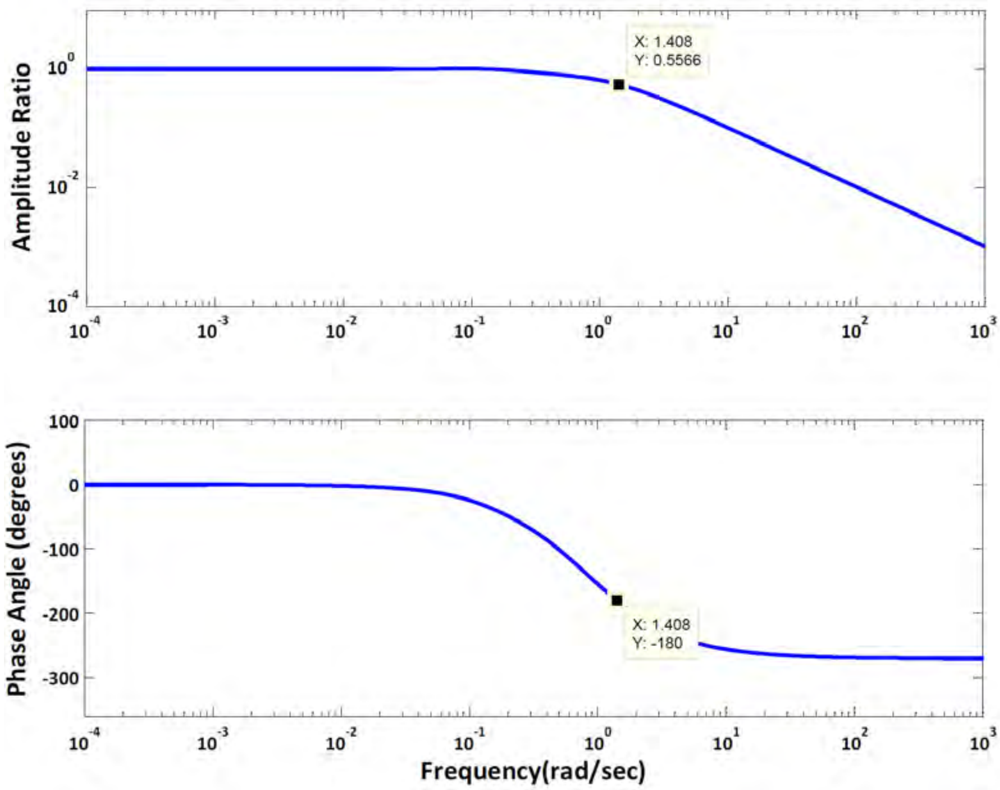


FIGURE 4.8: Bode plot for the positive estimation error in process time constant (servo)

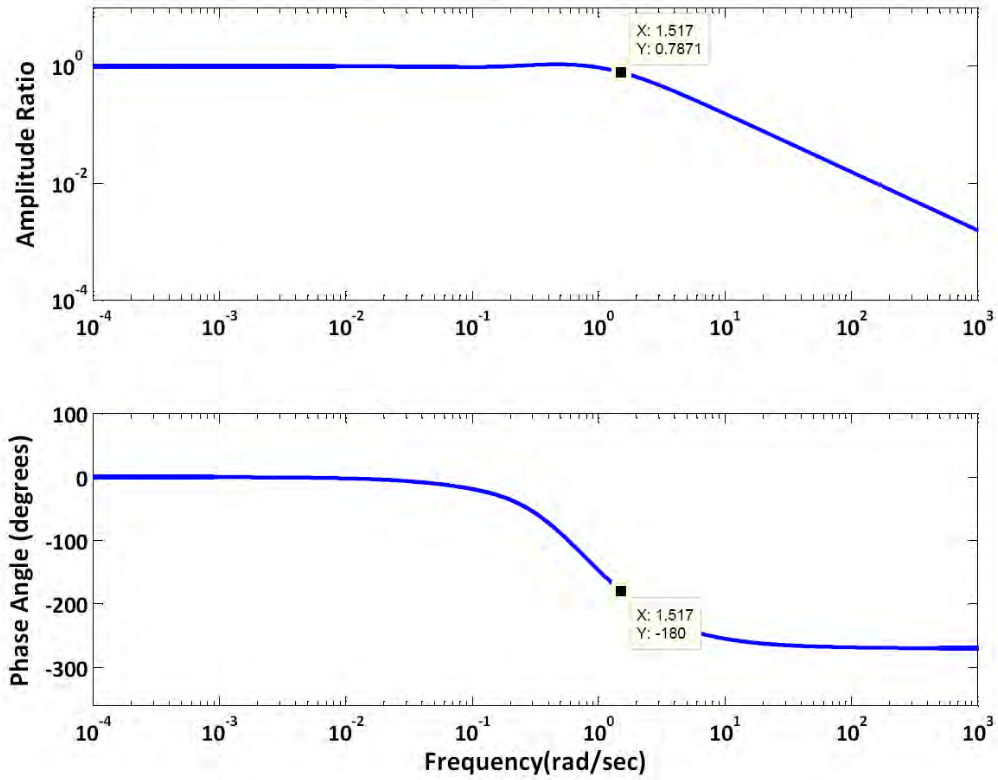
Figure 4.9.

4.3.2.2 Disturbance Rejection Response

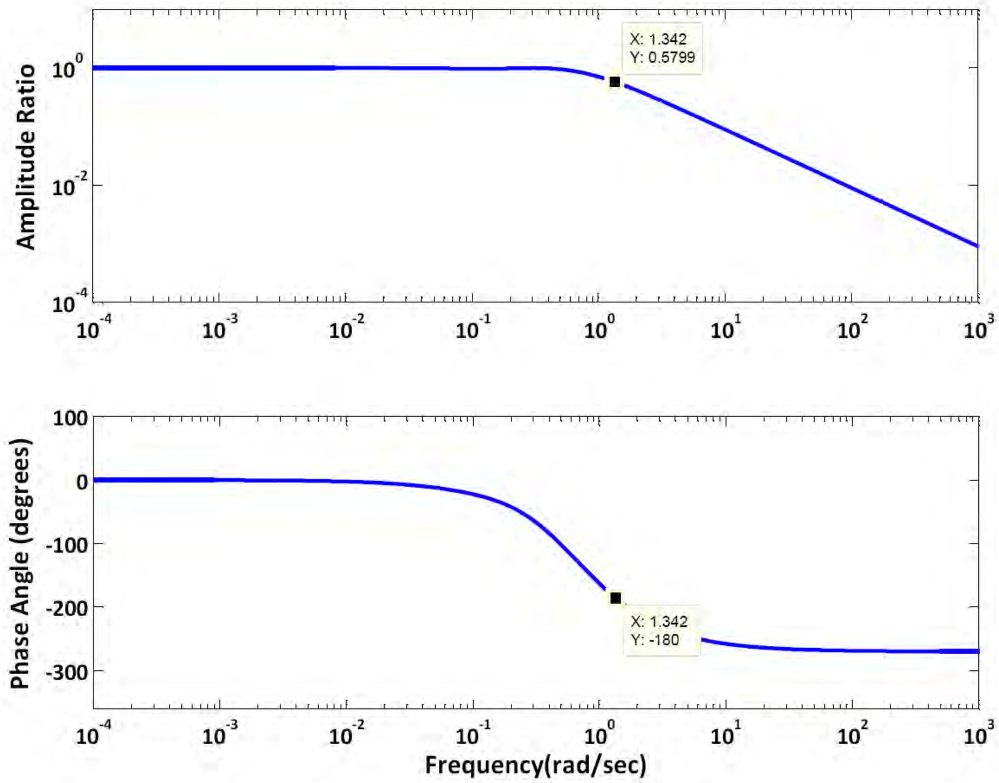
- Uncertainty in Dead Time Estimation: The transfer function between the output and disturbance is derived as

$$\frac{Y(s)}{D(s)} = \frac{K(1-\frac{L}{2}s)}{(Ts+1)(1+\frac{L}{2}s)}\left[\frac{\frac{T_2 L\Delta L}{4}s^3 + \frac{(T_2(L+\Delta L)+L)s^2}{2} + (T_2+\Delta L+\frac{L}{2})s}{\frac{T_2 L\Delta L}{4}s^3 + (T_2(L+\Delta L)-\frac{L\Delta L}{2})\frac{s^2}{2} + (T_2+\Delta L+\frac{L+\Delta L}{2})s+1}\right] \tag{4.40}$$

A 1/1 Pade approximation was considered for the Bode plot analysis in this case and ΔL is the dead time estimation error. The parameter of disturbance rejection filter would be 6 and 0.2 for Z and T_2 respectively for the process under analysis. For a 20% error in estimation, the resulting transfer function for disturbance rejection would be



(a) For filter parameter$T_1 = 0.8$



(b) For filter parameter $T_1 = 1.4$

Figure 4.9: Bode plots for negative error in process time constant estimation (servo)

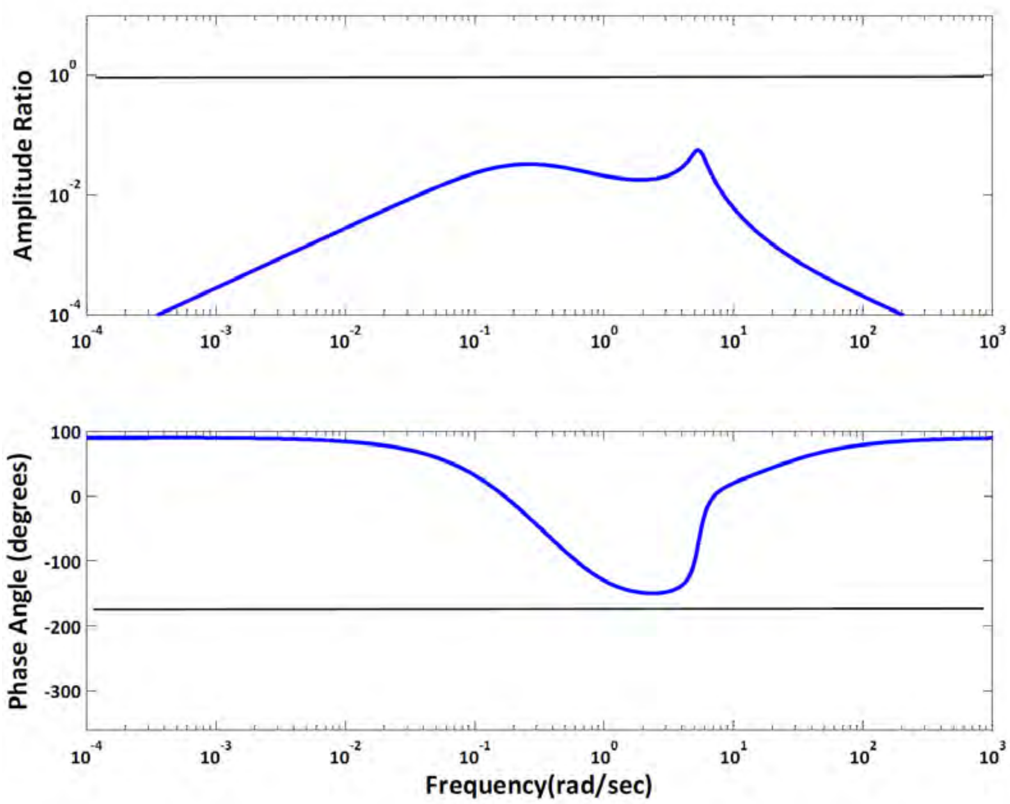


FIGURE 4.10: Bode plot for the positive estimation error in dead time (regulatory)

$$\frac{Y(s)}{D(s)} = \frac{0.12(1-1.5s)}{(6s+1)(1+1.5s)}\left[\frac{0.09s^3+1.86s^2+2.3s}{0.09s^3-0.09s^2+2.6s+1}\right] \tag{4.41}$$

Here from the Bode plot, no crossover frequency was found as the curve never reaches -180 degree of phase angle. Figure 4.10 shows that the values of amplitude ratio always remains below 1. So the gain margin never reaches the value below 1.

Again for -20% estimation error, the transfer function for the disturbance rejection response is

$$\frac{Y(s)}{D(s)} = \frac{0.12(1-1.5s)}{(6s+1)(1+1.5s)}\left[\frac{-0.09s^3+1.74s^2+1.1s}{-0.09s^3+0.69s^2+0.8s+1}\right] \tag{4.42}$$

Figure 4.11 shows that the value of the amplitude ratio remains at a lower value and does not come close to the value of 1. So the system remains

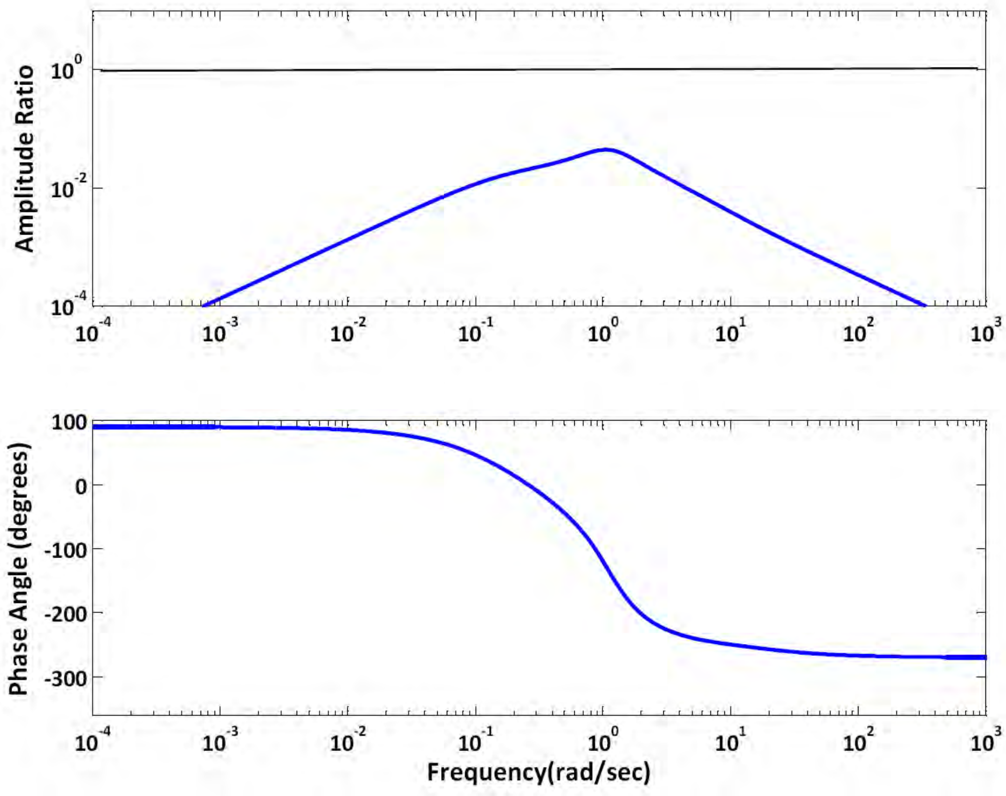


FIGURE 4.11: Bode plot for the negative estimation error in dead time (regulatory)

always at a stable state.

- Uncertainty in estimating the process gain: The equation derived for the disturbance response is given below -

$$\frac{Y(s)}{D(s)} = \frac{K(1-\frac{L}{2}s)}{(Ts+1)(1+\frac{L}{2}s)}\left[1-\frac{(1-\frac{L}{2}s)(Zs+1)}{(\frac{T}{KK_c}s+1)(T_2s+1)(1+\frac{L}{2}s)}\right] \tag{4.43}$$

Here, K and K_c are not equal and thereby no cancelation occurs. Considering an error of 20%, the transfer function for disturbance rejection for the process becomes

$$\frac{Y(s)}{D(s)} = \frac{0.12(1-1.5s)}{(6s+1)(1+1.5s)}\left[1-\frac{(1-1.5s)(6s+1)}{(\frac{6}{0.01728}s+1)(0.2s+1)(1+1.5s)}\right] \tag{4.44}$$

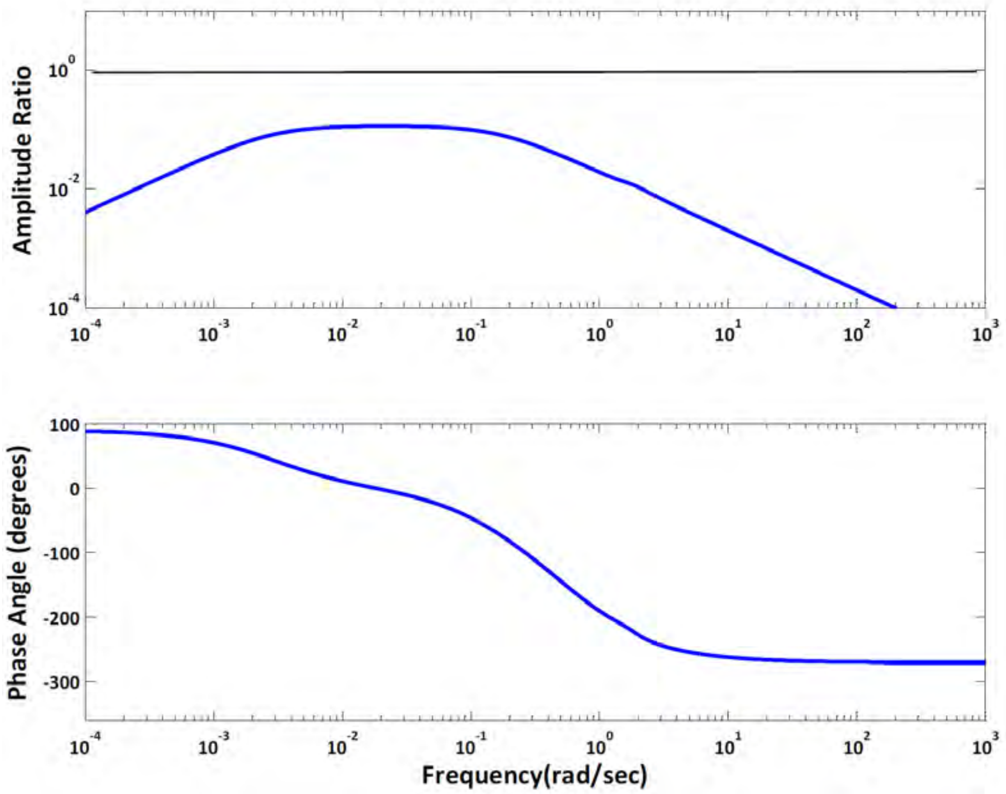


FIGURE 4.12: Bode plot for the positive estimation error in process gain (regulatory)

The Bode plot for positive error in gain estimation is shown in Figure 4.12. The stability of the process is not affected because the amplitude ratio never comes close to 1.

If an error of -20% in estimation of process gain is considered, the resulting transfer function for disturbance rejection would be

$$\frac{Y(s)}{D(s)} = \frac{0.12(1-1.5s)}{(6s+1)(1+1.5s)}\left[1 - \frac{(1-1.5s)(6s+1)}{(\frac{6}{0.01152}s+1)(0.2s+1)(1+1.5s)}\right] \quad (4.45)$$

From Bode plot, the amplitude ratio is always less than 1. The plot is shown in Figure 4.13. So the process always remains stable.

- Uncertainty in estimating the time constant of the process: The equation derived for the uncertainty in estimating the time constant of the process and the corresponding equation for a 20% error for the process under consideration are as follows

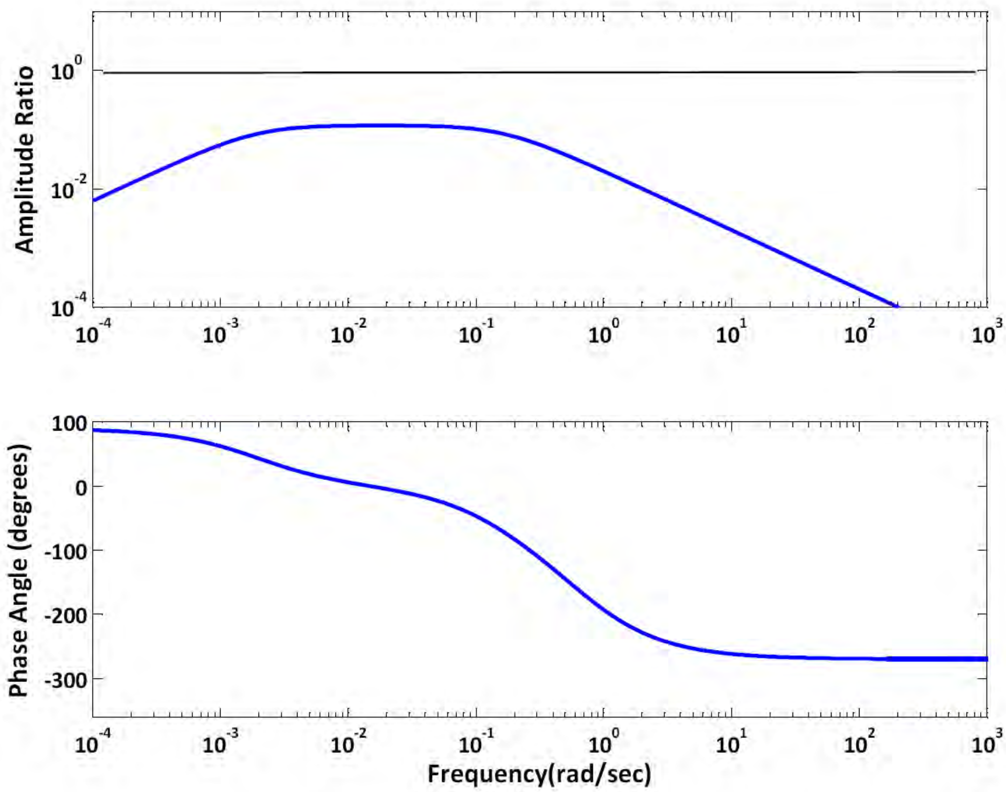


FIGURE 4.13: Bode plot for the negative estimation error in process gain (regulatory)

$$\frac{Y(s)}{D(s)} = \frac{K(1-\frac{L}{2}s)}{((T+\Delta T)s+1)(1+\frac{L}{2}s)}\left[1-\frac{(Ts+1)(1-\frac{L}{2}s)(Zs+1)}{(Ts[(T+\Delta T)s+1]+Ts+1)(T_2s+1)(1+\frac{L}{2}s)}\right] \tag{4.46}$$

$$= \frac{0.12(1-1.5s)}{(7.2s+1)(1+1.5s)}\left[1-\frac{-54s^3+18s^2+10.5s+1}{12.96s^4+73.04s^3+63.9s^2+13.7s+1}\right] \tag{4.47}$$

There is no crossover frequency for the response as the phase angle never reaches the value of -180 degree in Bode plot. Moreover, the value of amplitude ratio always remains below 1. So the system is perfectly stable with the error. The plot is shown in Figure 4.14.

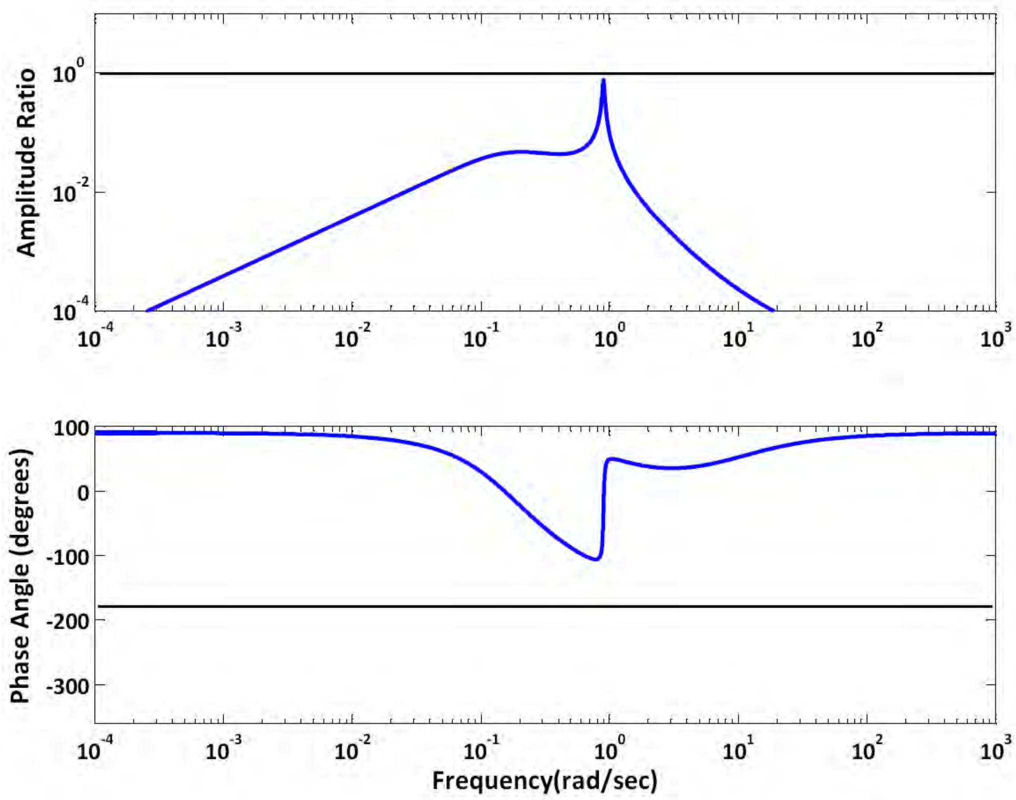


FIGURE 4.14: Bode plot for the positive estimation error in process time constant (regulatory)

Considering −20% error in time constant estimation, the transfer function becomes

$$\frac{Y(s)}{D(s)} = \frac{0.12(1-1.5s)}{(4.8s+1)(1+1.5s)}\left[1 - \frac{-54s^3+18s^2+10.5s+1}{8.64s^4+52.56s^3+49.5s^2+13.7s+1}\right] \tag{4.48}$$

Bode plot for negative estimation error in process time constant shows that the amplitude ratio is always much lower than 1. Then the gain margin is always higher than 1. It is shown in Figure 4.15.

From this analysis, it is evident that some estimation errors in model estimation do not make the process unstable. Also with increasing the values of T_1 and T_2, the robustness of the process may be increased as desired.

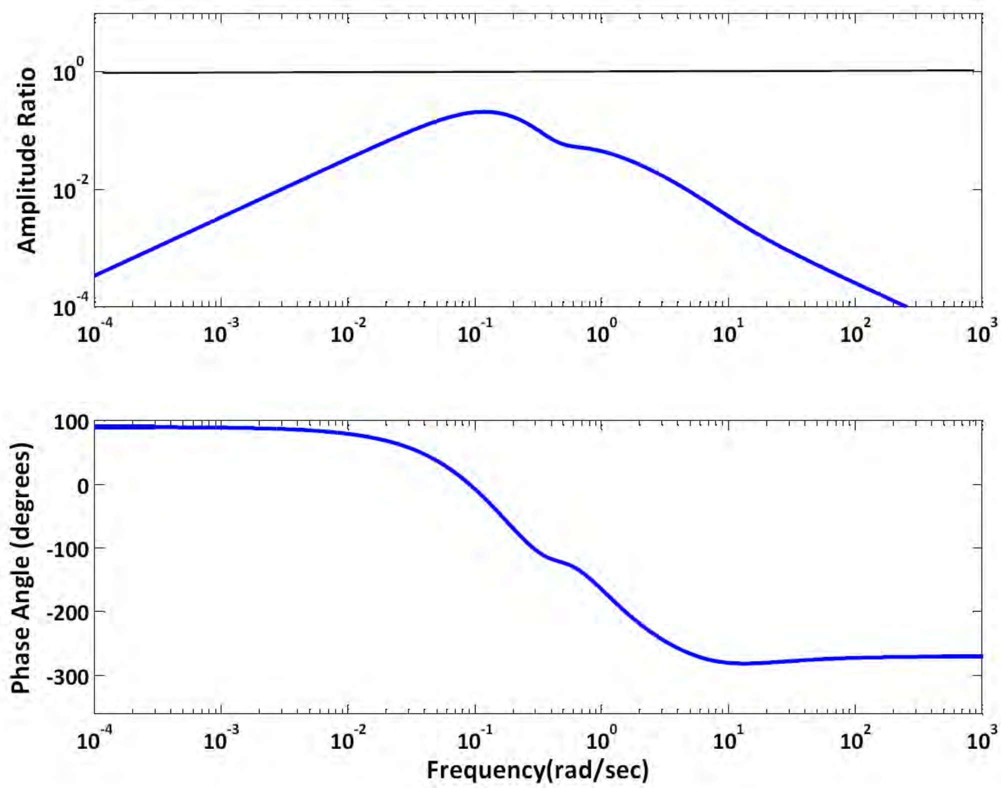


FIGURE 4.15: Bode plot for the negative estimation error in process time constant (regulatory)

4.4 Simulation Study

As has been mentioned, several papers have been proposed with modifications to the original Smith Predictor, some concerning the tuning of parameters of the original Smith Predictor and others proposing the modification of the control structure. In general, the later modifications have demonstrated better performance than the previous works. For the case of stable plants, the Dead Time Compensator (DTC) proposed in [6] in 2009 can be considered as the best solution among the studies proposed so far. Normey-Rico and Camacho [6] have denoted their scheme as the 'Filtered Smith Predictor' (FSP). Therefore, the proposed Modified Smith Predictor (MSP) results of this study has been compared to the FSP results.

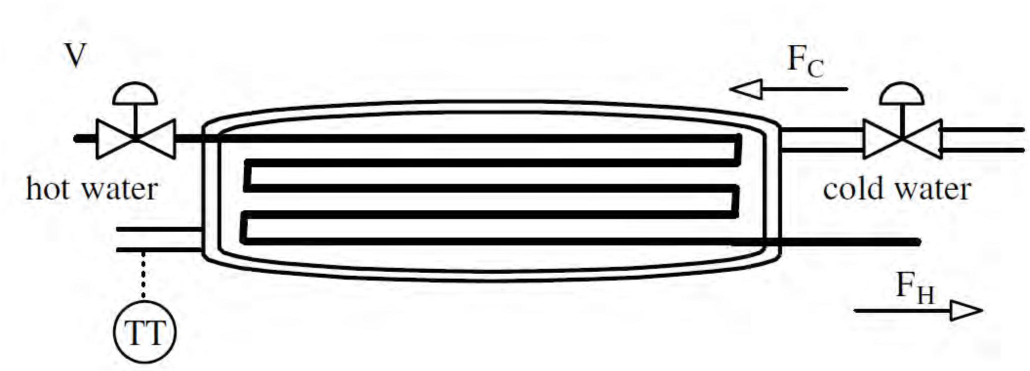


FIGURE 4.16: Water heat exchanger used in [6]

4.4.1 Example 1

A heat exchanger shown in Figure 4.16 is considered in [6] where the output temperature θ of the cold water is controlled using valve V that manipulates the input flow of the hot water. The temperature of the hot water is controlled by an independent controller. As described in [6], the process can be represented by the following stable first order model when it is close to the nominal operating point

$$P(s) = \frac{0.12}{6s+1}e^{-3s} \tag{4.49}$$

A dead time estimation error of 10% is considered here. The same model is used here for comparison by exciting it with a unit step change at t=1 and a disturbance change of 0.1 at t=70. In Normey-Rico and Camacho [6], only one filter was suggested for stable processes and their proposed filter was used in place of F_2. The filter they proposed for the process was $\frac{(1+6s)(1+4.38s)}{(1+2s)^2}$. The proposed controller gain and the integral constant are 8.33 and 6 seconds respectively. For the proposed Modified Smith Predictor (MSP) in this paper, the controller gain and integral time constant is found to be the same as in Normey-Rico and Camacho [6] and the filters designed as per the rules described in Section 4.2.2 and 4.2.3 can be found as

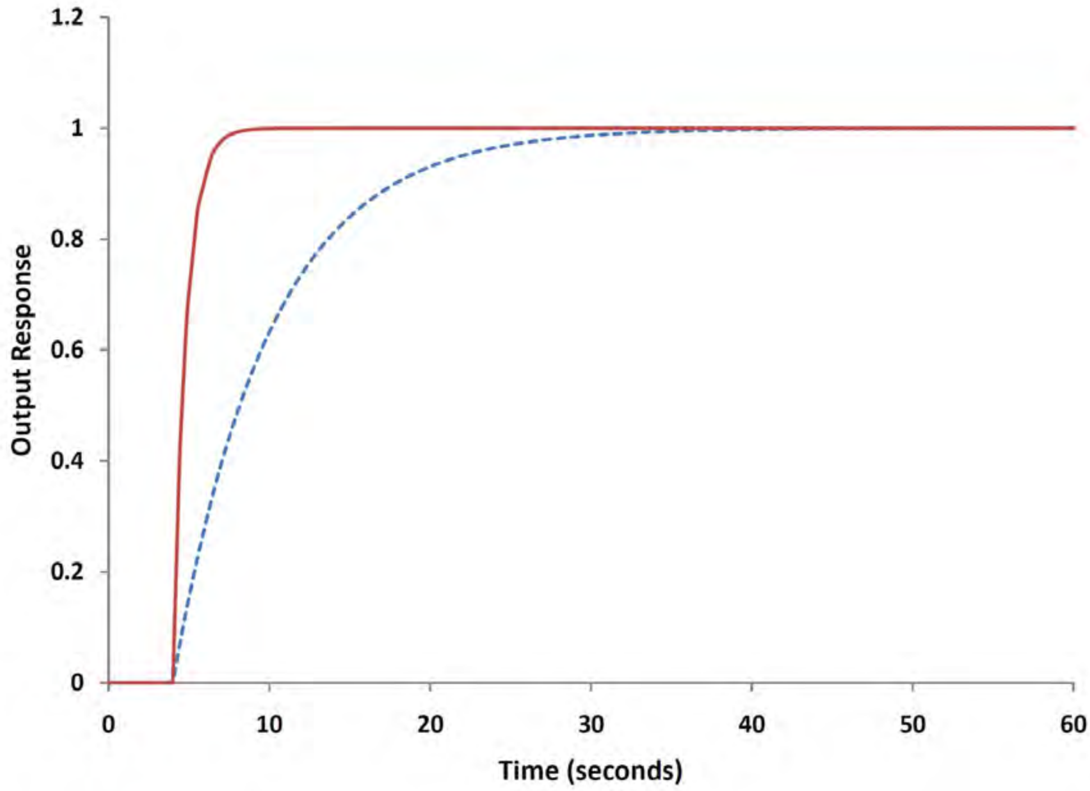


FIGURE 4.17: Comparative set point response of proposed MSP (solid line) and FSP (dashed line) by Normey-Rico and Camacho [6]

$$F_1(s) = \frac{6s+1}{0.8s+1}, \qquad F_2(s) = \frac{6s+1}{0.2s+1} \tag{4.50}$$

Here, the value of T_1 and T_2 are chosen to be 0.8 and 0.2, respectively. The set-point response is shown in Figure 4.17. It can be observed from Figure 4.17 that the set point response of the proposed MSP is better than the FSP proposed by Normey-Rico and Camacho [6]. The disturbance rejection response is shown separately in Figure 4.18. The disturbance response has also been improved slightly.

4.4.2 Example 2

Another process with a long dead time relative to the process time constant can be considered for evaluating the proposed method which was used in [9]. The process has the following transfer function

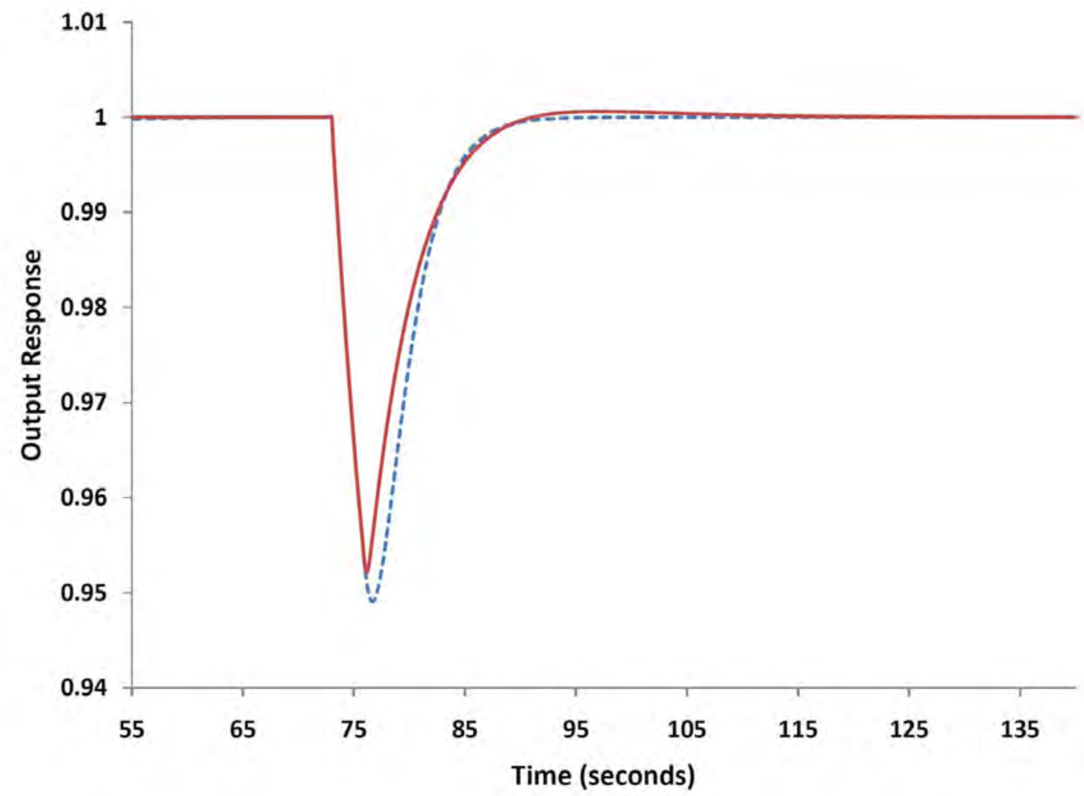


FIGURE 4.18: Comparative disturbance response of proposed MSP (solid line) and FSP (dashed line) by Normey-Rico and Camacho [6]

$$P(s) = \frac{1.02}{1.7s + 1} e^{-8.2s} \tag{4.51}$$

The dead time for the system is almost five times the time constant of the process. A PI controller is not capable of controlling this particular process satisfactorily. This response is shown in Figure 4.19. From the proposed method, the controller is tuned to have the proportional gain of 0.9804 and the integral time constant equal to the process time constant. The filters obtained for this system are

$$F_1(s) = \frac{1.7s + 1}{0.6s + 1}, \qquad F_2(s) = \frac{1.7s + 1}{s + 1} \tag{4.52}$$

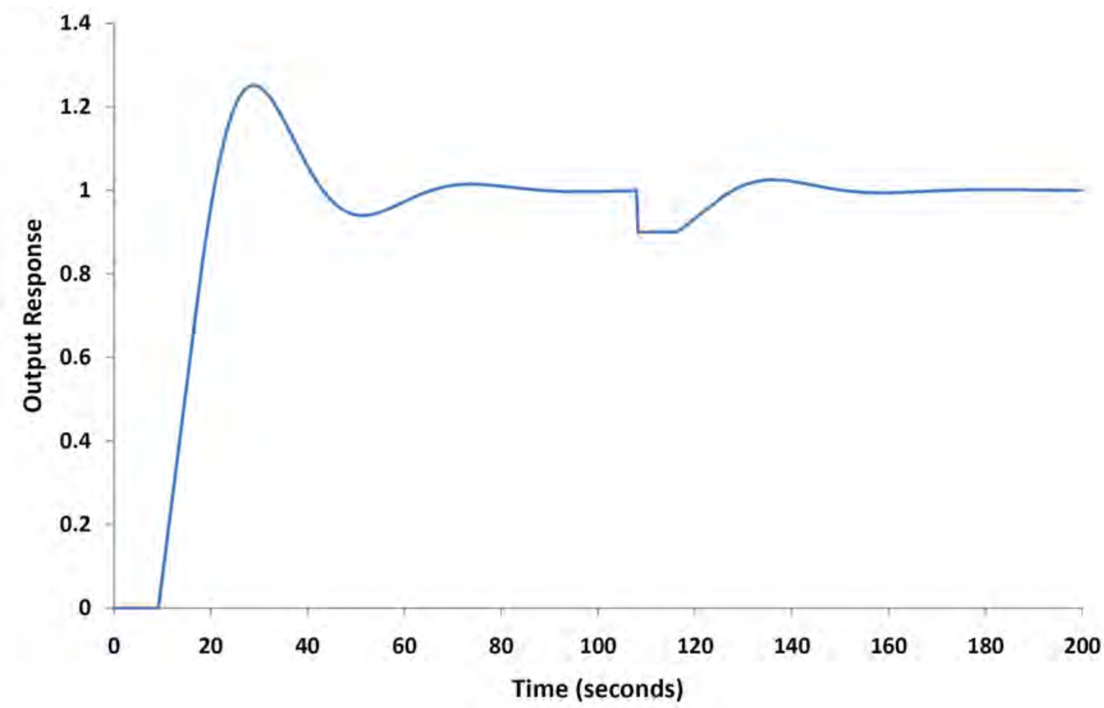


FIGURE 4.19: Response of PI controller tuned by IMC method

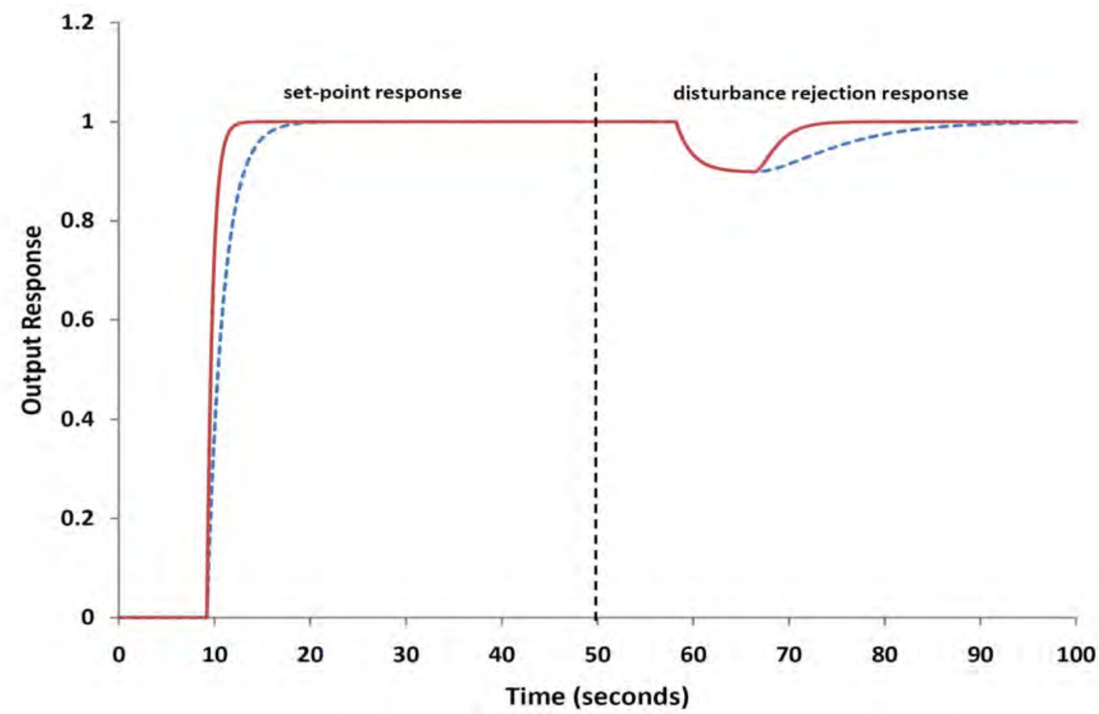


FIGURE 4.20: Comparative response of proposed MSP (solid line) with FSP (dashed line) for long dead time system

With the same controller tuning, the filter F_2 can be constructed using the FSP criterion of Normey-Rico and Camacho [6] as:

$$F_2(s) = \frac{(1.7s + 1)(1.65s + 1)}{(5s + 1)^2} \tag{4.53}$$

The output responses of the proposed Modified Smith Predictor and Filtered Smith Predictor are shown in Figure 4.20. It shows that the proposed method has performed significantly better than FSP for systems with long dead time.

Chapter 5

Experimental Evaluation and Comparison

5.1 Description of the Experimental Setup

The proposed method was evaluated on a two tank heating system pilot plant located in the Department of Chemical Engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh. A photograph of the set-up is shown in Figure 5.1 and the schematic diagram of the pilot plant is shown in Figure 5.2. These tanks have large time constants because they have a diameter of 26 inches. Both of them have a steam-coil for heating the water. Tank-1 has the facility to introduce dead time to the temperature control loop. So the experiments were performed on the temperature control loop of Tank-1. The temperature is controlled by the steam control valve TCV-01. The level of the tank was kept constant at 60% during all experiments. For uniform heating of the tank water by steam, an air bubbling system was used as a stirring mechanism.

From Figure 5.2, it can be seen that the temperature transmitters, TT-02, TT-03, TT-04, TT-05, of Tank-1 can be used to introduce variable time delay. The transmitter TT-05 would yield the longest dead time. The distance of the transmitters from the water outlet of the tank results in transportation delays and the delay

FIGURE 5.1: Photograph of the set-up

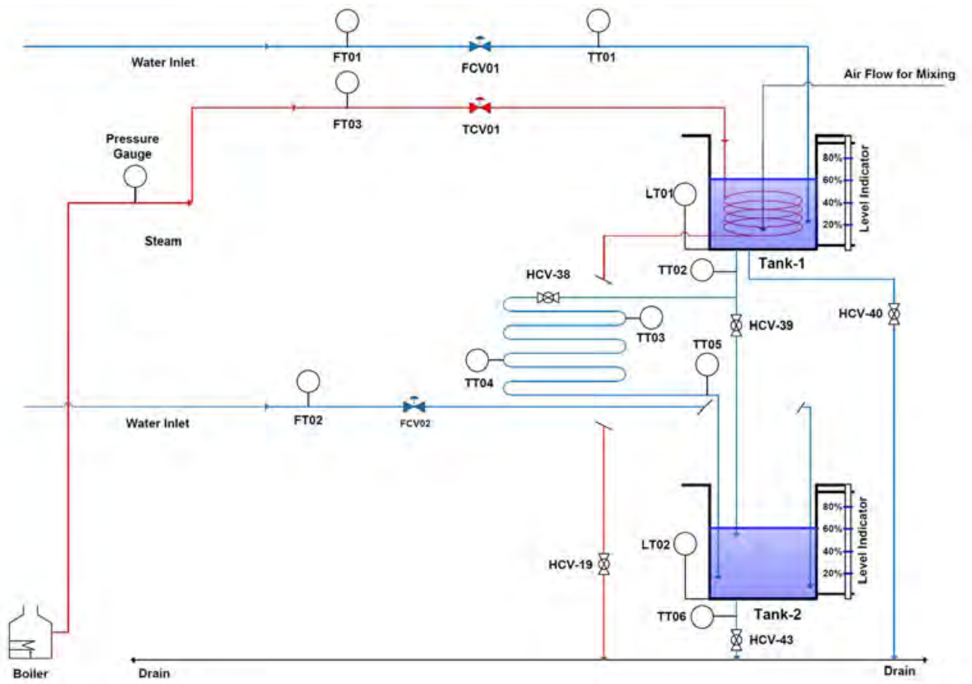


FIGURE 5.2: Schematic diagram of the pilot plant

becomes larger when the temperature sensor selected is farthest from the tank. The transmitter from the tank outlet that results in the largest delay is clearly TT-05.

5.2 Model Identification

To apply the method, a process model is needed. The process model would be same for all the transmitters except the delay which will vary. Open loop step tests were performed on Tank-1 temperature control loop and the model was identified from the step response data. The identified model is

$$G_n(s)e^{-L_n s} = \frac{0.2}{1020s + 1}e^{-110s} \tag{5.1}$$

The model response was compared with the experimental response and shown in Figure 5.3. As evident from the time constant of the model, the system is very slow. The delay, L_n, was found to be 110 seconds for TT-05. As per the rules suggested in Chapter 4, the controller gain and integral time constant parameters are obtained as 5 and 1020 seconds, respectively. This controller will be same for all the transmitters as the process model will remain the same.

Then the step test was performed on TT-04 which yields a dead time of 80 seconds. For dead time compensation, the experiments were performed on TT-04 and then on TT-05 to see the effect of uncertainty in the dead time of a process.

5.3 Dead Time Detection Experiments

Dead time detection was done by the algorithm developed in Chapter 3. The open loop test data was fed into the program to calculate the dead time of the process. The dead time for TT05 was 109 seconds. So it was very close to the actual delay

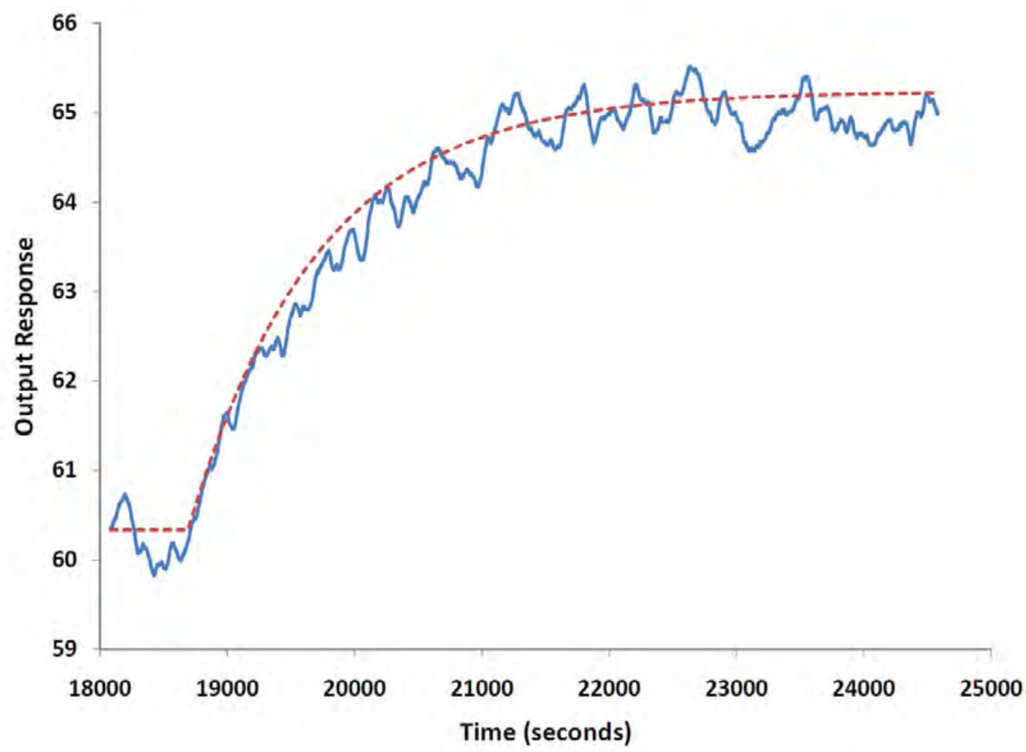


FIGURE 5.3: Comparative response of calculated model (dotted line) and actual process (solid line)

determined by the step test, which was found to be 110 seconds. So the method is useful for dead time estimation from real process output data.

5.4 Dead Time Compensation Experiments

5.4.1 Experimental Study Using TT-04

The experiments performed using transmitter can be divided into three major parts - performance of PI controller, performance of the proposed modified Smith predictor (MSP), performance of the filtered Smith predictor (FSP) by Normey-Rico and Camacho [6]. As TT-04 was found to have a delay of 80 seconds, the process model for the transmitter will be -

$$G_n(s)e^{-L_n s} = \frac{0.2}{1020s+1}e^{-80s} \tag{5.2}$$

The PI controller is tuned as per the well known IMC (Internal Model Control) method by assuming the value of τ_c = dead time. So it should provide a fast and strong control action on the process. The value of the proportional controller gain and the integral time constant for the process was found to be 31.875 and 1020 seconds, respectively. The filters for MSP found using the rules described in Chapter 4 are:

$$F_1(s) = \frac{1020s+1}{150s+1}, \qquad F_2 = \frac{1020s+1}{75s+1} \tag{5.3}$$

The set-point response comparing the MSP and PI controller is shown in Figure 5.4. Certainly, the overshoot for the MSP is less than the PI controller. But the response is almost same except the overshoot reduction. The disturbance rejection response is compared in Figure 5.5. So the response is almost same for both MSP and PI controller. This is a good example which implies that if the dead time is not dominating then the PI controller would be good enough.

The filter parameters of MSP can be tuned to obtain a better response than the PI controller. After changing the filter parameters T_1 and T_2 to 100 and 50 respectively, the comparative response of MSP and PI controller were obtained as Figure 5.6 and Figure 5.7. For this case, the overshoot for set-point response is lowered and the disturbance rejection response is improved. It is to be noted that the IMC method of PI controller tuning and the proposed modified Smith Predictor requires the same amount of effort to design or tune. So generally for any stable process with dead time can be satisfactorily controlled by the proposed dead time compensator.

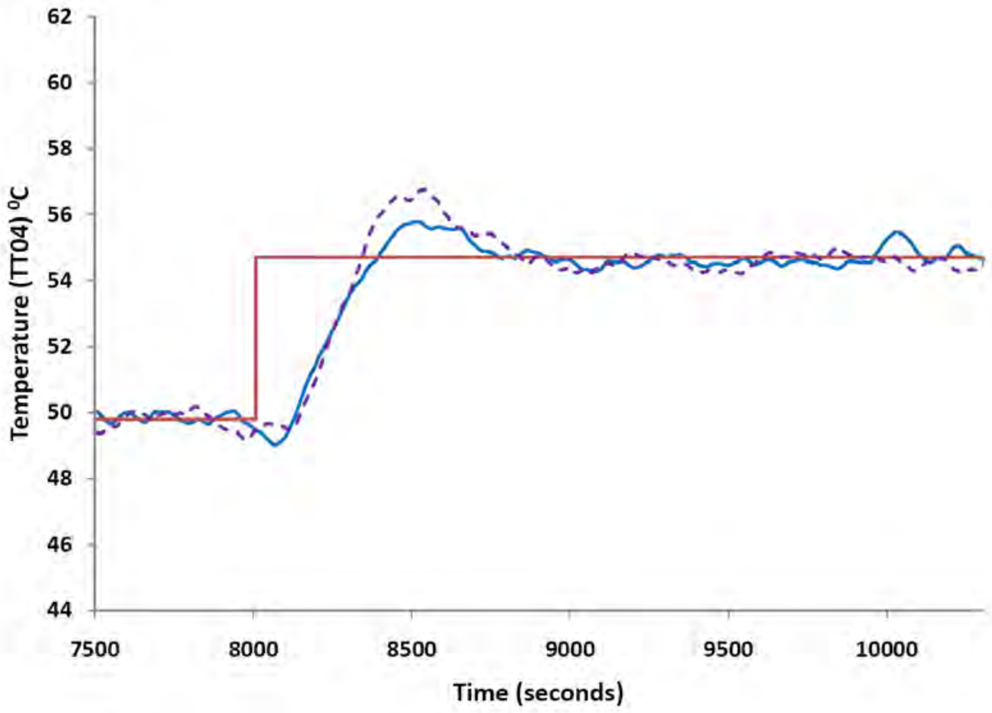


FIGURE 5.4: Comparative set-point response of PI controller (dashed line) and MSP (solid line)

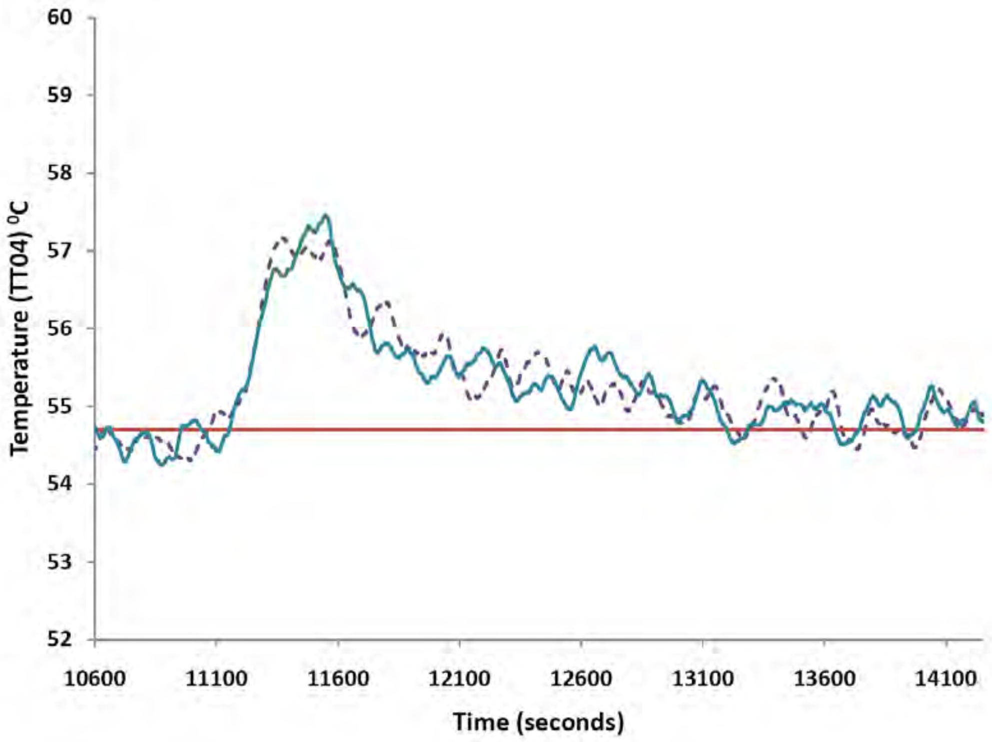


FIGURE 5.5: Comparative disturbance rejection response of PI controller (dashed line) and MSP (solid line)

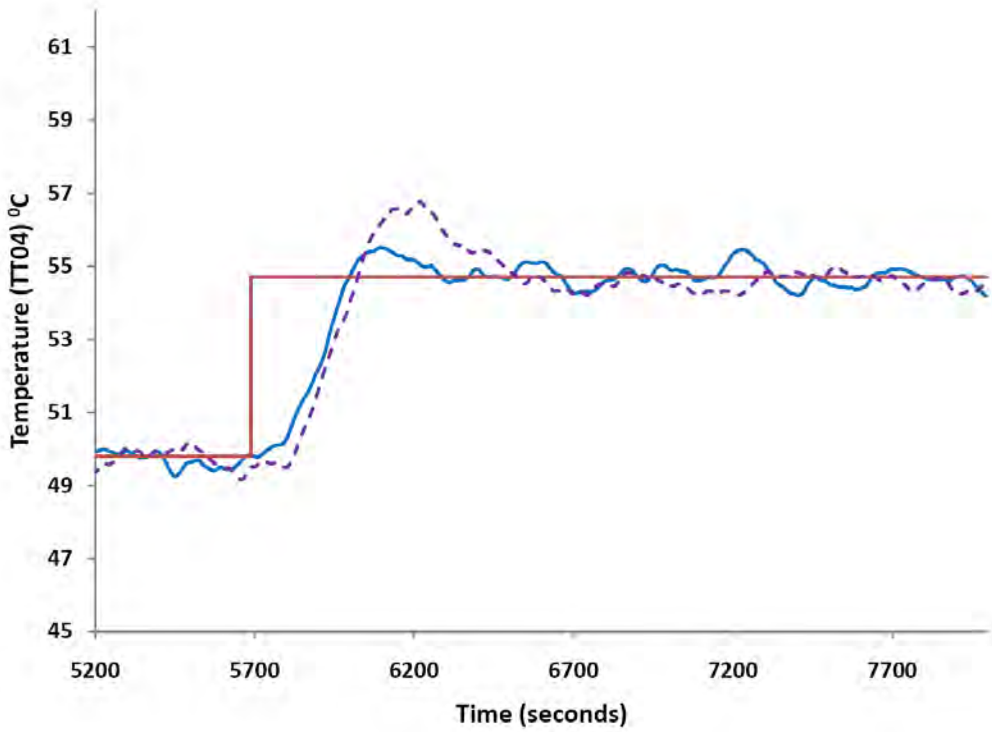


Figure 5.6: Comparative set-point response of PI controller (dashed line) and MSP (solid line) with tuned parameter

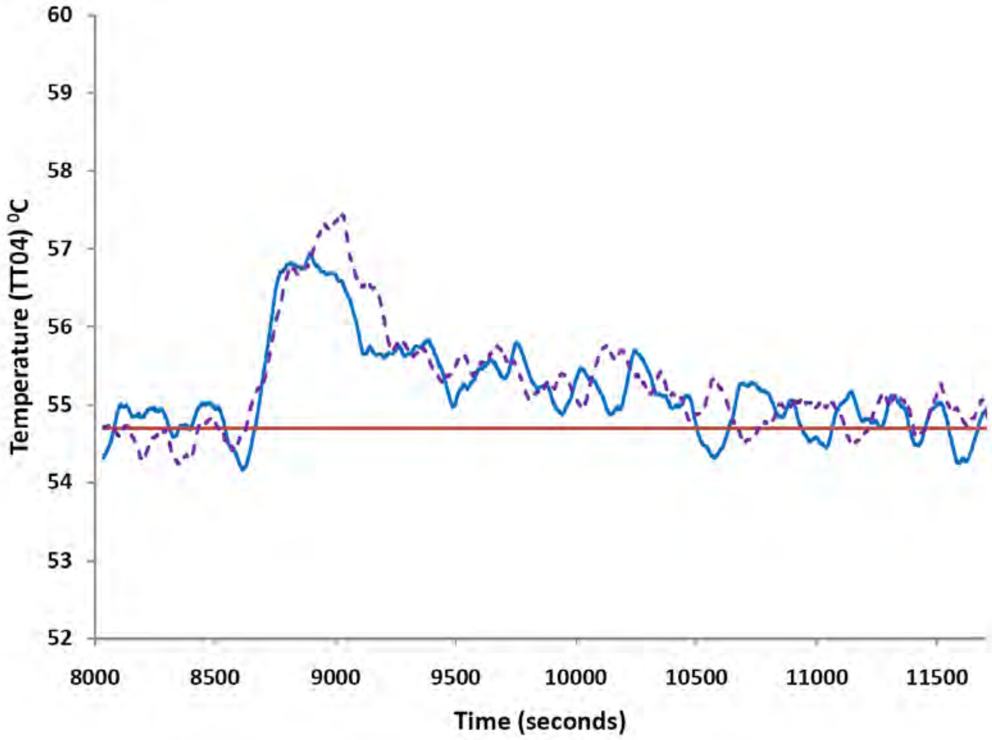


Figure 5.7: Comparative disturbance rejection response of PI controller (dashed line) and MSP (solid line) with tuned parameter

The most recent dead time compensator known as Filtered Smith Predictor (FSP) proposed by Normey-Rico and Camacho [6] was tested on the pilot plant to evaluate its performance. As they suggested to use one filter for stable processes, the filter was obtained as

$$F_2(s) = \frac{(158.32s + 1)(1020s + 1)}{(45s + 1)^2} \tag{5.4}$$

The implementation of this filter shows the response provided in Figure 5.8. The response was quite unsatisfactory, aggressive and crosses the set-point quickly. Then it never came back to the set-point. So the filter time constant for FSP was very aggressive. It was increased to 50 and the resulting filter is

$$F_2(s) = \frac{(167.134s + 1)(1020s + 1)}{(50s + 1)^2} \tag{5.5}$$

The response obtained by using the filter is shown in the Figure 5.9. It was surprising that this time the actuator did not move and the response was steady at a lower value than the set-point. The response never moved towards the set-point. In general, with different values of filter parameter, the FSP by Normey-Rico and Camacho [6] did not perform well on real systems with dead time.

5.4.2 Experimental Study on TT-05

The experiments were further performed using the temperature transmitter TT05 for which the dead time was found 110 seconds. For examining the robustness of the proposed method, the filters used for the transmitter TT-04 were also used for transmitter TT-05. The controller tuning was kept same as the process remained same. Only the delay parameter was changed to 110 in the compensator.

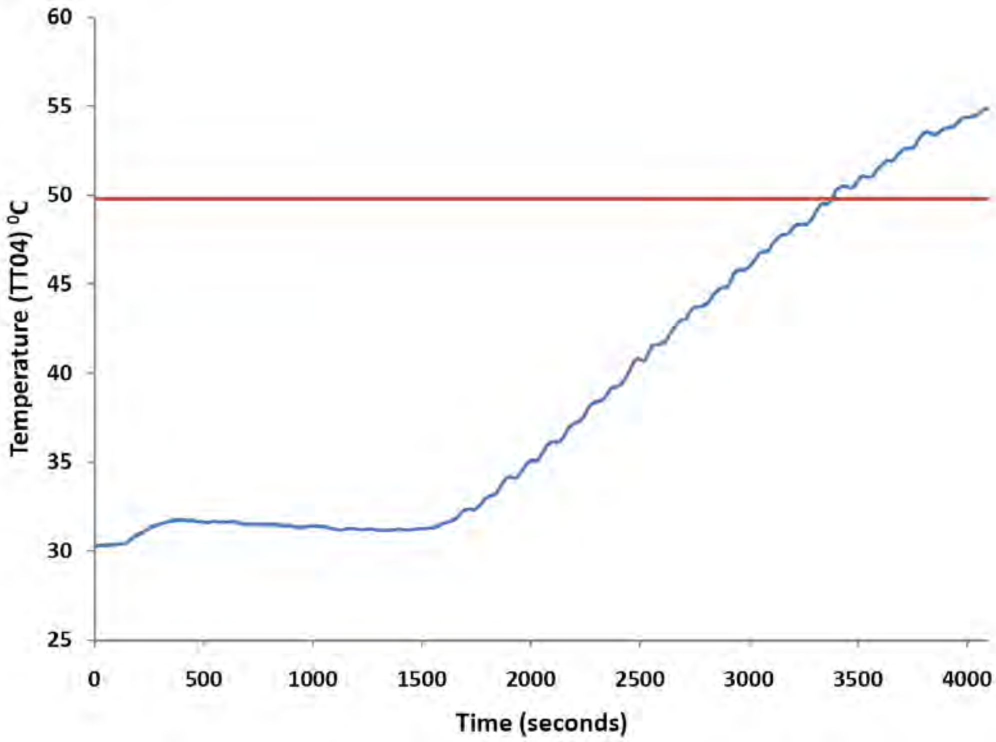


FIGURE 5.8: Set-point response of FSP proposed by Normey-Rico and Camacho [6] for filter $F_2(s) = \frac{(158.32s+1)(1020s+1)}{(45s+1)^2}$

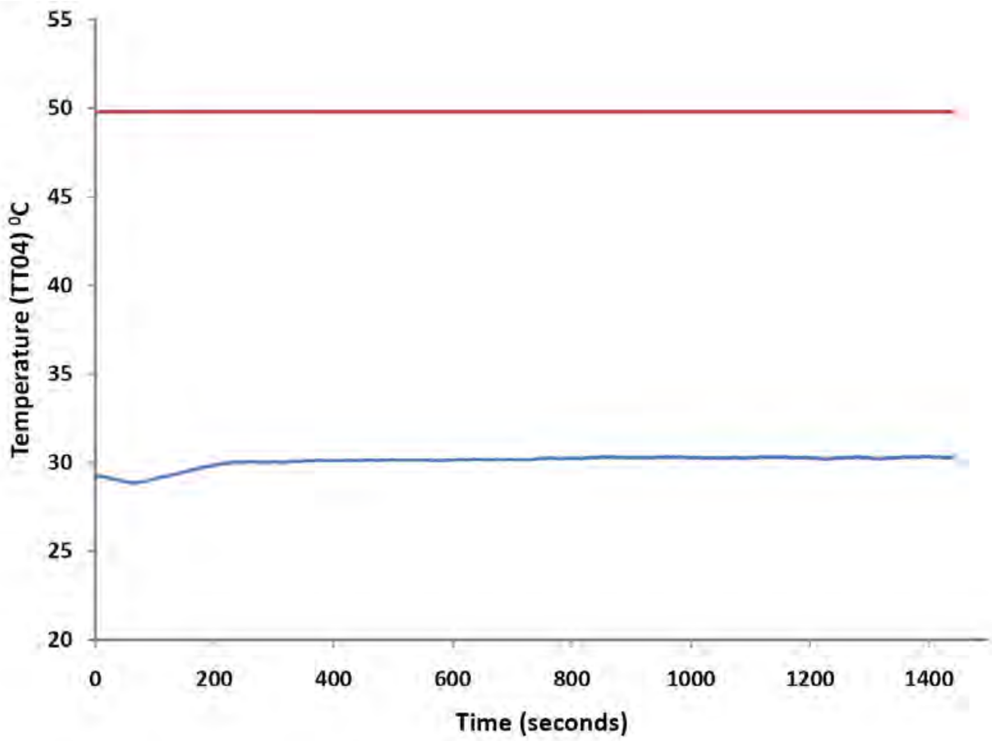


FIGURE 5.9: Set-point response of FSP proposed by Normey-Rico and Camacho [6] for filter $F_2(s) = \frac{(167.134s+1)(1020s+1)}{(50s+1)^2}$

5.4.2.1 PI Controller

The PI controller had a controller gain of 23.2 and integral time constant of 1020 seconds according to IMC tuning rules (taking τ_c = dead time). The PI controller was implemented in the system and the response as shown in Figure 5.10 was found to be oscillatory.

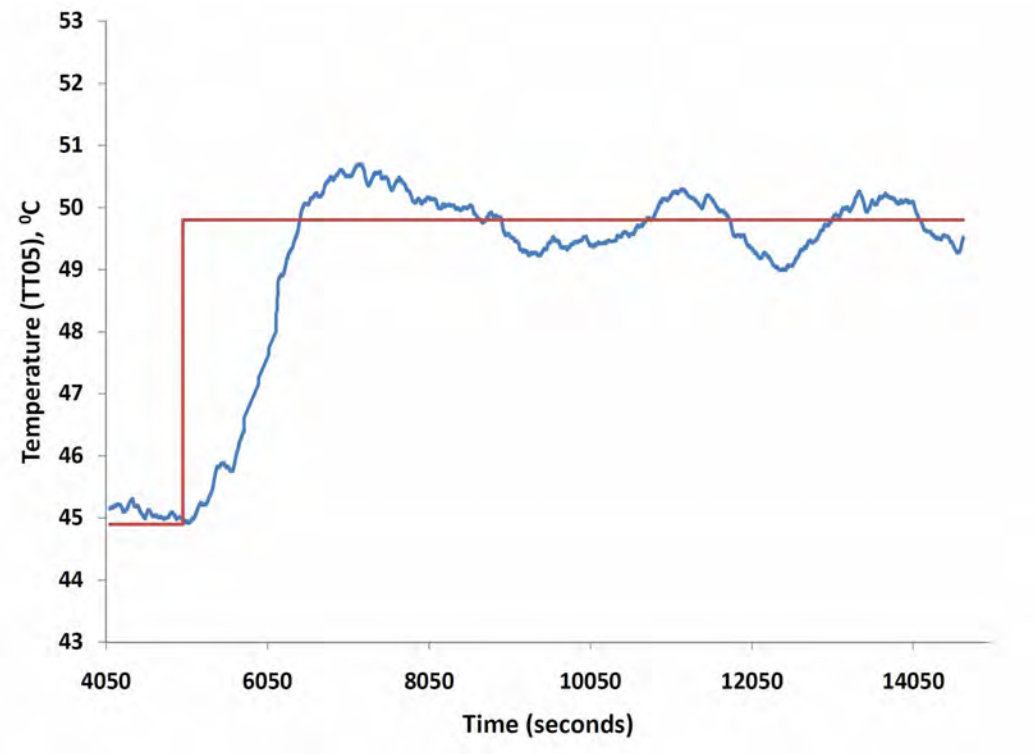


FIGURE 5.10: Oscillatory set-point response of PI controller for transmitter TT-05

5.4.2.2 The Proposed MSP

The proposed modified Smith predictor was evaluated on the pilot plant using various filter parameters. With two sets of values of T_1 and T_2, the MSP was implied on the pilot plant. For a robust response, the chosen values of the filter parameters, T_1 and T_2, were 150 and 75 and to achieve a faster response, the values of T_1 and T_2 were decreased to 100 and 50 respectively. The comparative set-point tracking and disturbance rejection response of the proposed method for different filter parameters are shown in Figure 5.11 and Figure 5.12. For conservative control, T_1 and T_2 should be larger and for better performance, they should be smaller.

5.4.2.3 FSP by Normey-Rico and Camacho [8]

For the same controller tuning, the filter $F_2(s)$ according to [6] was found to be $:\frac{(1020s+1)(208.84s+1)}{(60s+1)^2}$. The respective response is shown in Figure 5.13(a). The response of the process is static initially and then it begins to rise monotonically crossing the set-point and did not come back to the set-point. The filter parameter was changed to make the compensator less sensitive in which case the filter becomes $F_2(s) = \frac{(1020s+1)(217.27s+1)}{(65s+1)^2}$.With the implementation of the changed filter, the actuator is stuck at the same point and the response did not reach the set-point as shown in Figure 5.13(b).

From these experiments, it has become evident that the proposed Modified Smith Predictor is valid and suitable for stable processes with dead time. It can outperform the PI controller and the most recent dead time compensator [6] appeared in the literature. The PI controller can be used for processes with short dead time. But as it requires the same effort as the MSP, the proposed MSP can be used for all cases. Another important finding from the experiments is that the FSP proposed by Normey-Rico and Camacho [6] did not work well for real processes with dead time.

5.4.3 Performance Quantification

In order to quantify the response of the controllers and the DTCs, the Integral of Absolute Error (IAE) was calculated for each case. Graphical representation of IAE is given in Figure 5.14 where the shaded area is the IAE value. So a higher value of IAE means a larger deviation from the desired response.

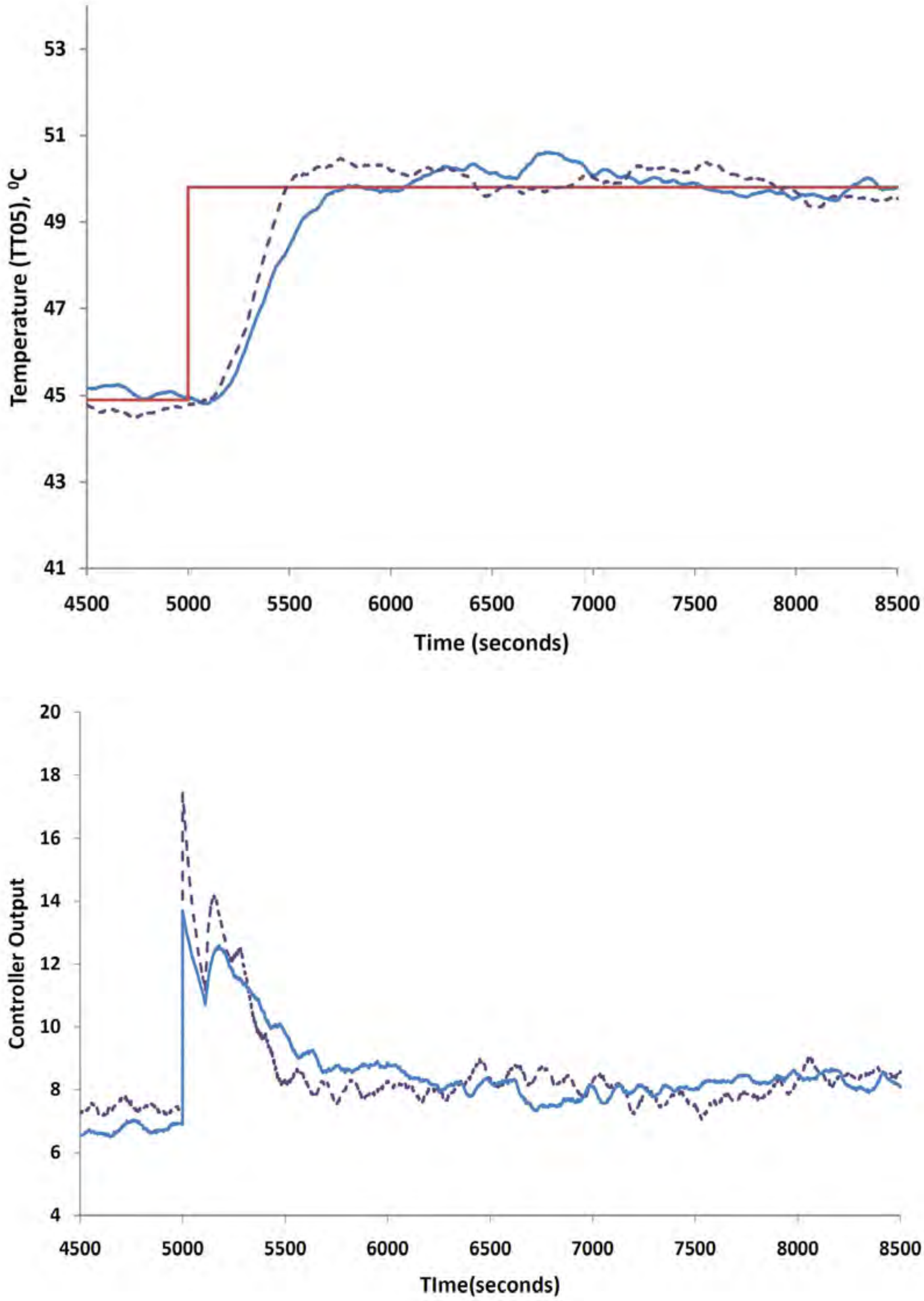


FIGURE 5.11: Comparative set-point response of proposed MSP with $T_1 = 100, T_2 = 50$ (dashed line) and $T_1 = 150, T_2 = 75$ (solid line)

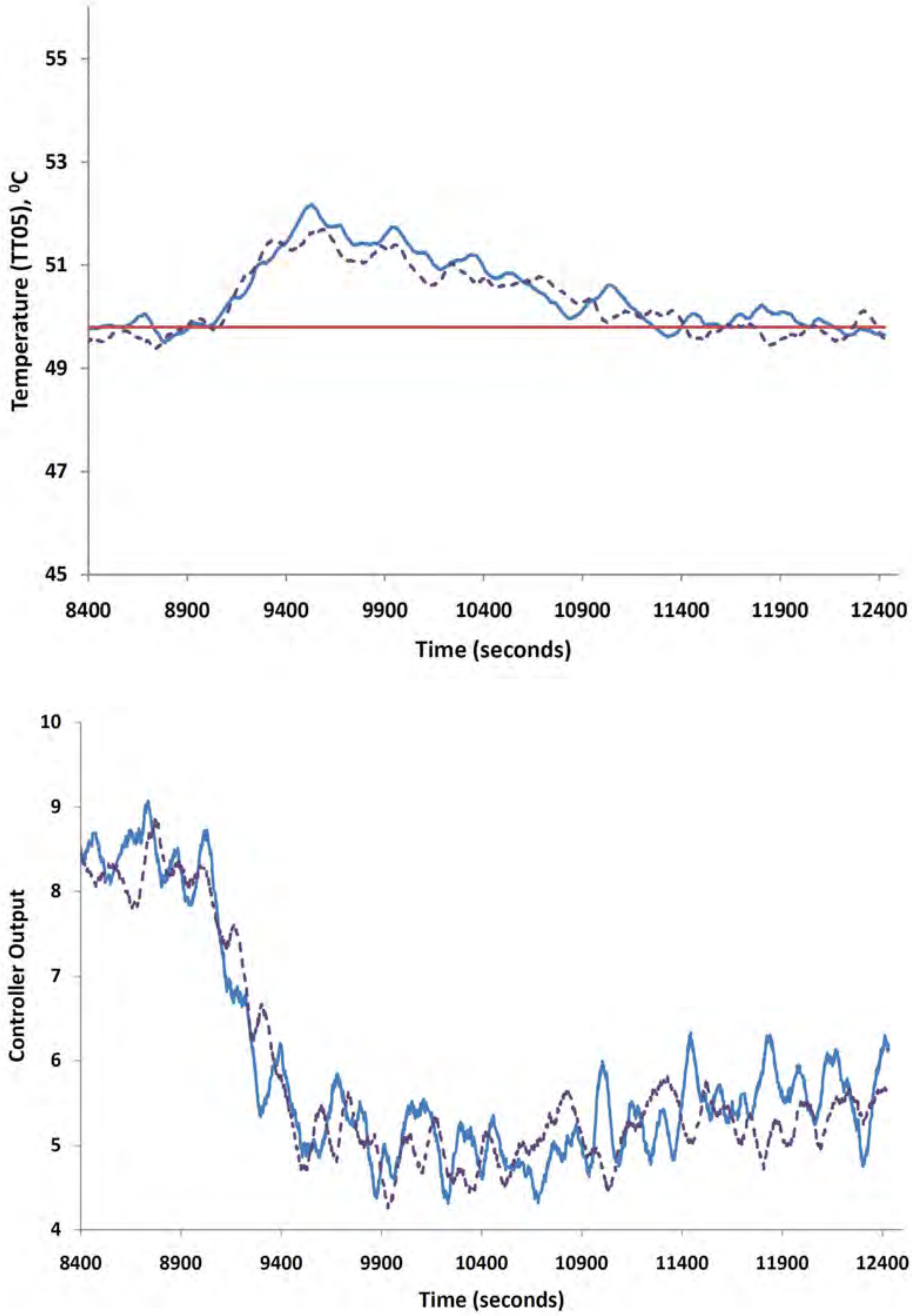
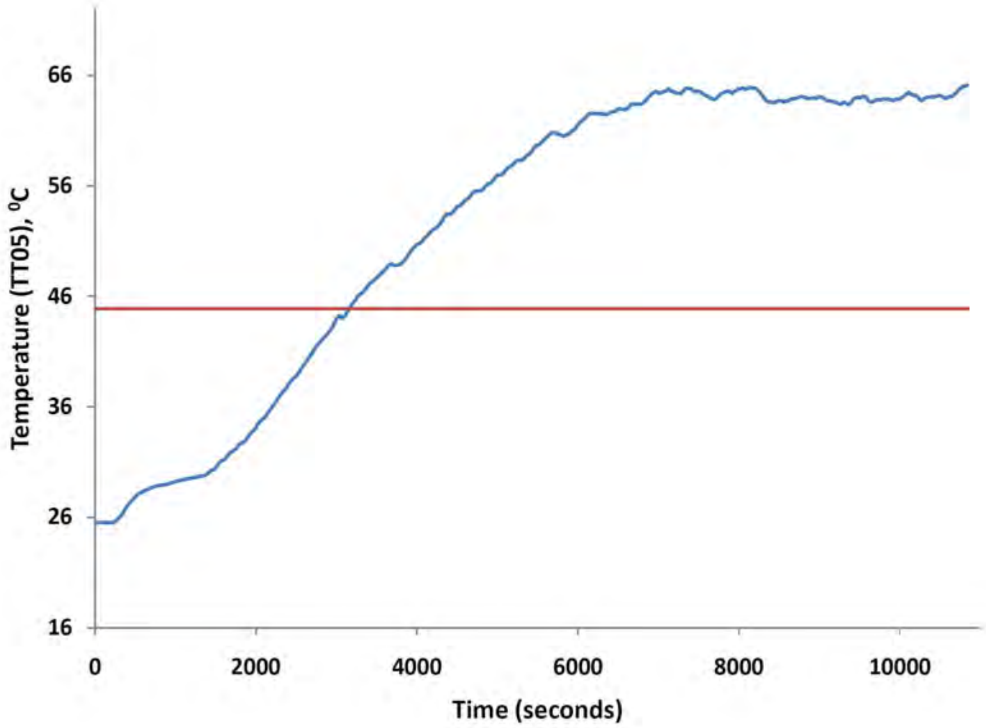
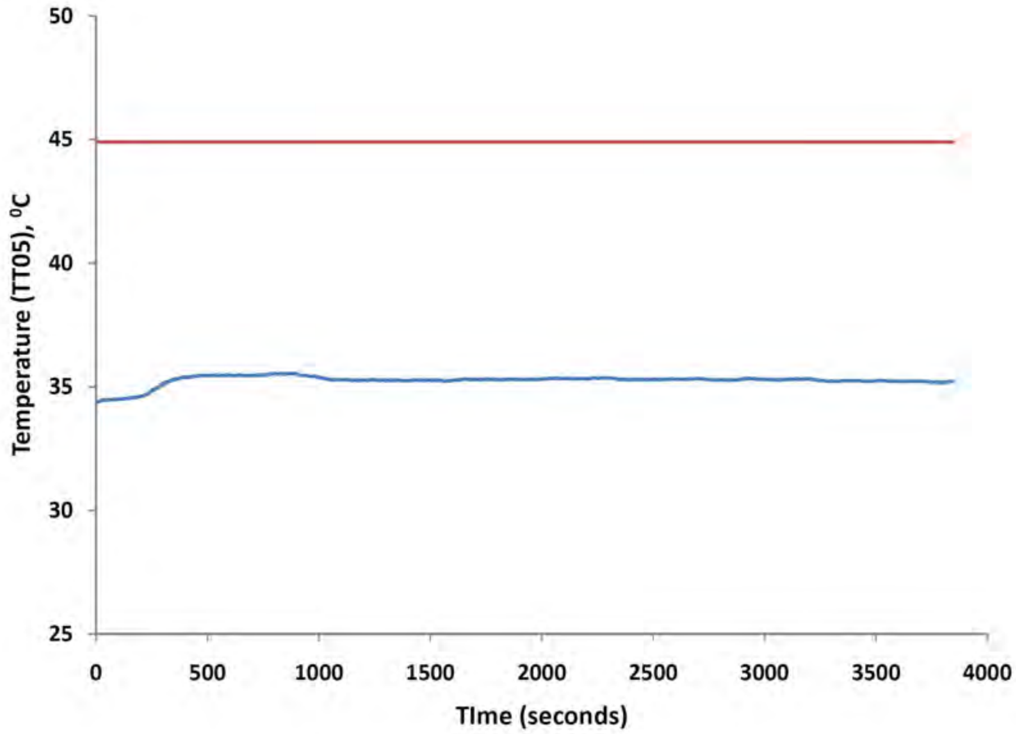


FIGURE 5.12: Comparative disturbance rejection response of proposed MSP with $T_1 = 100, T_2 = 50$ (dashed line) and $T_1 = 150, T_2 = 75$ (solid line)

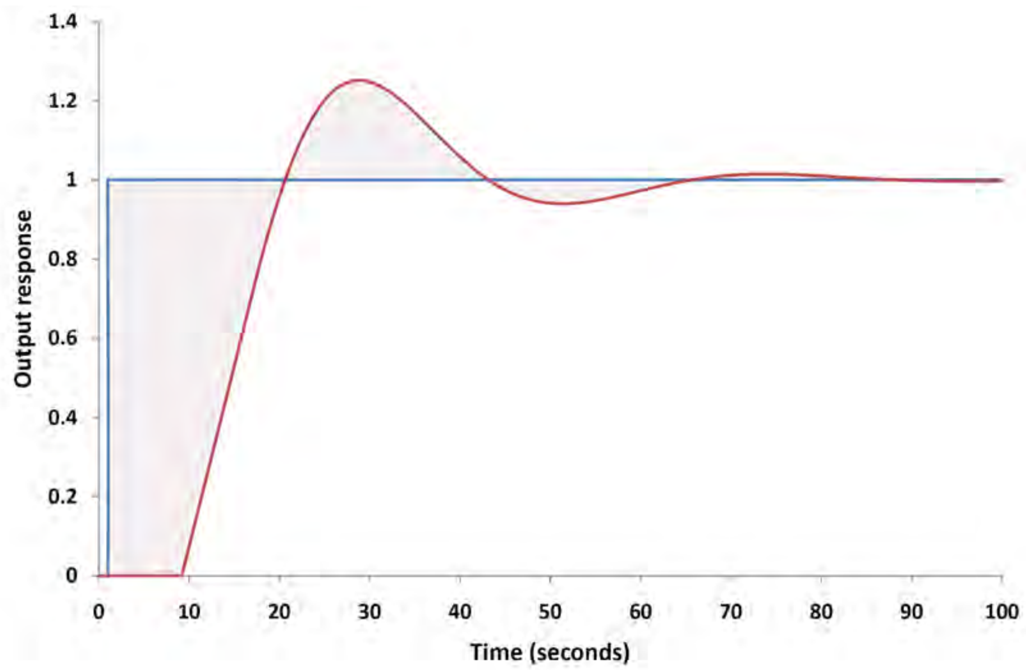


(a) For filter $F_2(s) = \frac{(1020s+1)(208.84s+1)}{(60s+1)^2}$

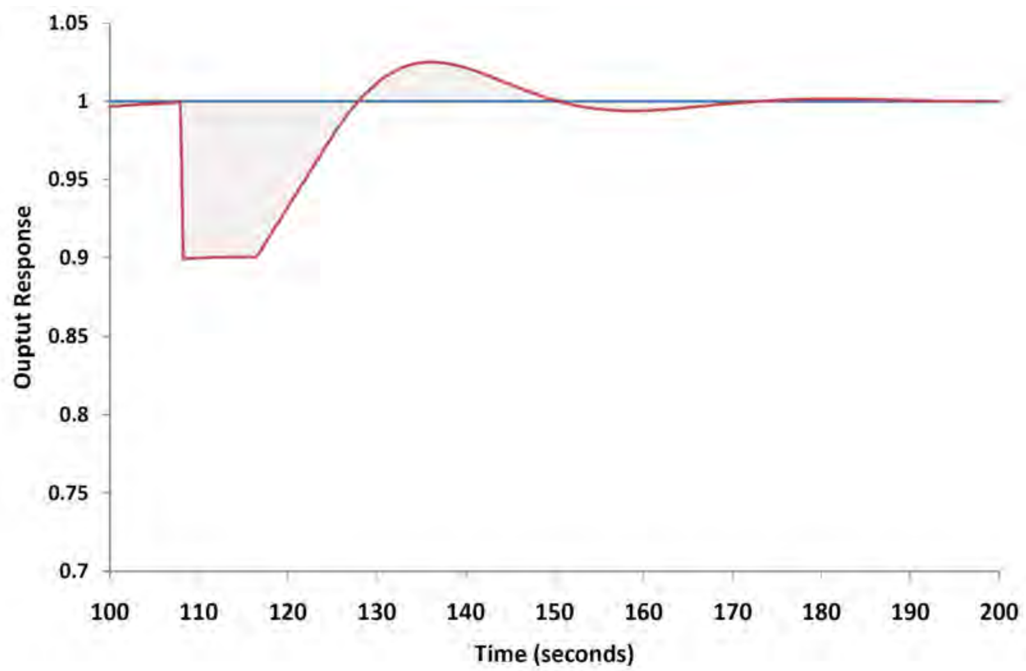


(b) For filter $F_2(s) = \frac{(1020s+1)(217.27s+1)}{(65s+1)^2}$

FIGURE 5.13: Experimental results of Filtered Smith Predictor proposed by [6]



(a) Set-point change



(b) Disturbance change

FIGURE 5.14: Graphical interpretation of IAE

TABLE 5.1: Table for the IAE for TT-04 for set-point change

	Time Span
	2000 seconds
PI Controller	80.27
FSP	-
Proposed MSP ($K_0 = 150 \& K_1 = 75$)	67.93
Proposed MSP ($K_0 = 100 \& K_1 = 50$)	58.66

TABLE 5.2: Table for the IAE for TT-04 for disturbance rejection

	Time Span
	2500 seconds
PI Controller	85.96
FSP	-
Proposed MSP ($K_0 = 150 \& K_1 = 75$)	85.77
Proposed MSP ($K_0 = 100 \& K_1 = 50$)	76.08

5.4.3.1 IAE for TT-04

The Integral of Absolute Error (IAE) of the compensators and PI controller calculated on different range of sample time are listed in Table 5.1 and 5.2 for TT04. The IAE is gradually decreased for the proposed modified Smith Predictor. With the changed parameter the IAE becomes lowest. No IAE is calculated for the FSP proposed by Normey-Rico [6] as it never tracked the set-point. In case of disturbance rejection, the proposed compensators are always better than PI controller by IAE comparison. For the case of tuned MSP, the PI controller was found always inferior for both set-point response and disturbance rejection response.

5.4.3.2 IAE for TT-05

The IAE calculated for the controller and compensators at various conditions for TT05 are listed in Tables 5.3 and 5.4. The set point was changed at 5000 seconds for all cases. In Table 5.3, the value of IAE for 4500 to 8000 seconds reflects the slow response of PI controller and it is almost double the value of IAE of the response obtained for the proposed modified Smith Predictor for the parameter values of $T_1 = 150$ and $T_2 = 75$. The value of IAE for FSP was not calculated

Table 5.3: Table for the IAE for TT05 for set-point change

	Time Span
	3500 seconds
PI Controller	221.39
FSP	-
Proposed MSP ($T_1 = 150 \& T_2 = 75$)	107.98
Proposed MSP ($T_1 = 100 \& T_2 = 50$)	99.47

Table 5.4: Table for the IAE for TT-05 for disturbance rejection

	Time Span
	3500 seconds
PI Controller	-
FSP	-
Proposed MSP ($T_1 = 150 \& T_2 = 75$)	107.41
Proposed MSP ($T_1 = 100 \& T_2 = 50$)	94.47

because the response was not satisfactory and IAE calculation in this case would make no sense. A step type disturbance was introduced in the system at 8890 seconds. The IAE value for disturbance rejection is calculated for the range of 8500-12000 seconds. In case of disturbance rejection, IAE is not calculated for PI controller because the PI controller could not control the process and it became unstable. The proposed compensator shows the best performance in terms of IAE value.

By comparing the performance on both transmitter, the proposed MSP is found to be the best choice for any stable process with dead time.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

A new dead time estimation technique was developed which can detect the dead time from a step test data of a process. The method was formulated on the basis of increasing area under the curve for step response. The technique was easy and found applicable to real processes.

A new dead time compensator which has been proposed by modifying the structure of the well known Smith Predictor [1]. The modified Smith Predictor (MSP) predictor has two filters for providing two degrees of freedom. With this new proposed dead time compensator, the set-point response and disturbance response are isolated. The first filter can monotonically improve the set-point response whereas the second filter can improve the disturbance rejection. The modified Smith Predictor has the following properties -

- It is applicable to any stable process.
- It requires the same amount of effort as a standard PI controller needs for its IMC design. Then it can be tuned to have better performance.

- It can handle uncertainties in process modeling and dead time estimation up to a certain degree.
- It outperforms the most recently developed dead time compensator proposed by Normey-Rico and Camacho [6].
- It is tested on a real process containing two tank heating system to evaluate its applicability.

The performance of the newly proposed modified Smith Predictor (MSP) was measured and compared by calculating the Integral of Absolute Error (IAE). IAE values showed that new modified Smith Predictor had the lowest value than the standard PI controller and the dead time compensator proposed by Normey-Rico and Camacho [6].

Both in simulation and practical implementation, the new dead time compensator was successful in demonstrating its utility and practicality.

6.2 Recommendations for Future Work

- The experimental studies were done on a pilot scale process with relatively large time constant compared to the dead time. The new dead time compensator can be evaluated on a process with small time constant with large dead time.
- The dead time compensation method can be extended for integrating and unstable processes.

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