DESIGN OF INTERNAL MODEL CONTROL AND INTERNAL MODEL FEED-FORWARD CONTROL FOR LIQUID LEVEL SYSTEM

Thesis submitted in partial fulfillment of the requirements for the degree of

Master of Technology

In

Electronics &Instrumentation Engineering

By

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CERTIFICATE

This is to certify that the thesis report titled **"DESIGN OF INTERNAL MODEL CONTROL AND INTERNAL MODEL FEED-FORWARD CONTROL FOR A LIQUID LEVEL SYSTEM"** Submitted by **Mr. Rohit Singh (**Roll No: 213EC3230) in partial fulfillment of the requirements for the award of Master of Technology in the Electronics and Communication Engineering with specialization in **"Electronics and Instrumentation Engineering"** during Session 2013-2015 at National Institute of Technology, Rourkela and is an authentic work carried out by him under my supervision and guidance.

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ABSTRACT

This project is concerned with the study of liquid level system and designing Internal Model Control (IMC) and Internal Model-Feed-Forward Control (IMC-FF) for this system. Liquid Level System has various configurations such as: Single Tank System, Two-Tank Interacting and Non-Interacting System, Three-Tank Non-Interacting System. In this project IMC and IMC-FF are designed for all these configurations and the responses of these controllers are compared with PID, PID plus Feed-Forward controllers. After comparison it is found that for first order system (single tank system) there is not much difference between IMC and IMC-FF but for higher order systems (two-tank interacting, two –tank non-interacting, three-tank non-interacting system) IMC-FF performs better than IMC. PID and PID plus Feed-Forward performance are not good enough as compared to IMC and IMC-FF. PID plus Feed-Forward perform better than PID in case of negative disturbances but if the disturbances are positive the performance of PID is better than PID plus Feed-Forward.

At the end of the project empirical formulae are derived for rise time, settling time, percentage overshoot and peak time. When desired values of these performance indices have to be obtained these formulae are used to evaluate the filter coefficient for IMC-FF. Once the filter coefficient is known, IMC-FF can be designed very easily.

The software used for the simulation purpose is MATLAB and for mathematical modeling, a practical set up of four tank system is used.

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ACRONYMS

IMC	Internal Model Control
IMC-FF	Internal Model Feed-Forward Control
PID	Proportional Integral Derivative
DAQ	Data Acquisition

CHAPTER-1
INTRODUCTION

1.1 LITERATURE SURVEY

1.2 OBJECTIVE

1.3 THESIS OUTLINE

1.1 Literature Survey

B. Wayne Bequette has proposed a method of designing Internal Model Controller (IMC) for various processes such as Boiler drum, Furnace system, Isothermal Chemical Reactor etc. He has proposed Feed-Forward control strategy for rejecting major disturbance. At last he has combined the Feed-Forward Control strategy with the IMC resulting in Internal Model Feed-Forward Controller which has the quality good set-point tracking as well as better disturbance rejection. He has also suggested an algorithm by which IMC controller can be deduced in equivalent feedback form.

Surekha Bhanot has proposed the mathematical modeling of Liquid Level System. Liquid Level System consists of various configurations like Non-interacting and Interacting systems. She has proposed the mathematical modeling of both the system as well as the modeling of the system having non-linear resistance elements.

Singh Ashish Kumar, Sandeep Kumar have proposed the mathematical modeling of Three tank Interacting and Non Interacting Level control system. They have also compared the performance of Feedback and Feed-Forward plus Feedback controllers.

Mishra, Rakesh Kumar, and Tarun Kumar Dan have proposed an algorithm for designing of Internal Model Control for distillation column. They have also proposed a strategy called "Gamma-Correction" to improve the disturbance rejection in distillation column.

Zhong, Hua, Lucy Pao, and Raymond de Callafon has suggested an algorithm for designing the Feed-Forward Controller. They have also suggested effect of model matching and mismatching in IMC controller.

Coleman Brosilow and Babu Joseph have proposed one-Degree of freedom and Two-Degree of freedom IMC controllers.They have proposed an algorithm for designing Feed-Forward control for various uncertain processes.

1.2 Objective

The objective of this thesis is to design IMC and IMCFF for various configurations of Liquid Level Systems. These configurations include Single Tank, Two-Tank Interacting, Two-tank

Non-Interacting and Three-Tank Non-Interacting System. This thesis aims to suggest an algorithm for tuning IMCFF to achieve good set-point tracking and better disturbance rejection.

1.3 Thesis Outline

This thesis has 5 chapters. After the Chapter-1 Introduction, there are four more chapter which are described here under:

Chapter 2 Mathematical Modeling of Liquid Level System

This chapter gives the basic idea of the mathematical modeling. This chapter mainly focuses on the mathematical modeling of Liquid Level System for various configurations such single tank system, Two-Tank Non-Interacting, Two-Tank Interacting and Three-Tank Non-Interacting systems.

Chapter 3 Internal Model Controller

This chapter gives the algorithm for designing IMC controller. This chapter also focuses on the tuning of IMC controller to achieve good set-point tracking and better disturbance rejection.

.

Chapter 4 Internal Model Feed-Forward Controller

This chapter focuses on basic structure of Feed-Forward controller and design of Internal Model Feed-Forward Controller. Various Simulation results concerned with IMCFF are incorporated in this chapter.

Chapter 5 Conclusion

This chapter focuses on the various results of the thesis and deduces the key-points of IMC and IMCFF.

CHAPTER-2
MATHEMATICAL MODELING

3.1 INTRODUCTION

3.2 TYPES OF MATHEMATICAL MODELIN

3.3 USE OF MATHEMATICAL MODELING

3.4 LIQUID LEVEL SYSTEM

3.5 MATHEMATICAL MODELING OF LIQUID LEVEL SYSTEM

3.6 OBSERVATIONS AND EXPERIMENTAL RESULTS

2.1 INTRODUCTION

Before controlling a process, the behavior of the process needs to be understood i.e. how the output of the process is affected by the disturbances and manipulated variables. Quite often the process is not available so experiments cannot be performed to investigate how the process output is changing with respect to various inputs. Sometimes even if the process is available the experiments cannot be performed because the procedure is very costly. In all above cases a simple description of the process is needed which is provided by the mathematical model.

A mathematical model describes the various characteristics of the process. Generally, with the help of Mathematical modeling a process is represented by a set of Mathematical equations. This theoretical approach has become very popular now a days because it offers the possibility of understanding the behavior of the process under various conditions without tampering with the actual experimental setup.

Due to various practical reasons, it is always desirable that the mathematical model of the process should be as simple as possible. For making the mathematical model simple various assumptions are made. For example, often it is assumed that the density of the liquid is constant in the liquid level system and the liquid is incompressible.

A key-point that is need to be remembered that the mathematical model is just an approximation of the process because deriving an exact mathematical model is very difficult.

2.2 TYPES OF MATHEMATICAL MODELING

There are generally three types of models used in process control:

a) Theoretical models
b) Empirical models
c) Semi-empirical models

In Theoretical models material, energy and momentum balance equations are used. They do not need experimental data but for verification experimental data can be used.

There are some processes for which mathematical modeling cannot be done because it is very complex. But the data obtained from the experimental set-up can be fitted into a mathematical equation called empirical equation.

In Semi-empirical models the combined approach of theoretical and empirical models is used. The material, energy and momentum balance equations are for deriving mathematical model and empirical model is used for calculating some process constants such as reaction rate of chemical reaction, heat transfer coefficient in heat exchanger.

2.3 USES OF MATHEMATICAL MODELING

Mathematical modeling is used very frequently in process control. Some of the important uses of mathematical modeling are:

a) Mathematical model helps to understand the process very clearly without carrying out the expensive experiments.
b) Mathematical model can be used to determine the best operating conditions for the actual process.
c) Mathematical model is to design the controller for the process. Control strategies like Model-Predictive control can be used to determine the best mathematical model for the process.
d) Mathematical model can be used to train the operator to deal with the complex processes and emergency situations.

2.4 LIQUID LEVEL SYSTEM

Liquid level systems are composed of tanks filled with liquid and connected through pipes, tubes or any other flow restricting device like orifice, control valve etc.

Liquid level system can be analyzed with the help of fundamental laws governing the flow of liquids. Suppose there is a tank in which the fluid is entering with the rate Q_i (cm^3/sec) and leaving the tank with the rate Q (cm^3/sec). The height of the liquid in the tank is H (cm). If the valve remains open to the same extent throughout the process the outlet flow rate of the tank will be constant. But if the opening of valve is varied and the inlet flow rate is constant, the height of the fluid in the tank will increase or decrease accordingly.

There are two types of flow in liquid level system:

a) Laminar flow
b) Turbulent flow

For Laminar flow the Reynolds number should be less than 2100 and for turbulent flow it should be greater than 4000.

Figure 2.1 shows a Four tank liquid level system which is interfaced with Data Acquisition System. This figure represents the experimental set-up that is used for generating results throughout this thesis.

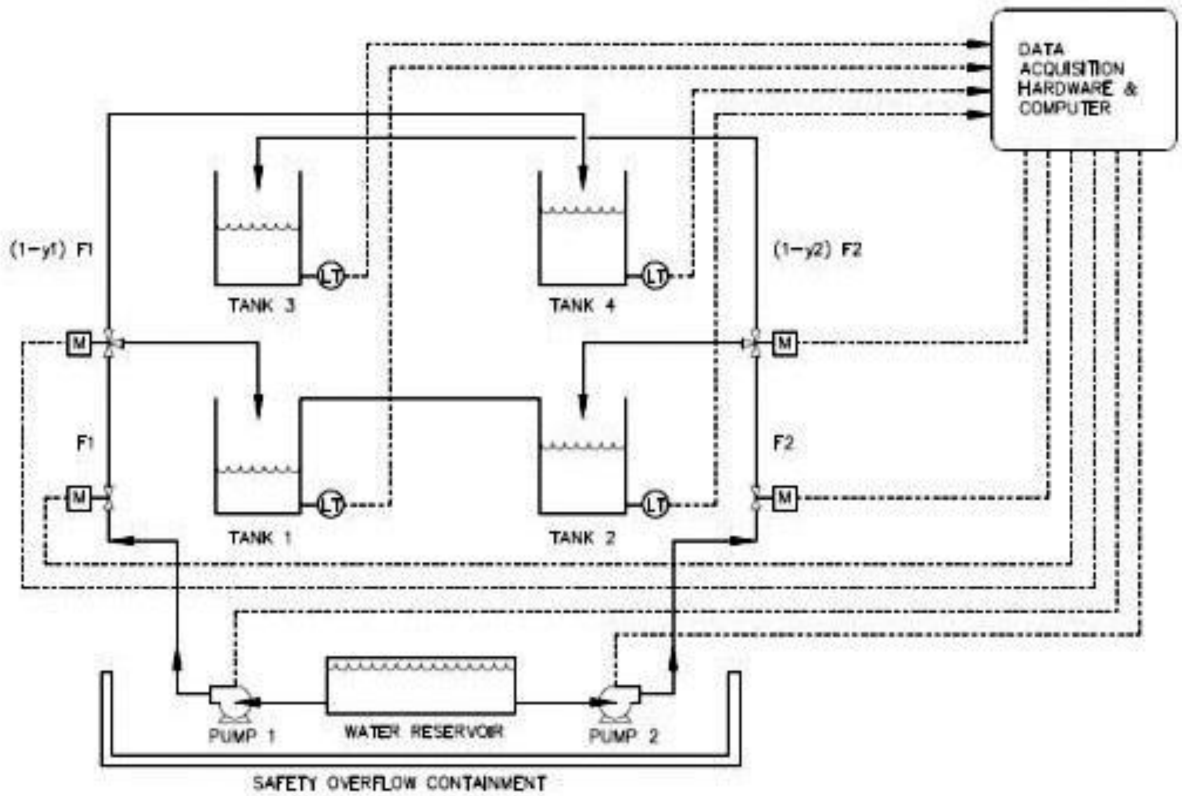

Figure 2.1 a Four Tank Liquid Level System

2.5 MATHEMATICAL MODELING OF LIQUID LEVEL SYSTEM

2.5.1 Mathematical Modeling of a Single Tank System

The schematic diagram of a single tank system is shown in Figure 2.2.

Mass-Balance equation is given as:

$$Q_i - Q = A\frac{dH}{dt} \tag{2.1}$$

Where,

Q_i = Inlet flow rate (cm^3/sec)

Q = Outlet flow rate (cm^3/sec)

A = Area of the tank (cm^2)

H = Height of the liquid in tank (cm)

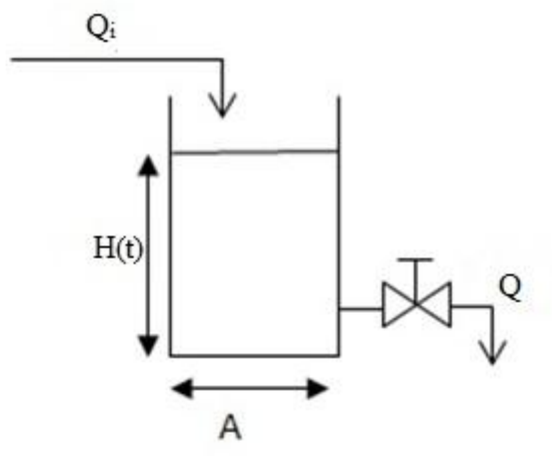

Figure 2.2 Single Tank Liquid Level System

Valve Equation can be written as:

$$Q = K\sqrt{H} \tag{2.2}$$

Apply Taylor's theorem to linearize this equation about steady state height H_s

$$A\frac{dH}{dt} = Q_i - K\left(\sqrt{H_s} + 0.5\frac{H - H_s}{\sqrt{H}}\right) \tag{2.3}$$

At Steady State

$$A\frac{dH_s}{dt} = Q_{is} - K\sqrt{H_s} \tag{2.4}$$

On subtracting equation (2.3) from (2.4)

$$A\frac{dh}{dt} = q_i - 0.5K\frac{\sqrt{H}}{\sqrt{H_s}} \tag{2.5}$$

Where,
$q_i = Q_i - Q_{is}$
$h = H - H_s$
On taking Laplace transform of (2.5)

$$\frac{H(s)}{Q_i(s)} = \frac{R}{\tau s + 1} \tag{2.6}$$

Where,

$$R = \frac{2\sqrt{H_s}}{K}$$

$$\tau = \frac{2A\sqrt{H_s}}{K}$$

2.5.2 Mathematical Modeling of Two-Tank Non-Interacting System

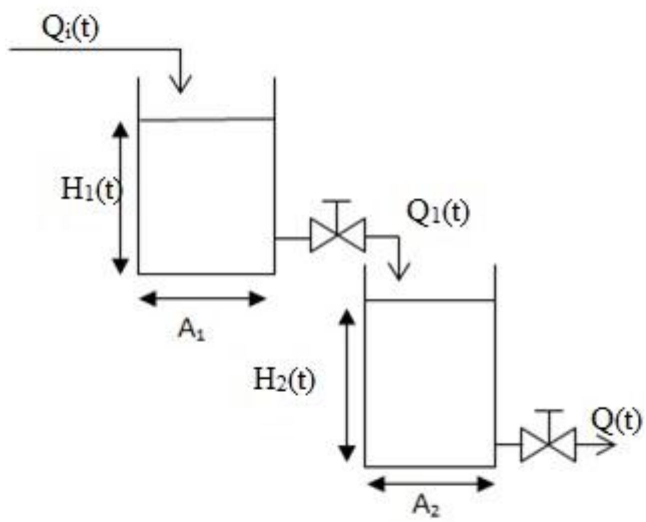

Figure 2.3 Two Tank Non-Interacting Liquid Level System

With the help of equation (2.6), the transfer function of tank 1 can be written as:

$$\frac{H_1(s)}{Q_i(s)} = \frac{R_1}{\tau_1 s + 1} \tag{2.7}$$

Similarly, the transfer function of the second tank can be written as:

$$\frac{H_2(s)}{Q_1(s)} = \frac{R_2}{\tau_2 s + 1} \tag{2.8}$$

By combining equation (2.7) and (2.8)

$$\frac{H_2(s)}{Q_i(s)} = \frac{R_2}{(\tau_1 s + 1)(\tau_2 s + 1)} \tag{2.9}$$

2.5.3 Mathematical Modeling of Two-Tank Interacting System

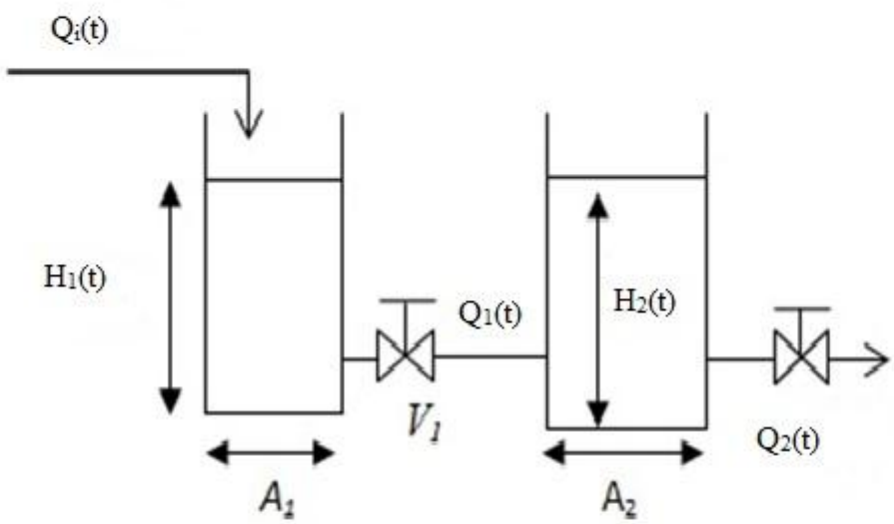

Figure 2.4 Two Tanks Interacting Liquid Level System

Mass balance equation for the first tank will be:

$$Q_i - Q_1 = A_1 \frac{dH_1}{dt} \tag{2.10}$$

Mass balance equation for the second tank will be:

$$Q_1 - Q_2 = A_2 \frac{dH_2}{dt} \tag{2.11}$$

$$Q_1 = \frac{H_1 - H_2}{R_1} \tag{2.12}$$

$$Q_2 = \frac{H_2}{R_2} \tag{2.13}$$

On solving the above equations

$$\frac{H_2(s)}{F_i(s)} = \frac{R_2}{(\tau_1\tau_2 s^2 + \tau_1 s + \tau_2 s + A_1 R_2 s + 1)} \tag{2.14}$$

2.5.4 Mathematical Modeling of Three-Tank Non-Interacting System

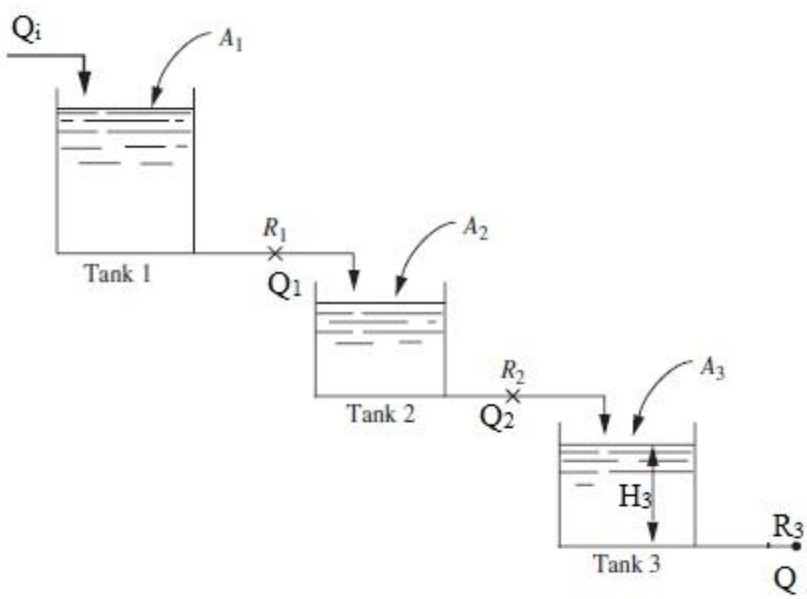

Figure 2.5 Three Tanks Non-Interacting Liquid Level System

Mass Balance equation for the tank 1 will be:

$$A_1 \frac{dH_1}{dt} = Q_i(t) - Q_1(t) \tag{2.15}$$

Valve relation is given by:

$$Q_1\,(t) = \frac{H_1}{R_1} \tag{2.16}$$

Mass Balance equation for the tank 2 will be:

$$A_2 \frac{dH_2}{dt} = Q_1(t) - Q_2(t) \tag{2.17}$$

Valve relation is given by:

$$Q_2(t) = \frac{H_2}{R_2} \tag{2.18}$$

Mass Balance equation for the tank 3 will be:

$$A_3 \frac{dH_3}{dt} = Q_2(t) - Q_3(t) \tag{2.19}$$

Valve relation is given by:

$$Q_3(t) = \frac{H_3}{R_3} \tag{2.19}$$

The overall transfer function of three tank non-interacting system can be given with the help of equation (2.15) to equation (2.19):

$$\frac{H_3(s)}{Q_i(s)} = \frac{R_3}{(\tau_1 s + 1)(\tau_2 s + 1)\,(\tau_3 s + 1)} \tag{2.20}$$

2.6 OBSERVATIONS AND PRACTICAL RESULTS

A number of experiments are performed for calculating the transfer function of a single tank system on a four tank liquid level system. The observations are given in the following table:

Flow(cm^3/sec)	Height(cm)
97.2	49.5
91.6	40.7
86.1	32.4
80.5	26.1
75.0	19.4
69.4	13.3
63.8	7.3
58.3	2.7
52.7	1.0

Table 2.1 Flow and corresponding Height

There are two main constraints that has been imposed while performing experiments:

a) The height of liquid in tank is restricted unto 55 cm.

b) The manipulated variable is 200 cm^3/sec.

With the help of the Table 2.1 the transfer functions for a single tank system for various ranges are calculated. These transfer functions are listed in Table 2.2

Flow(cm^3/sec)	Height(cm)	Transfer Function
97.2	49.1	$\frac{1.9}{334s+1}$
91.6	40.3	$\frac{1.8}{306s+1}$
86.1	32.6	$\frac{1.572}{277s+1}$
80.5	25.4	$\frac{1.4}{248s+1}$
75.0	18.6	$\frac{1.2}{216s+1}$
69.4	13.1	$\frac{1.05}{184s+1}$
63.8	7.2	$\frac{0.75}{144s+1}$
58.3	2.2	$\frac{0.50}{90s+1}$
52.7	1.0	$\frac{0.30}{54s+1}$

Table 2.2 Transfer Functions

Various other parameters of the tank are listed below:

a) Area of the tank is 176 $cm^{2.}$

b) Height of the tank is 55 cm.

c) Flow range is from 20 to 200 cm^3/sec.

CHAPTER-3
INTERNAL MODEL CONTROL

3.1 INTRODUCTION

3.2 ALGORITHM FOR DESIGNING IMC

3.3 TUNING OF IMC

3.4 SIMULATION RESULTS

3.1 INTRODUCTION

In the classical process control system generally feedback configuration is used for controlling the process and PID controller was used. It has following advantages:

a) It reduces the sensitivity due to system parameter variation.

b) It compensates for external disturbances.

c) It improves the time response of the system by reducing the time constant.

d) It increases the bandwidth of the system

On the other hand, it has various disadvantages. It can affect the stability of the system. It can introduce the oscillations in the closed loop response of the system.

In the advanced process control era model based controllers are used extensively. These controllers have various advantages to offer over conventional PID controller. IMC is one of them. In IMC a process model is used which receives same manipulated variable signal as the actual process. It can be observed in the figure 3.1:

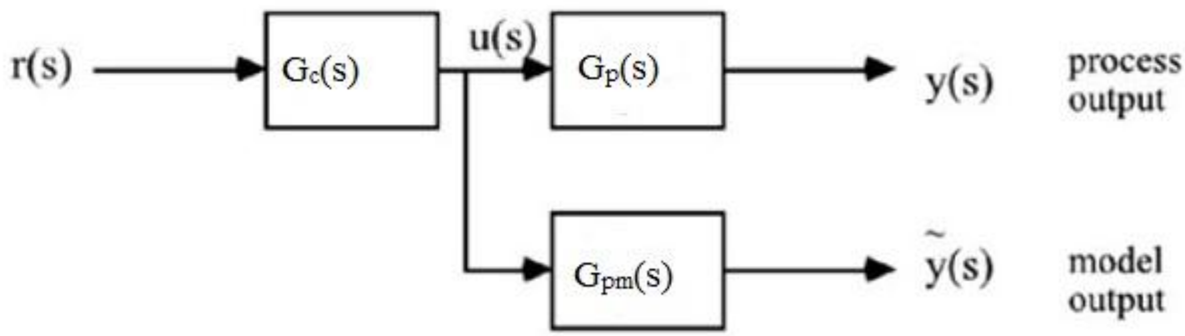

Figure 3.1 Basic IMC System

Where,

$G_c(s)$ = IMC controller

$G_P(s)$ = Actual process

$G_{Pm}(s)$ = Process model

r(s) = Set-point

u(s) = Manipulated variable

d(s) = Disturbance

y(s) = Process output

The output obtained from actual process and process model can be utilized to remove model uncertainty. This makes the IMC a feedback system. It can be seen in figure 3.2:

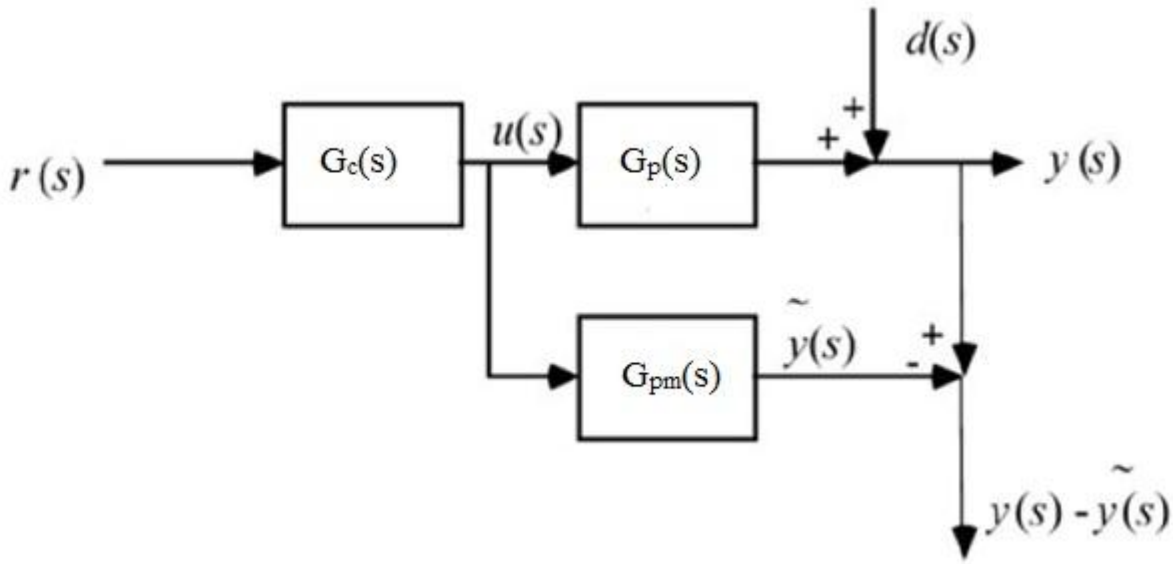

Figure 3.2 IMC System showing model-error

The biggest advantage of IMC is that it has a transparent frame-work for controller designing and tuning. The IMC system can be easily represented in the form of standard feedback structure and this feedback structure can be easily converted into PID controller. This is amazing because there are various algorithms and equipment available to realize PID controller. It can be seen in figure 3.3:

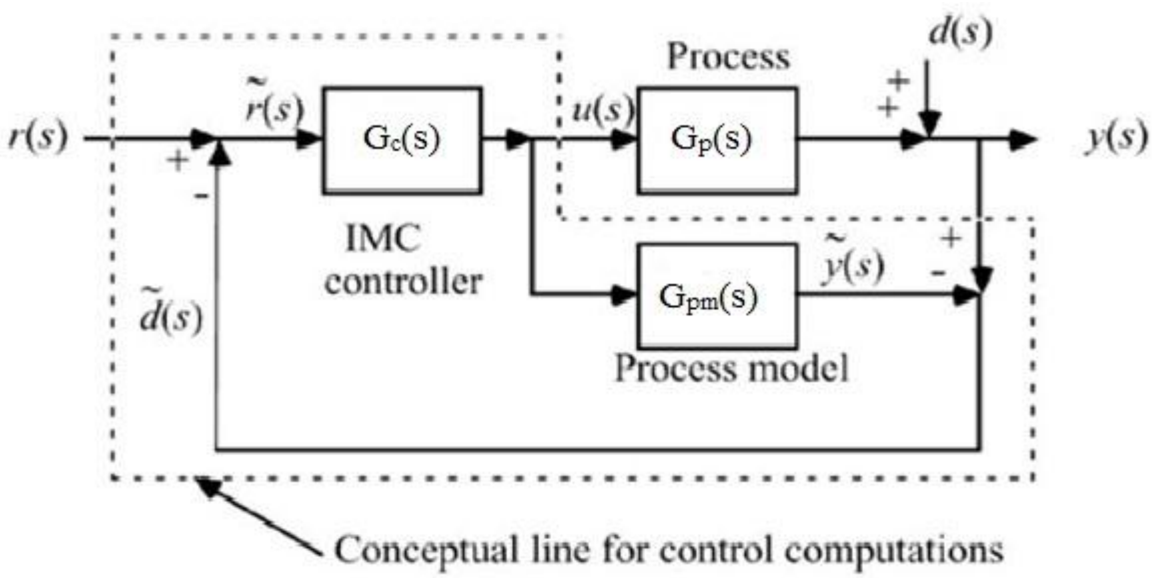

Figure 3.3 Feedback structure of the IMC

In IMC if the controller and the process are stable, the overall system is stable. This is because if two stable transfer functions are cascaded together then the stability of the combination is guaranteed. But this is not the case if PID is used. If PID controller and the process both are stable then the overall system can be unstable. So it is one of the advantages of IMC over PID. The main restriction of IMC is that the process should be stable.

3.2 ALGORITHM FOR DESIGNING IMC

Algorithm for designing IMC consists of the following steps:

a) Factorize the process model transfer function into invertible and non-invertible elements. Invertible elements are those elements that upon inverting results in a stable elements. Non-invertible elements result in unstable elements upon inverting like time delay, zeros located in right half of s-plane. This step is done to make the controller stable.

$$\mathrm{G_{pm}(s) = G_{p+}(s)G_{p-}(s)} \tag{3.1}$$

Where,

$G_{p+}(s)$ = the non-invertible element

$G_{p-}(s)$ = the invertible element

b) IMC controller transfer function will be inverse of $G_{p-}(s)$:

$$\mathrm{G_{c1}(s)} = \frac{1}{G_{p-}(s)} \tag{3.2}$$

Where,

$G_{c1}(s)$ = Ideal IMC controller

c) Now a filter transfer function is added to make the IMC controller transfer function proper. A transfer function is said to be proper if the order of the denominator is at least as high as the order of numerator.

$$\mathrm{G_c(s) = G_{c1}(s)\,G_{c2}(s)} \tag{3.3}$$

Where,

$$\mathrm{G_{c2}(s)} = \frac{1}{(\lambda s + 1)^{n}} \tag{3.4}$$

$G_{c2}(s)$ is a filter transfer function. This filter transfer function is used if set-point tracking is more important and n is selected to make the controller transfer function proper or semi-proper.

d) Now the tuning parameter λ is varied to achieve the desired speed of response. If λ is very small, the closed loop system will be very fast. If λ is large, the closed loop system will be immune to model uncertainties.

3.3 TUNING OF IMC

For tuning of IMC there are no prescribed rules like Ziegler-Nicholas. Tuning of IMC is done by hit and trial method which is given below:

a) Vary the filter coefficient λ and generate a number of responses for set-point tracking, disturbance-rejection and manipulated variable.

b) Identify for which value of λ the responses are violating the physical constraints.

c) Choose that value of λ for which all the responses are within prescribed limit. This is the optimal value of λ.

3.4 SIMULATION RESULTS

3.4.1Two-Tank Non-Interacting system

For single tank system, the transfer function obtained in the range of 30-40 cm height of liquid is:

$$\frac{1.572}{277s+1} \tag{3.5}$$

So for the two-tank non-interacting system the overall transfer function will be:

$$\mathrm{G_p(s)} = \frac{1.572}{76729s^2+554s+1} \tag{3.6}$$

The controller transfer function can be given as:

$$\mathrm{G_c(s)} = 0.83\,\frac{67600\mathrm{s}^2+520\mathrm{s}+1}{(\lambda \mathrm{s}+1)^2} \tag{3.7}$$

3.4.1.1Disturbance Variation and Set-Point Tracking

The disturbance used in two tank non-interacting system has the following transfer function and is additive in nature. It means that a certain amount of liquid is adding continuously in first tank. The set-point is taken as 10 cm.

$$G_d(s) = \frac{1.0}{27s + 1} \tag{3.8}$$

If the various set-point values for disturbance are taken as 5, 10,-5,-10 and 0 then the response of IMC controller to these varying disturbances is shown in figure 3.4. The IMC controller transfer function can be given as:

$$G_c(s) = 0.83\frac{67600s^2 + 520s + 1}{2500s^2 + 100s + 1} \tag{3.9}$$

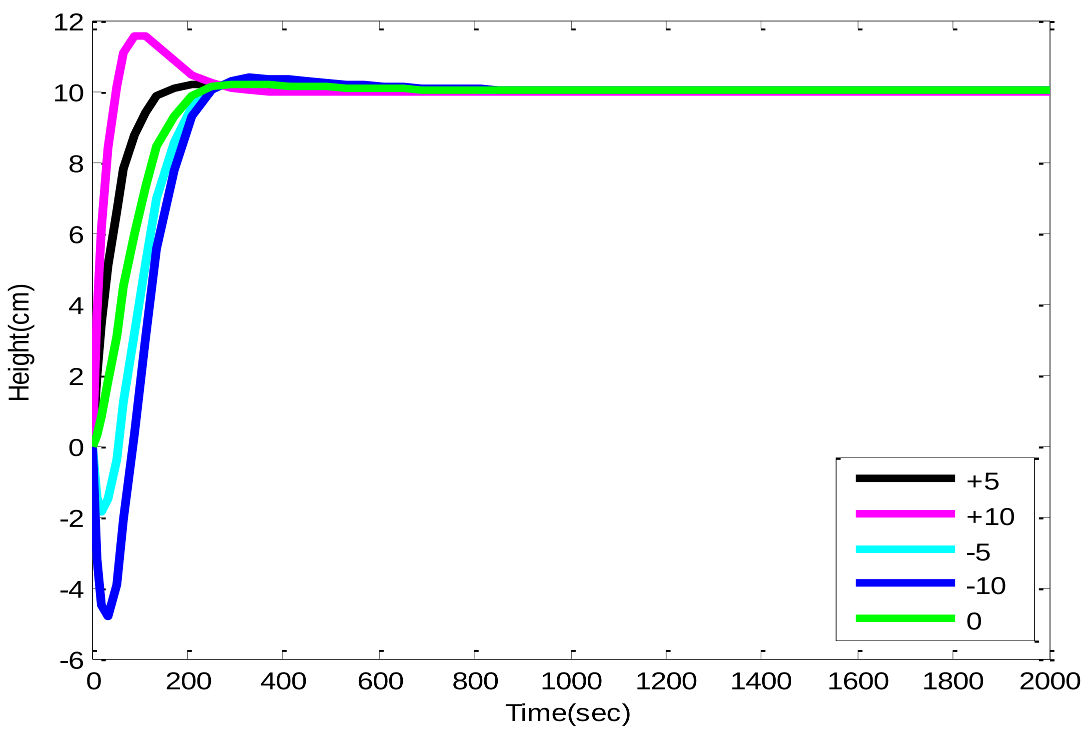

Figure 3.4 Set-point tracking with varying disturbance

3.4.1.2 VARIATION OF FILTER COEFFICIENT

If filter coefficient (λ) is varied as 30, 50,100 and 120 then it was observed that as the value of filter coefficient (λ) increase, response becomes sluggish. But as the filter coefficient (λ) increases, response becomes more immune to external disturbance. It can be observed in figure 3.5. As it is said in section 3.3 that for tuning the IMC controller, filter coefficient (λ) is varied and it is checked that for which value of filter coefficient (λ) the physical constraints are more satisfied. So for tuning purpose manipulated variable and first tank response have been plotted against time for various values of λ which are shown in figure 3.6, figure 3.7 and figure 3.8.

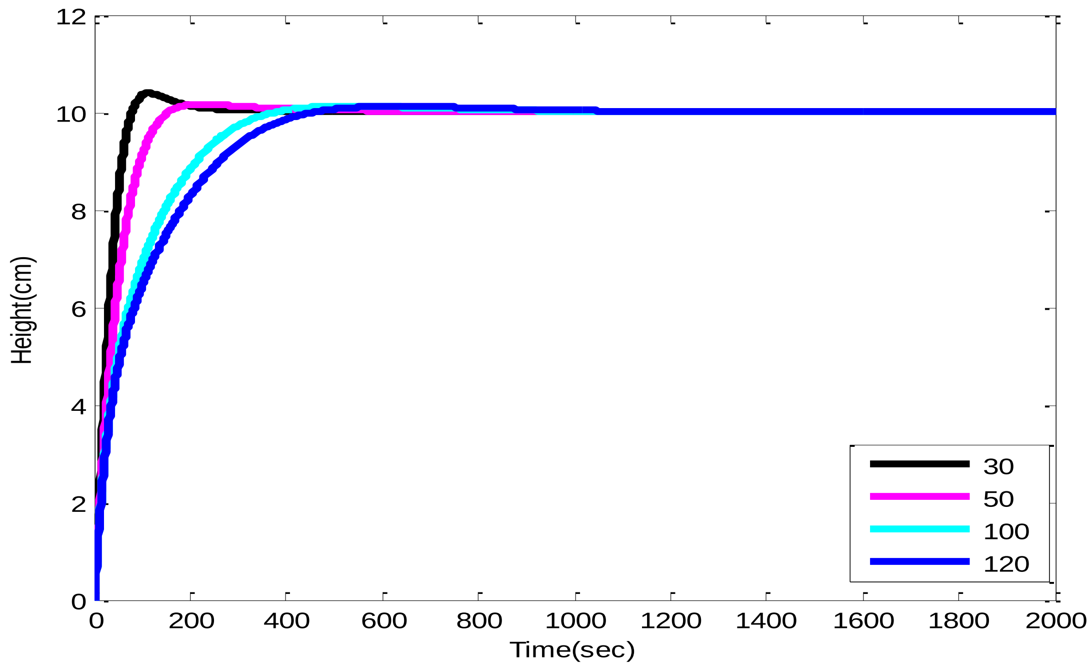

Figure 3.5 Effect of filter coefficient variation on primary tank

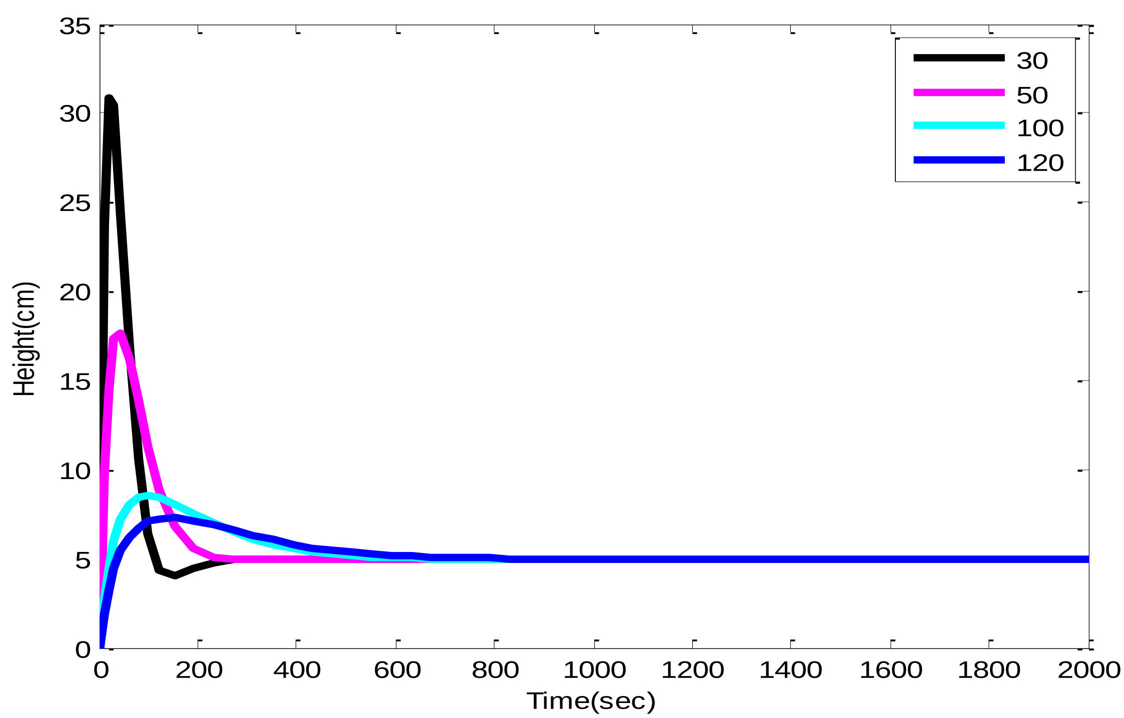

Figure 3.6 Effect of filter coefficient variation on secondary tank

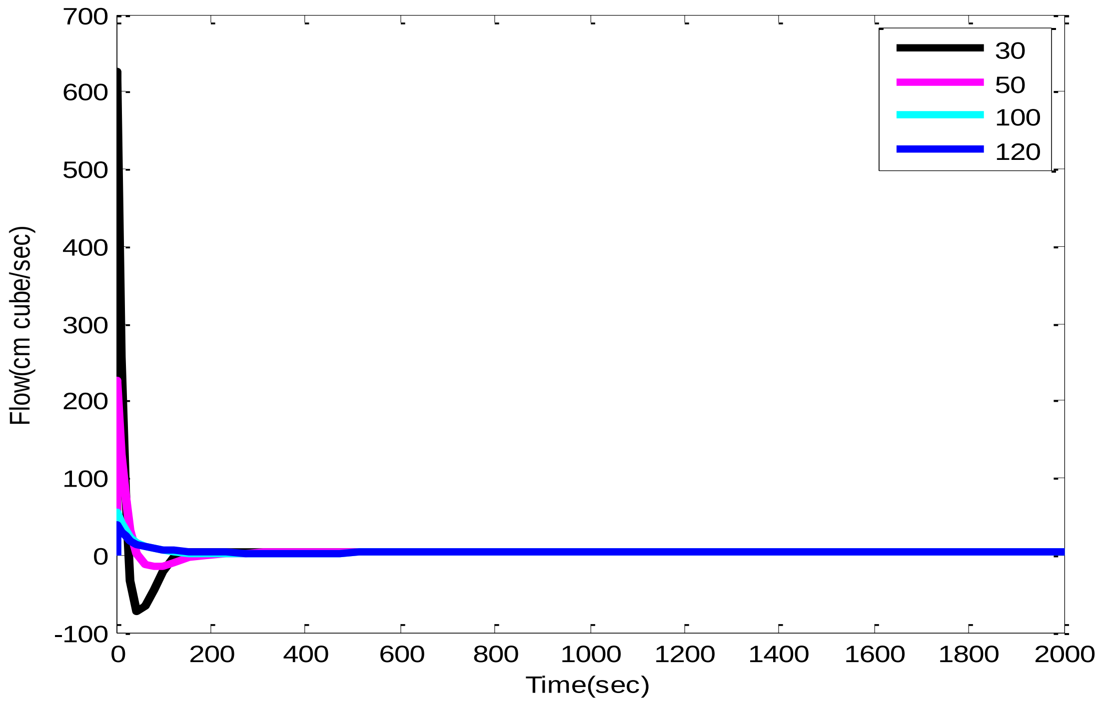

Figure 3.7 Effect of filter coefficient variation on manipulated variable

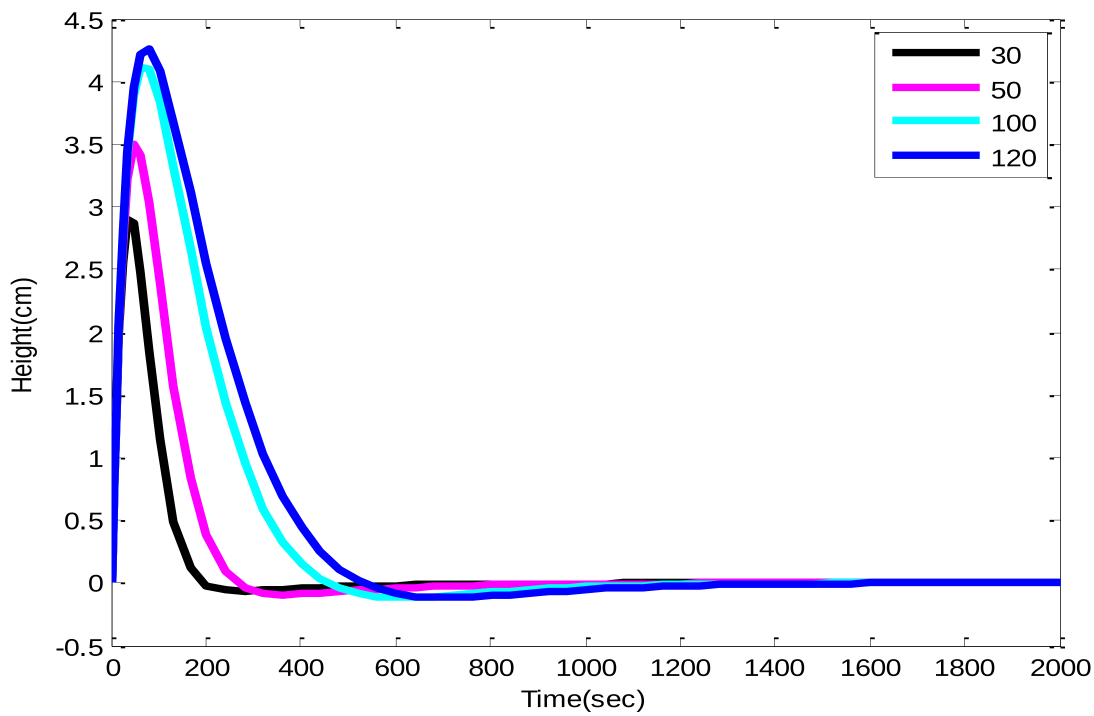

Figure 3.8 Effect of filter coefficient variation in disturbance rejection

In figure 3.3 it can be observed that λ = 30 and 50 both are having fast primary tank response while λ = 100 and 120 are having sluggish response. But for λ = 30 the value of manipulated variable is going above 600 cm^3/sec (figure 3.7) so λ= 30 is rejected. Therefore the optimal value of filter coefficient (λ) for two-tank non-interacting system is 50. From figure 3.8 it is clear that at λ = 50 IMC is rejecting the disturbance nicely.

For each value of λ various performance indices like rise time, settling time, overshoot and peak time are listed in Table 3.1. It is also evident from table that λ= 50 is the best possible value of λ for two tank non-interacting system considered here.

	λ=30	λ=50	λ=100	λ=120
Rise Time(sec)	52	90	206	254
Settling time(sec)	177	135	318	387
Percentage Overshoot	3.95	1.68	1.28	1.25
Peak time(sec)	116	226	530	633

Table 3.1 Comparison of performance indices for various filter coefficients for non- interacting tank system

3.4.2Two-Tank Interacting system

In two- tank interacting system the transfer function of the single tank is given by equation by 3.5 but the overall transfer function is given as:

$$G_p(s) = \frac{1.572}{76729s^2 + 831s + 1} \tag{3.10}$$

The transfer function of the controller can be given as:

$$\mathrm{G_c(s)} = 0.83\frac{76000s^2 + 800s + 1}{(\lambda s + 1)^2} \tag{3.11}$$

3.4.2.1Disturbance Variation and Set-Point Tracking

The disturbance used in two-tank interacting system is same as two-tank non-interacting system given by equation 3.8. The set-point is taken as 10 cm and various values for disturbance set-point are +5,+10,-5,-10 and 0. The controller transfer function will be:

$$\mathrm{G_c(s)} = 0.83\frac{76000s^2 + 800s + 1}{2500s^2 + 100s + 1} \tag{3.12}$$

The response of the IMC to these varying disturbances is shown in figure 3.9.

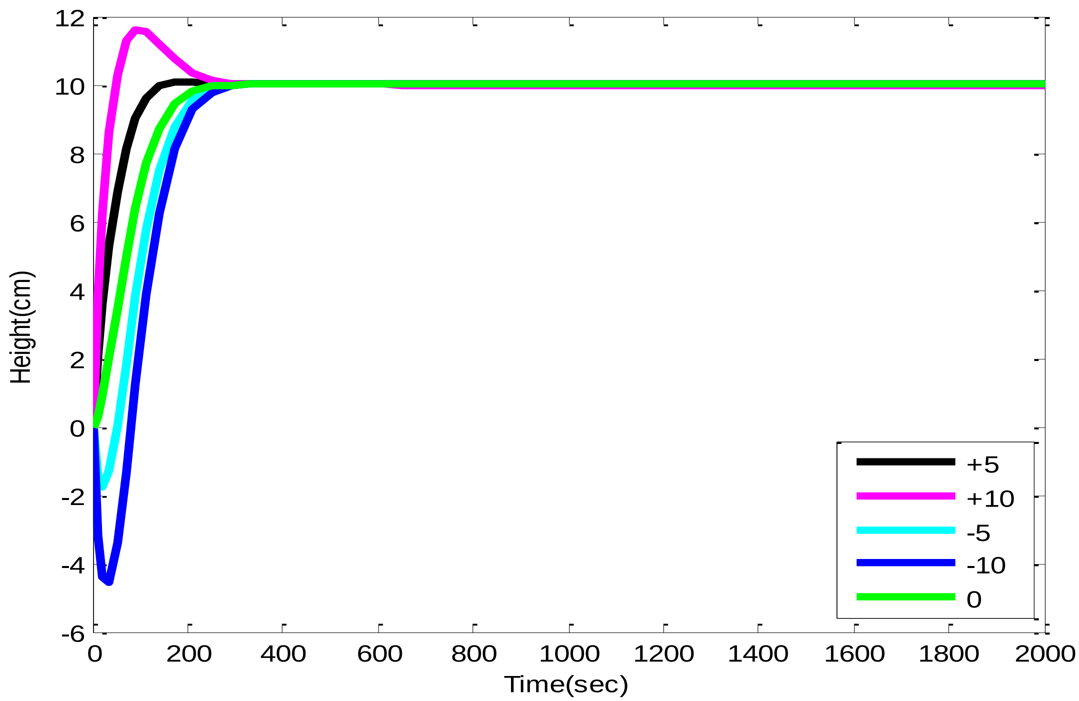

Figure 3.9 Set-point tracking with varying disturbance

3.4.2.2 VARIATION OF FILTER COEFFICIENT

In two-tank interacting system also, the filter coefficient λ is varied to monitor the variation of primary tank response, manipulated variable and secondary tank response. The variation of primary tank response with λ is shown in figure 3.10, the variation of secondary tank response with λ is shown in figure 3.11 and the variation of manipulated variable is shown in figure 3.12.

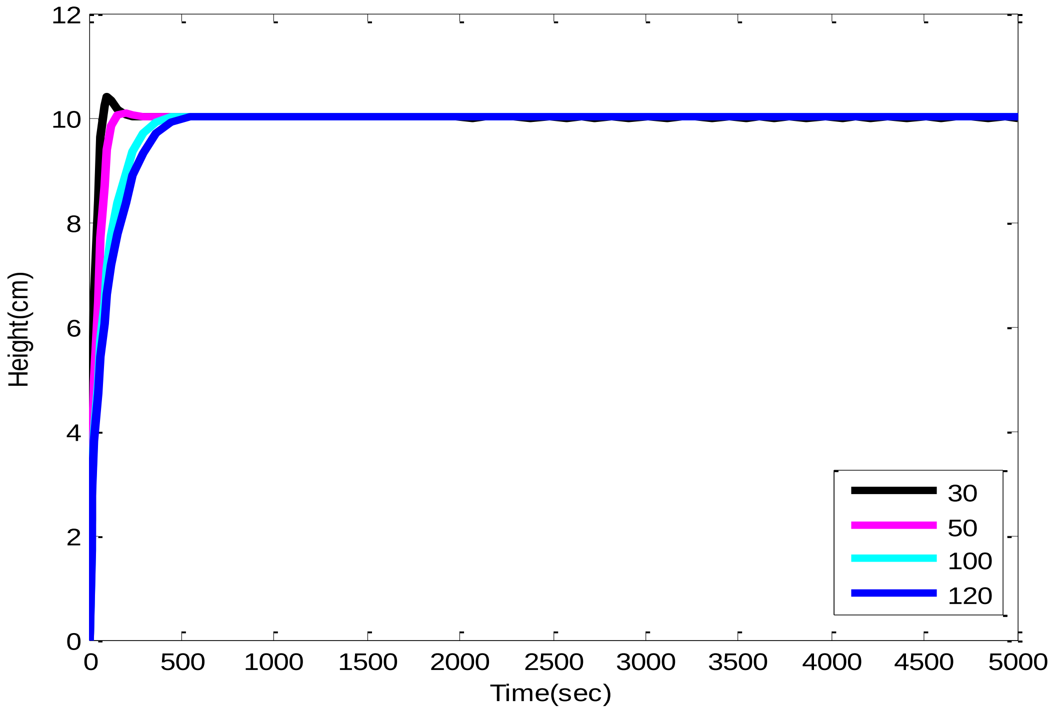

Figure 3.10 Effect of filter coefficient variation on primary tank

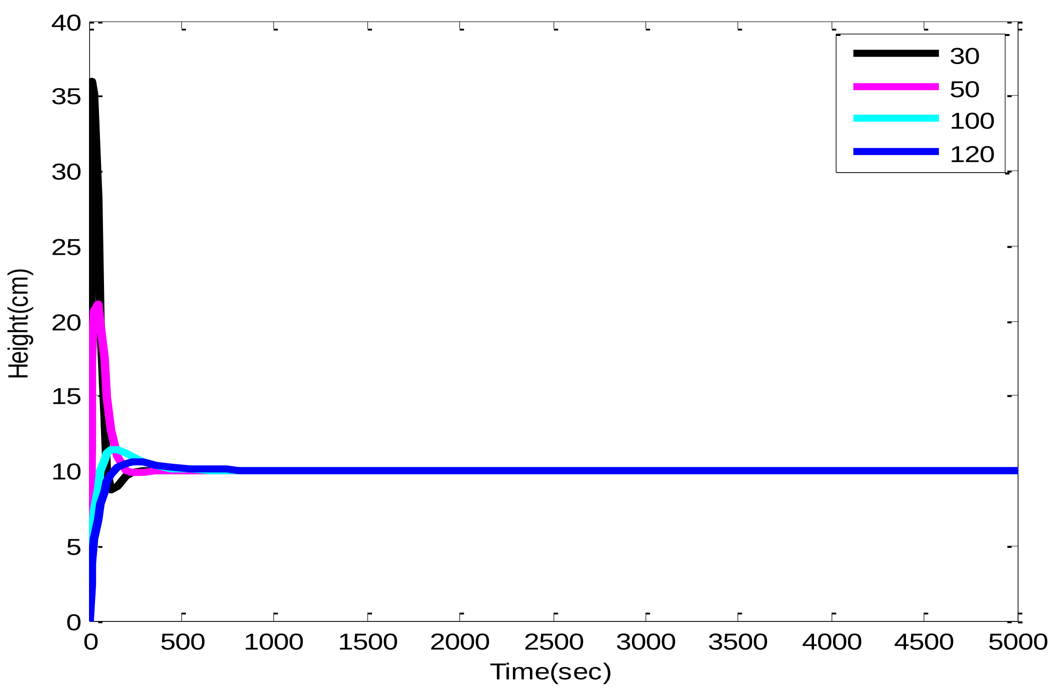

Figure 3.11 Effect of filter coefficient variation on secondary tank

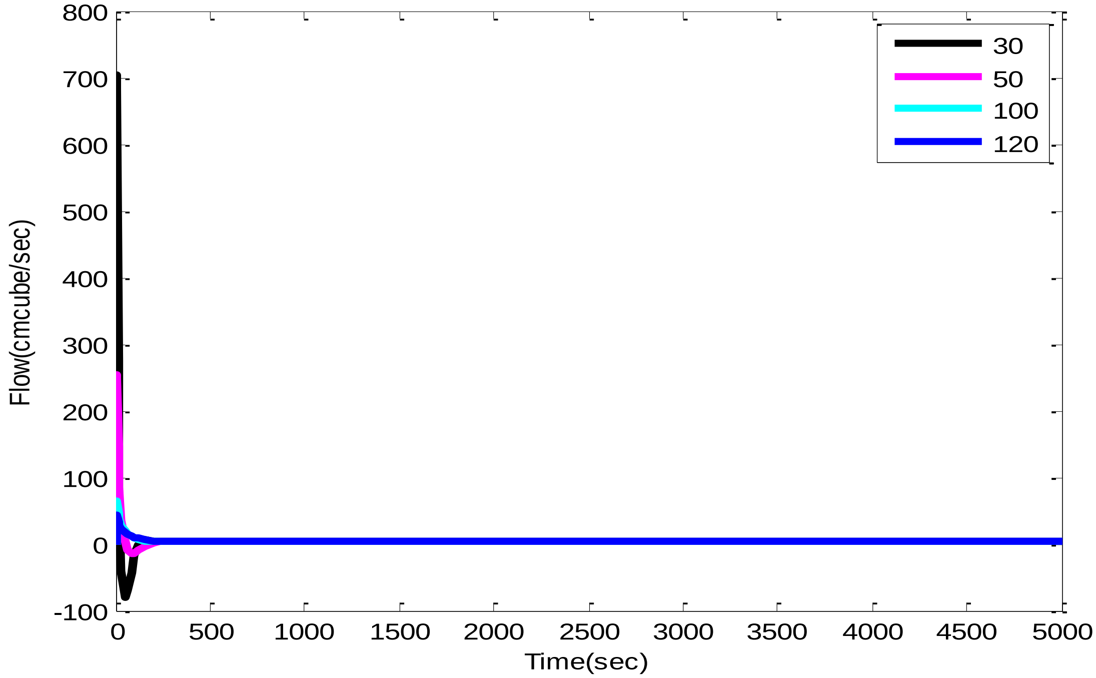

Figure 3.12 Effect of filter coefficient variation on manipulated variable

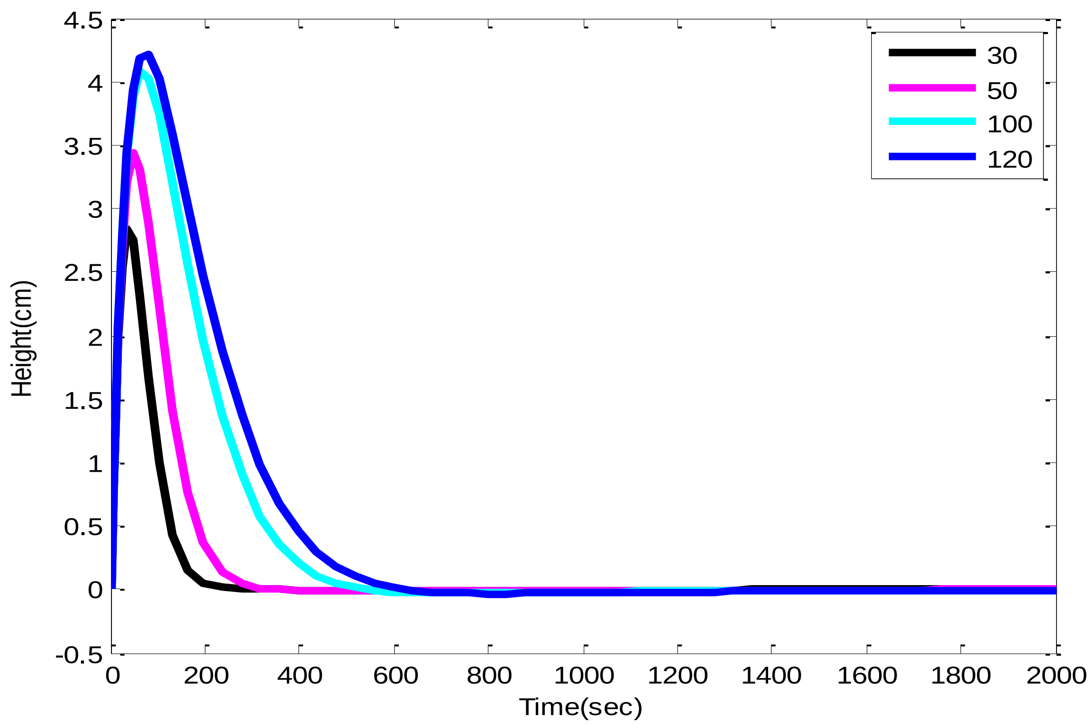

Figure 3.13 Effect of filter coefficient variation in disturbance rejection

From figure 3.10 it is clear that λ=30 and λ=50 both are having fast response while λ=100 and λ=120 are having very sluggish responses. So λ=100 and λ=120 got eliminated. From figure 3.12 it can be inferred that λ=30 require greater magnitude of manipulated variable as compared to λ=50. So λ=30 got eliminated, therefore for two-tank interacting system the optimal value of λ is 50.

In Table 3.2 various performance indices are shown for different values of λ. Table 3.2 also justifies the choice of λ=50.

	λ=30	λ=50	λ=100	λ=120
Rise Time(sec)	48	83	195	244
Settling time(sec)	148	125	323	399
Percentage Overshoot	4.08	1.0	0.3	0.4
Peak time(sec)	103	189	608	729

Table 3.2 Comparison of performance indices for various filter coefficients for interacting tank system

CHAPTER-4
IMC-FF CONTROLLER

4.1INTRODUCTION

4.2 IMC-FF CONTROLLER DESIGN

4.3 SIMULATION RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

4.1.1 Feed-Forward Controller

PID controllers used in classical process control can never control the system perfectly. For PID controllers, it is very difficult to maintain the controlled variable continuously at the desired set-point in the presence of various disturbances and set-point changes. The biggest drawback of PID controller is that it reacts only when the disturbance is felt by the whole system i.e. PID reacts when it detects the deviation of controlled variable form the set-point change. But this is not the case when Feed-Forward controller is used.

Feed-Forward controller takes action before the disturbance is felt by the process. Theoretically Feed-Forward controller can achieve perfect control. Feed-Forward controller measures the disturbance and changes the manipulated variable accordingly so that the effect of the disturbance gets canceled. The basic block diagram of Feed-Forward controller is shown in figure 4.1.

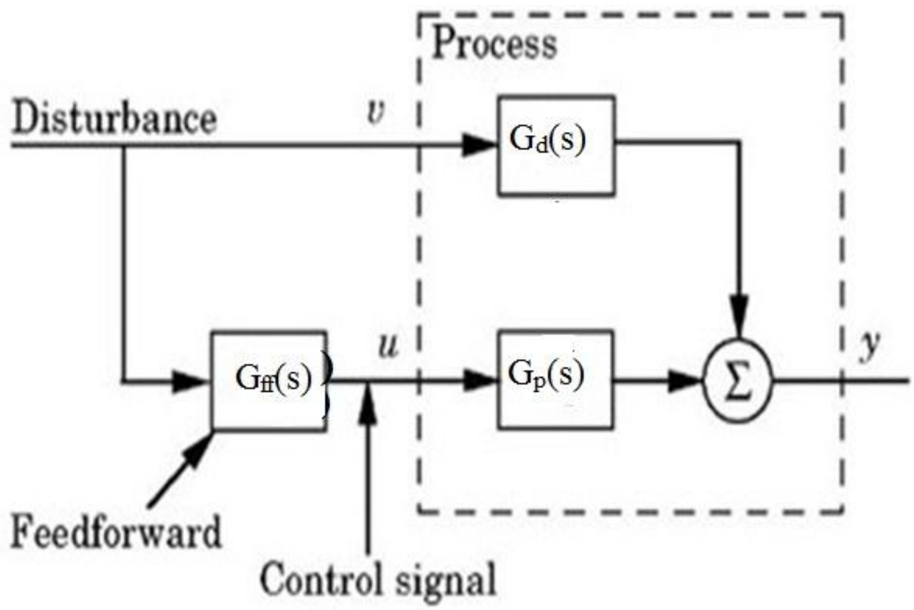

Figure 4.1 Block diagram of Feed-Forward controller

Where,

$G_p(s)$ = Process Transfer Function

$G_{ff}(s)$ = Feed-Forward Controller

$G_d(s)$ = Disturbance Transfer Function

Signals which are trying to affect the controlled variable are sent to Feed-Forward controller, Feed-Forward controller performs calculations with the help of this information, calculate the new values of manipulated variable and send these new values to the Actuator. Because of these new values of manipulated variable, the controlled variable remains unaffected in spite of disturbances. It can be observed in figure 4.2.

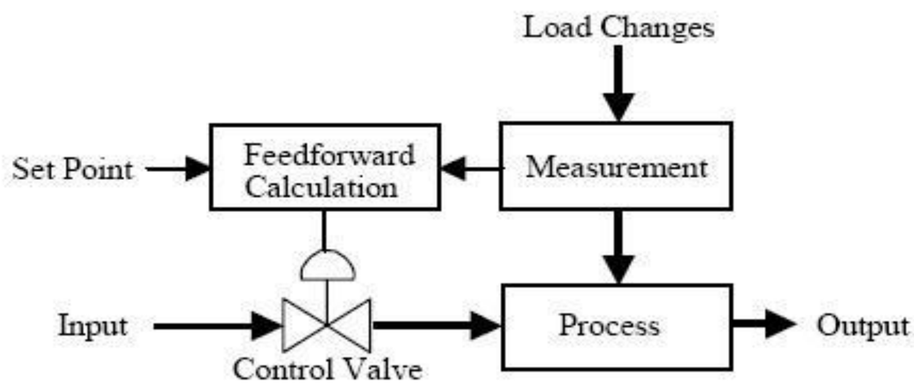

Figure 4.2 Block diagram of Feed-Forward controller showing Control valve

4.1.2 Design of Feed-Forward Controller

For designing Feed-Forward controller refer figure 4.3. It represents a process in which a disturbance is affecting the process.

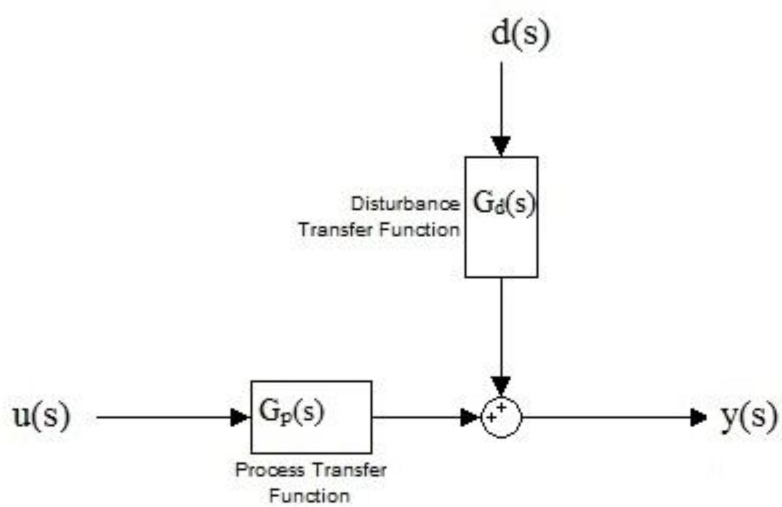

Figure 4.3 Block diagram of a process

The output variable can be written as:

$$y(s) = G_p(s)u(s) + G_d(s)d(s) \tag{4.1}$$

Now assume that $y_{sp}(s)$ is the set-point for the output variable y(s). Then above equation can be written as:

$$y_{sp}(s) = G_p(s)u(s) + G_d(s)d(s) \tag{4.2}$$

Above equation can be written as:

$$u(s) = \left[\frac{y_{sp}(s)}{G_d(s)} - d(s)\right] \frac{G_d(s)}{G_p(s)} \tag{4.3}$$

Therefore, the transfer function of the Feed-Forward controller can be given as:

$$G_{ff}(s) = -\frac{G_d(s)}{G_p(s)} \tag{4.4}$$

Equation (4.4) tells that Feed-Forward controller is different from PID and it is like a computing machine. Equation (4.4) tells one more thing that the performance of Feed-Forward controller depends upon the knowledge of the process.

4.1.3 Advantages of Feed-Forward Controller

a) Feed-Forward controller acts before the occurrence of disturbance.
b) Feed-Forward controller cannot make the system unstable.
c) Feed-Forward controller performs better for systems having large time constants or systems having dead time.

4.1.4 Disadvantages of Feed-Forward Controller

a) Feed-Forward controller can act against measurable disturbance, it cannot reject immeasurable disturbances.
b) The effectiveness of Feed-Forward controller depends on the knowledge of the process. So it is sensitive to process parameters.

4.1.5 Comparison of Feed-Forward Controller and Feedback Control

a) Design Methodology: Feed-Forward controller follows the conservation methodology while Feedback follows Classical control theory.

b) Measurement: Feed-Forward controller measures the disturbance while Feedback measures the process output.
c) Structure: Feed-Forward controller is an open loop structure while Feedback is a closed loop structure.
d) Role: Feed-Forward controller plays a role of anticipator while Feedback plays the role of compensator.

4.1.6 Thumb rule for selecting Controllers

Feed-Forward controller is applied where process is well known and variables used in equations governing process are well known. Feedback controller is used where the process is not much known and disturbances are immeasurable.

4.1.7 Feedback plus Feed-Forward Controller

Feed-Forward controller can be used with Feedback controller. The structure is shown in figure 4.4.

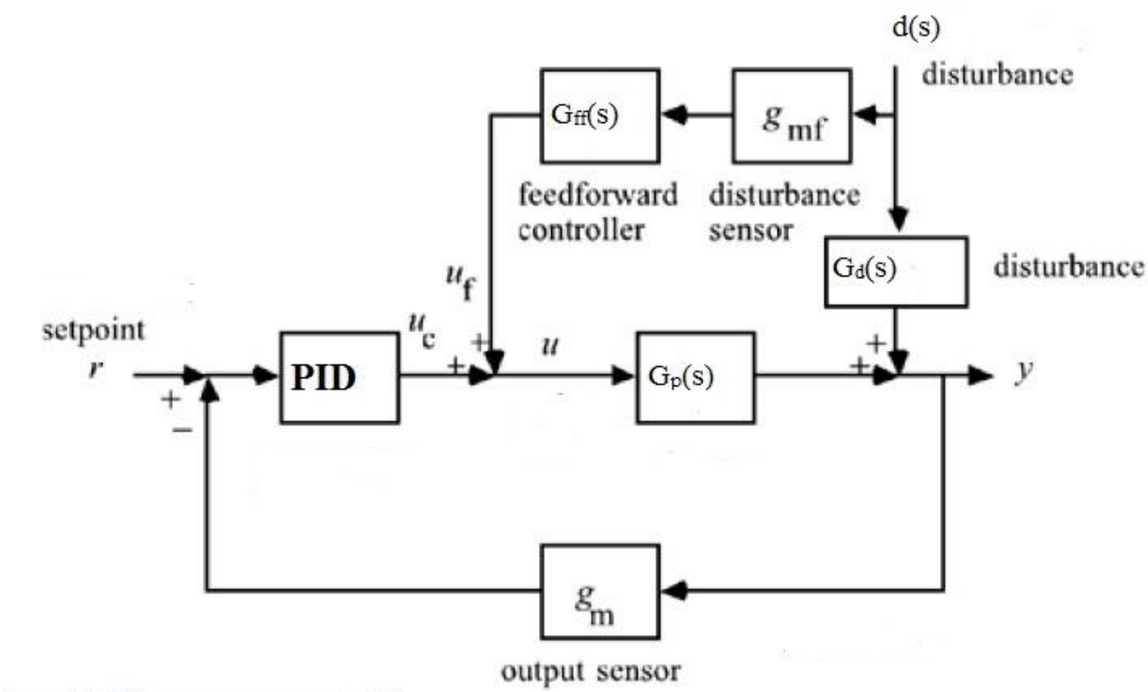

Figure 4.4 Feed-Forward plus Feedback Controller

Whenever Feed-Forward plus Feedback controllers are used together, Feed-Forward controller is used to reject major, measurable disturbance and feedback controller is used for set-point tracking as well as rejecting minor and uncertain disturbances. It is evident from the transfer function of Feed-Forward controller that it cannot reject the unknown disturbances so that minor and immeasurable disturbance is rejected by Feedback controller. Thus the overall structure performs nicely in set-point tracking as well as in disturbance rejection. The derivation of the overall transfer function for the figure 4.4 is given below:

The expression for the output variable y(s) can be written as

$$\mathrm{y(s) = G_d(s)d(s) + G_p(s)u(s)} \tag{4.5}$$

Now u(s) can be written as:

$$\mathrm{u(s) = u_c(s) + u_f(s)} \tag{4.6}$$

Put equation (4.6) in equation (4.5)

$$\mathrm{y(s) = G_d(s)d(s) + G_p(s)(u_c(s) + u_f(s))} \tag{4.7}$$

$$\mathrm{y(s) = G_d(s)d(s) + G_p(s)}\left[G_{ff}(s)d(s) + G_c(s)(r(s) - y(s))\right] \tag{4.8}$$

Here $G_c(s)$ is used for PID controller. After re-arranging equation (4.9) we get:

$$\mathrm{y(s)} = \frac{G_d(s) + G_p(s)G_{ff}(s)}{1 + G_p(s)G_c(s)}\mathrm{d(s)} + \frac{G_p(s)G_c(s)}{1 + G_p(s)G_c(s)}\mathrm{r(s)} \tag{4.9}$$

Here it is assumed that g_m and g_{mf} are equal to one. It is clear from equation (4.9) that Feed-Forward controller does not affect the stability of system.

4.1.8 Static Feed-Forward Controller

Sometimes for designing the Feed-Forward controller only static part i.e. gain of the transfer function is considered. So this type of controller is called Static Feed-Forward controller. Design of Static Feed-Forward controller is illustrated below:

Suppose the transfer function of process and disturbance can be written as:

$$G_p(\mathrm{s}) = \frac{K_p}{(\tau_p \mathrm{s} + 1)} \tag{4.10}$$

$$G_d(\mathrm{s}) = \frac{K_d}{(\tau_d \mathrm{s} + 1)} \tag{4.11}$$

So the transfer function of Static Feed-Forward Controller will be:

$$G_{ff}(\mathrm{s}) = -\frac{G_d(s)}{G_p(s)} = -\frac{K_d}{K_p} \tag{4.12}$$

Here it is evident from the equation (4.12) that the dynamic part of process transfer function and disturbance transfer function is ignored and only gains are used to realize the Feed-Forward Controller.

4.1.9 Important Points Regarding Feed-Forward Controller:

While designing Feed-Forward Controller it should be kept in mind that the Feed-Forward Controller must be stable i.e. no pole of Feed-Forward Controller transfer function should lie in right half of s-plane. Following points need to be taken care of while designing Feed-Forward Controller:

a) The time delay involved in disturbance should be greater enough as compared to delay present in process.
b) If the process is having zeros lying in right half of s-plane then there zeros must be avoided while designing Feed-Forward Controller.
c) If process transfer function is higher in order as compared to disturbance, skip that dynamic part in process transfer function which has a low value of time constant.
d) Feed-Forward Controller does not affect the set-point tracking; it only deals with measurable disturbance.
e) Feed-Forward Controller is always implemented with Feedback controller or with IMC controller.

4.2 INTERNAL MODEL FEED-FORWARD CONTROLLER:

As it was stated in the last section that Feed-Forward Controller is always used with Feedback or IMC, therefore in this section Feed-Forward Controller is used with IMC and the resulted controller is called as Internal Model Feed-Forward Controller (IMCFF). IMCFF is a controller having two qualities: very good set-point tracking like IMC and nice disturbance rejection like Feed-Forward Controller. The structure of IMCFF is shown in figure 4.5. The transfer function of IMC is calculated according to section 3.2 and the transfer function of Feed-Forward Controller is calculated according to equation (4.4).

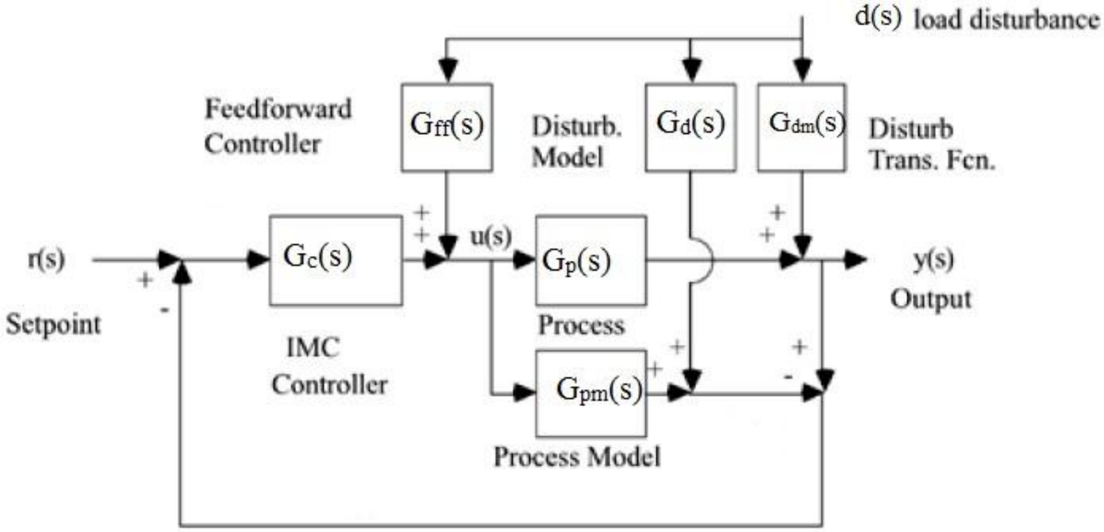

Figure 4.5 Block Diagram of IMC-FF Controller

Where,

r(s) = Set-Point

y(s) = Controlled Variable

d(s) = Disturbance Variable

u(s) = Manipulated Variable

$G_c(s)$ = IMC Transfer Function

$G_p(s)$ = Process Transfer Function

$G_d(s)$ = Disturbance Transfer Function

$G_{pm}(s)$ = Transfer Function of Process Model

$G_{dm}(s)$ = Transfer Function of Disturbance Model

$G_{ff}(s)$ = Transfer Function of Feed-Forward Controller

If the steps of section 4.1.6 are followed then the closed loop response can be derived for IMCFF. The controlled variable y(s) can be written as:

$$\mathrm{y(s)} = y_1(s) + y_2(s) \tag{4.13}$$

Where,

$$y_1(s) = \frac{G_p(s)G_c(s)}{1 + G_c(s)\left[G_p(s) - G_{pm}(s)\right]} r(s) \tag{4.14}$$

$$y_2(s) = \frac{G_p(s)G_c(s) - G_p(s)G_c(s)[G_d(s) - G_{dm}(s)]}{1 + G_c(s)\left[G_p(s) - G_{pm}(s)\right]} d(s) + G_d(s)d(s) \tag{4.15}$$

4.2.1 TUNING OF IMC-FF:

Tuning of IMC-FF is done same as IMC. Take various values of filter coefficient λ and plot the responses of primary tank, secondary tank and manipulated variable. Select that value of λ for which all the three responses are satisfying all the desired specifications.

4.3 SIMULATION RESULT:

4.3.1 Two-Tank Non-Interacting System:

The block diagram which is drawn in Simulink to generate the results is shown in figure 4.5:

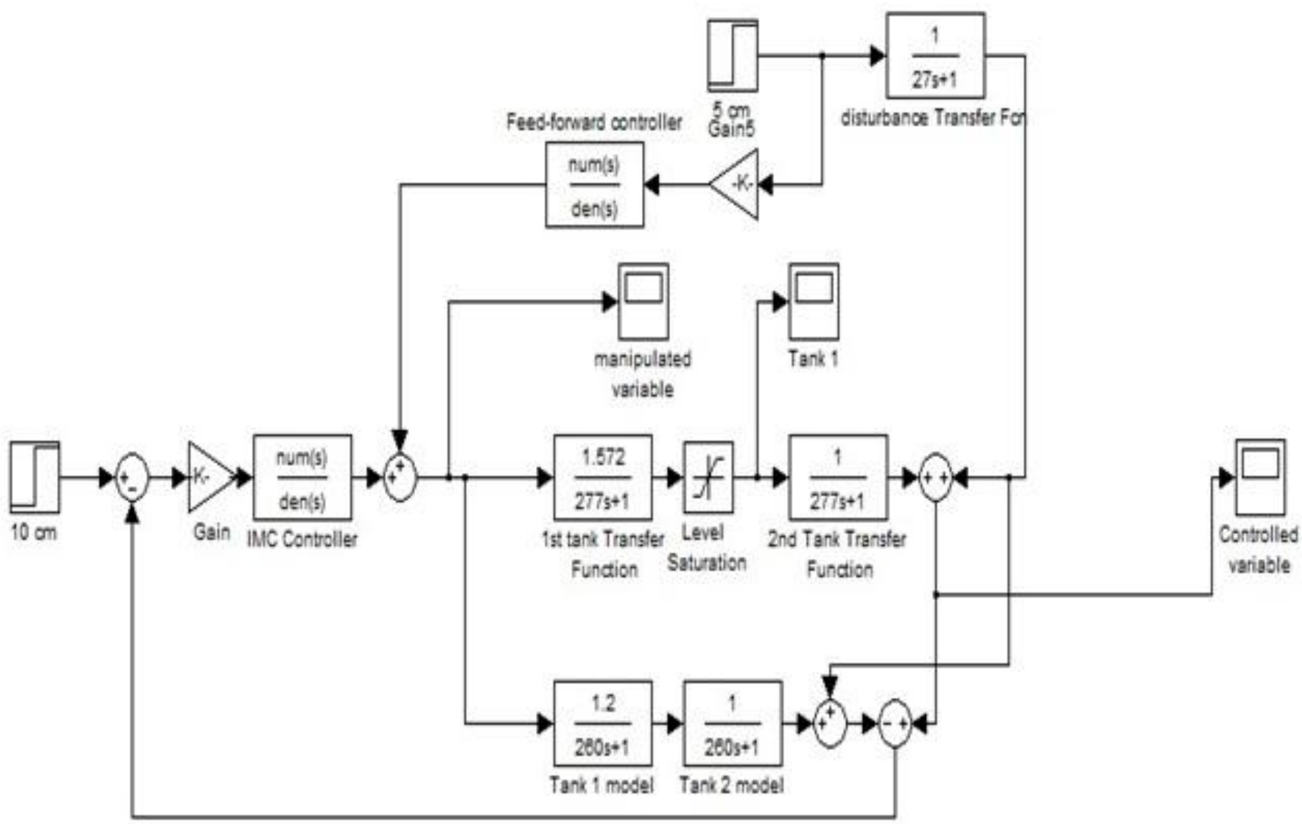

Figure 4.6 Block Diagram of IMCFF Controller for Two-Tank Non-Interacting System

The transfer function for the Two-Tank Non-Interacting system is same as given in equation (3.6):

$$G_p(s) = \frac{1.572}{76729s^2 + 554s + 1}$$

If the disturbances transfer function is same as given in equation (3.8):

$$G_d(s) = \frac{1.0}{27s + 1}$$

According to equation (4.4), the transfer function for the Feed-Forward controller will be:

$$G_{ff}(s) = -\frac{G_d(s)}{G_p(s)} = -0.83\frac{67600s^2 + 520s + 1}{729s^2 + 54s + 1} \tag{4.16}$$

The transfer function of the IMC controller will be same as equation (3.7):

$$G_c(s) = 0.83\frac{67600s^2 + 520s + 1}{(\lambda s + 1)^2}$$

4.3.1.1 Variation of Filter Coefficient:

The filter coefficient (λ) of IMC controller is varied as 30, 50,100,120,130 and response of Primary tank, secondary tank and manipulated variable are observed.

It is found that as the value of filter coefficient (λ) is increased the response becomes sluggish. At λ=100,120 and 130 the action of feed-forward controller becomes visible. It can be seen in figure 4.7 as a peak located in lower part of graph. Figure 4.7 represents the primary tank response, 4.8 represents the secondary tank response and 4.9 represents manipulated variable.

From figure 4.7 it can be concluded that λ = 30 and 50 two values better than any other values because of fastness of response. At λ =100,120 and 130 response is becoming much slow. But figure 4.8 tells that at λ=50 the height of the liquid has gone to negative which is not possible, So λ=50 is rejected. One more reason is there for the rejection of λ=50 is that manipulated variable is becoming negative for this value. So the optimal value of filter coefficient λ for two-tank non-interacting system is 50.

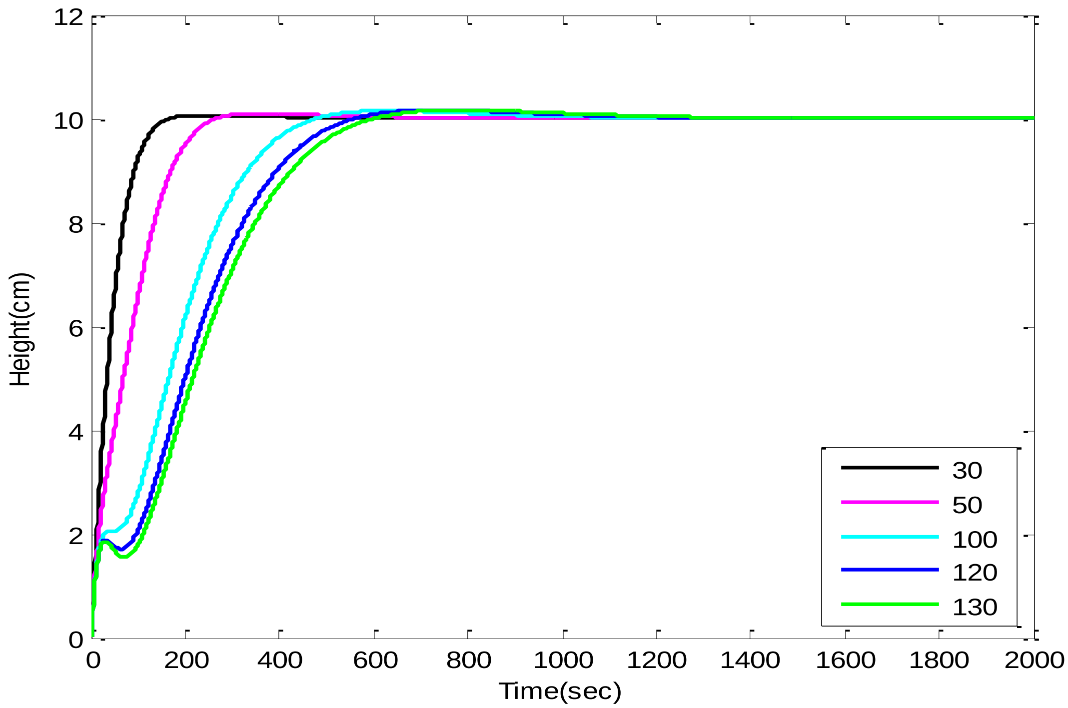

Figure 4.7 Effect of Filter Coefficient Variation on Primary Tank

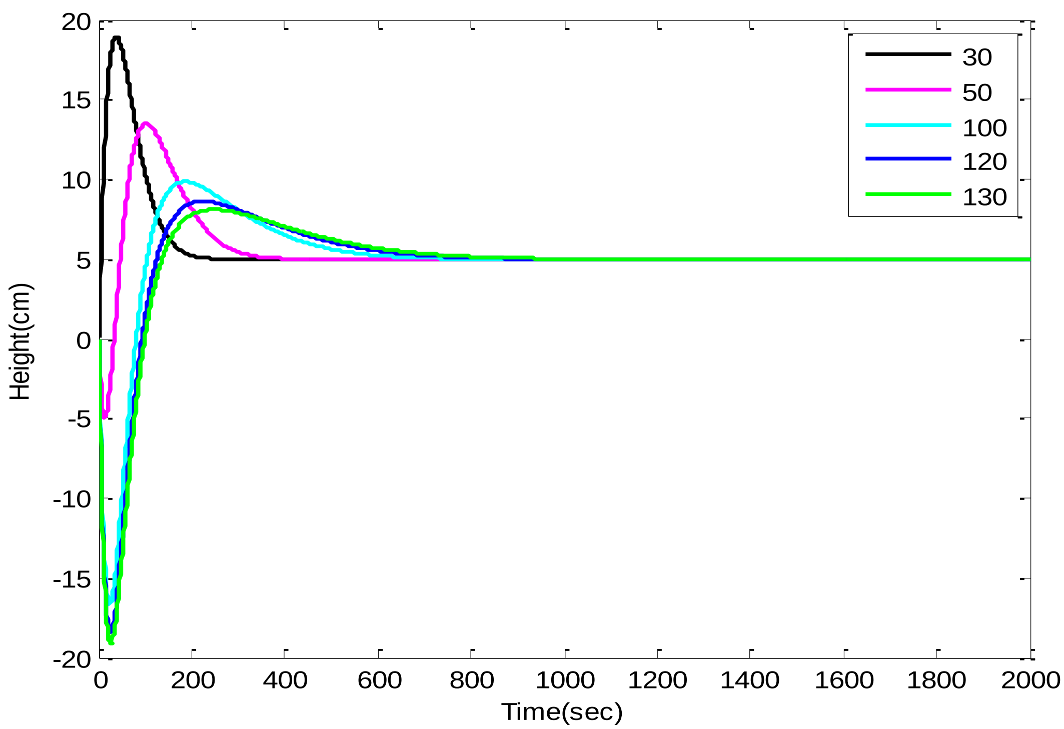

Figure 4.8 Effect of Filter Coefficient Variation on Secondary Tank

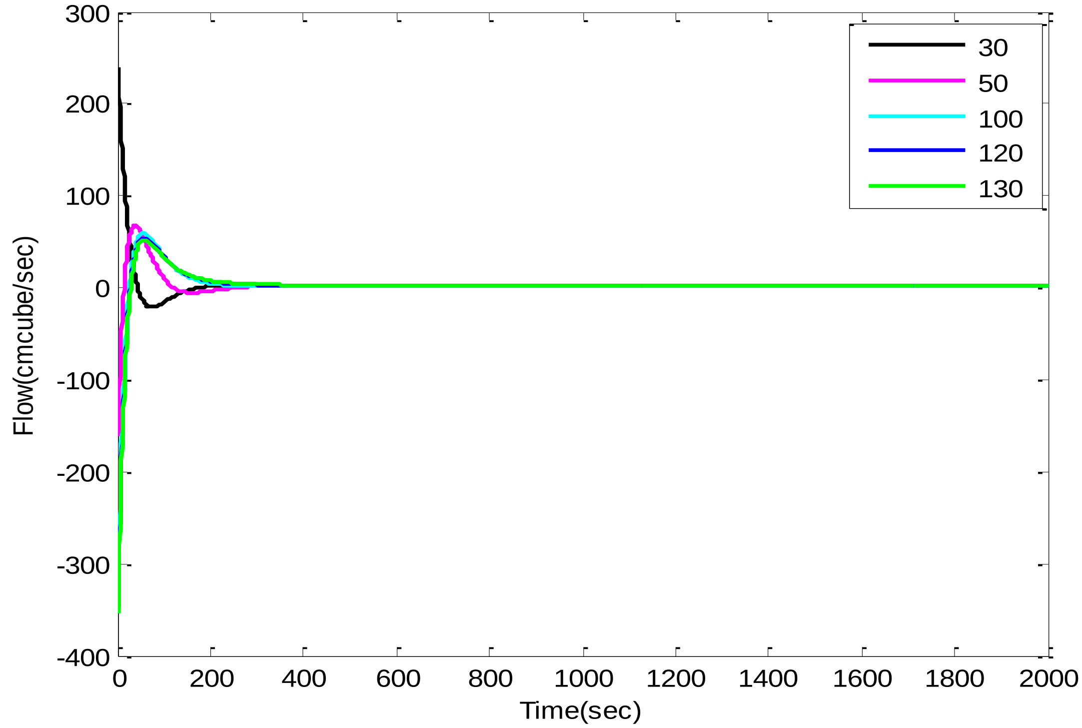

Figure 4.9 Effect of Filter Coefficient Variation on manipulated variable

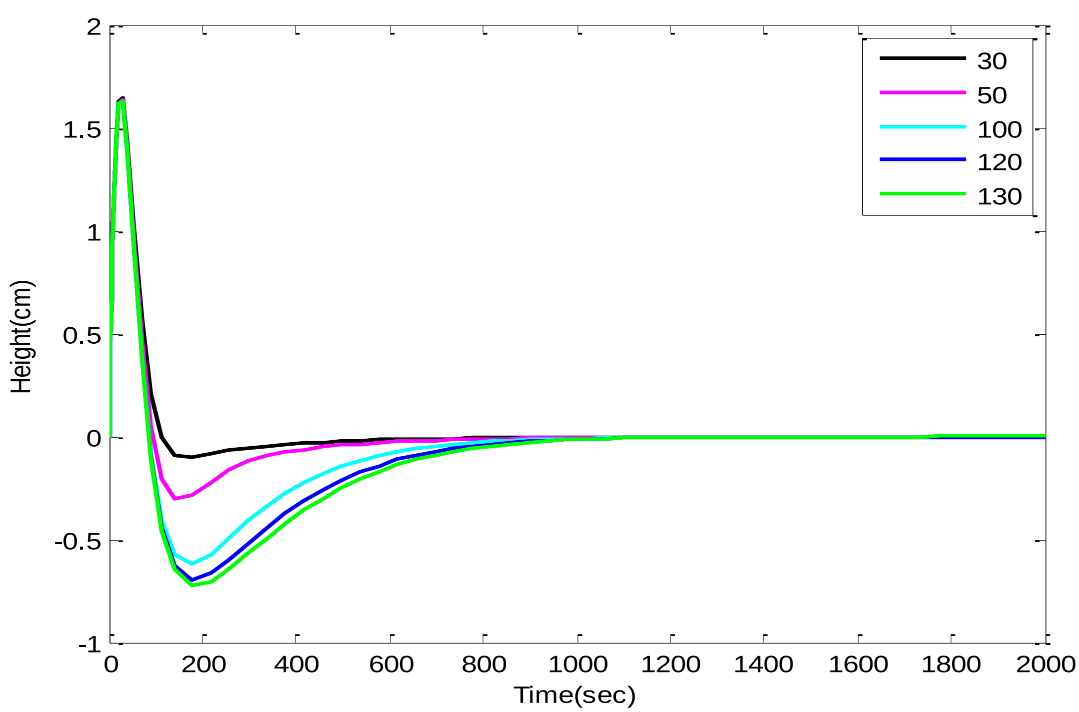

Figure 4.10 Effect of Filter Coefficient Variation on disturbance rejection

Effect of filter coefficient variation λ on disturbance rejection is shown in figure 4.10. It is evident that with the increase of filter coefficient λ , the undershoot of the response increases. This undershoot represents the action of feed-forward controller which is becoming pre-dominant as the response is becoming sluggish i.e. value of λ is increasing.

Various performance indices are calculated for different values of filter coefficient λ which are listed in Table 4.1. This table also justifies why λ= 30 is the optimal filter coefficient.

	λ=30	λ=50	λ=100	λ=120	λ=130
Rise Time(sec)	86	163	324	386	417
Settling time(sec)	134	230	428	504	542
Percentage Overshoot	0.0	1.03	1.6	1.7	1.8
Peak time(sec)	0	358	630	734	784

Table 4.1 Comparison of performance indices for various filter coefficients for non- interacting tank system

4.3.1.2 Disturbance Variation and Set-Point Tracking

The IMC transfer function for studying the disturbance rejection and set-point tracking of IMC-FF is given below:

$$\mathrm{G_c(s)} = 0.83\frac{67600\mathrm{s}^2 + 520\mathrm{s} + 1}{(50\mathrm{s} + 1)^2} \tag{4.17}$$

The feed-forward controller equation will be same as before which is given below:

$$G_{ff}(\mathrm{s}) = -\frac{G_d(s)}{G_p(s)} = -0.83\frac{67600s^2 + 520s + 1}{729s^2 + 54s + 1}$$

Set-point is 10 and the value applied at disturbance input is varied as +5,+15,-5,-15 and 0 and the result is plotted which is shown in figure 4.11.

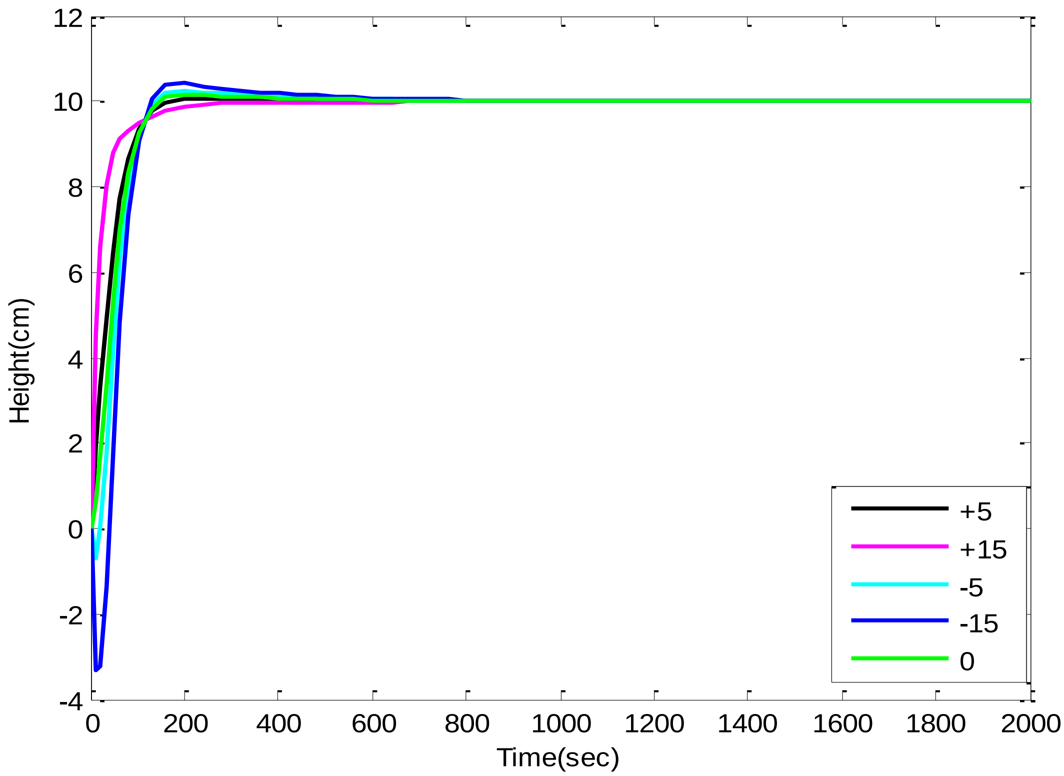

Figure 4.11 Set-point tracking with varying disturbance

From figure 4.11 it is clear that due to strong rejection of disturbance by feed-forward controller, disturbance is not able to affect the process and the responses are settling quickly without any delay.

4.3.1.3 Comparison of IMC-FF with Other Controllers:

In this section the response of IMC-FF is compared with the response of feedback, feedback plus feed-forward and IMC for two tank non-interacting system and various performance indices are calculated for all these controllers. IMC-FF is the only controller having zero overshoot and rise time, settling time are lowest among all other controllers. This proves that IMC-FF is the best controller for the two-tank non-interacting system under various considerations made in this thesis. The response comparison is shown in figure 4.12 and various performance indices are listed in Table 3.2.

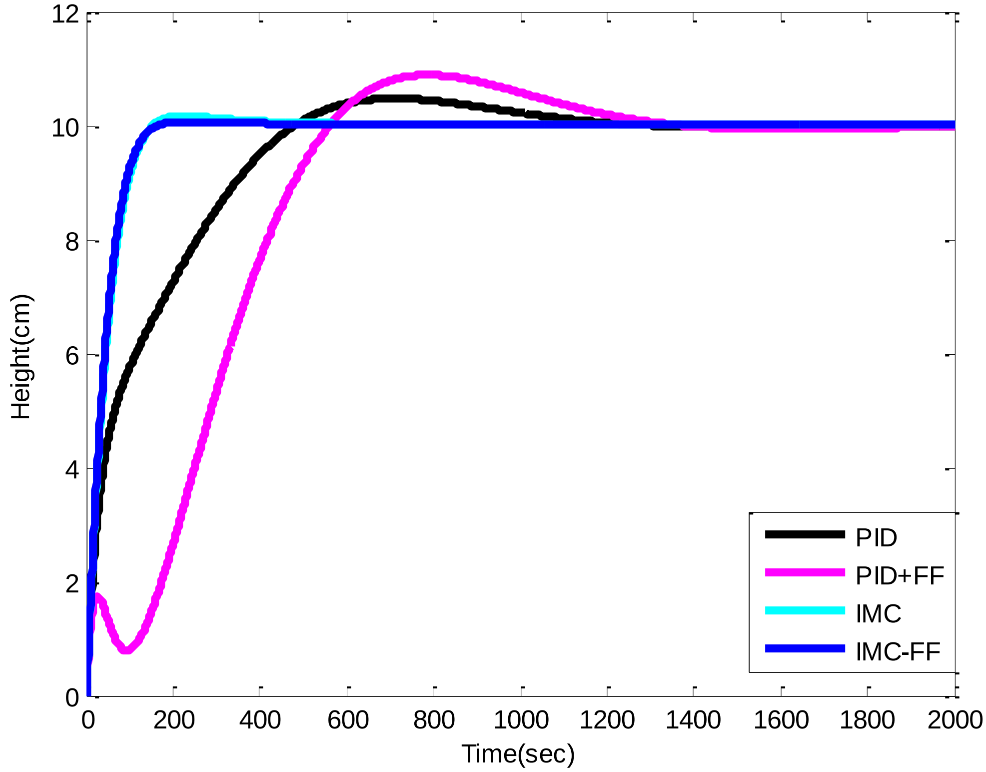

Figure 4.12 Comparison of various controllers with IMC-FF

	PID	PID+FF	IMC	IMC-FF
Rise Time(sec)	338	468	90	86
Settling time(sec)	1029	1209	135	134
Percentage Overshoot	4.80	9.0	1.68	0.0
Peak time(sec)	712	790	226	0

Table 4.2 Comparison of performance indices of various controllers with IMC-FF for non-interacting tank system

4.3.2 Two-Tank Interacting System:

The block diagram which is drawn in Simulink to generate the results for two-tank interacting system is shown in figure 4.13:

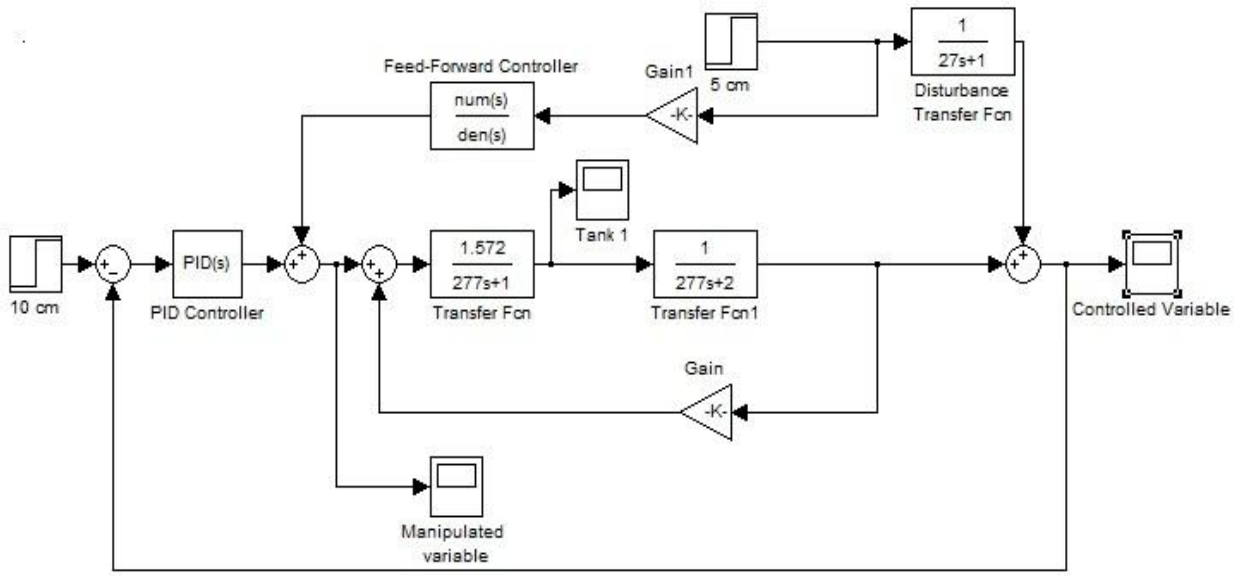

Figure 4.13 Block Diagram of IMCFF Controller for Two-Tank Interacting System

The transfer function of the overall process is same as given in equation (3.10) i.e.

$$G_p(s) = \frac{1.572}{76729s^2 + 831s + 1}$$

The IMC transfer function for the two-tank interacting system will be:

$$G_c(s) = 0.83\frac{76000s^2 + 800s + 1}{(\lambda s + 1)^2}$$

Feed-Forward controller transfer function can be written as:

$$G_{ff}(s) = -\frac{G_d(s)}{G_p(s)} = -0.83\frac{76000s^2 + 800s + 1}{729s^2 + 54s + 1} \quad (4.18)$$

4.3.2.1 Variation of Filter-Coefficient:

Now the Filter coefficient of IMC is varied for two-tank interacting system and the responses are shown in figure 4.14.

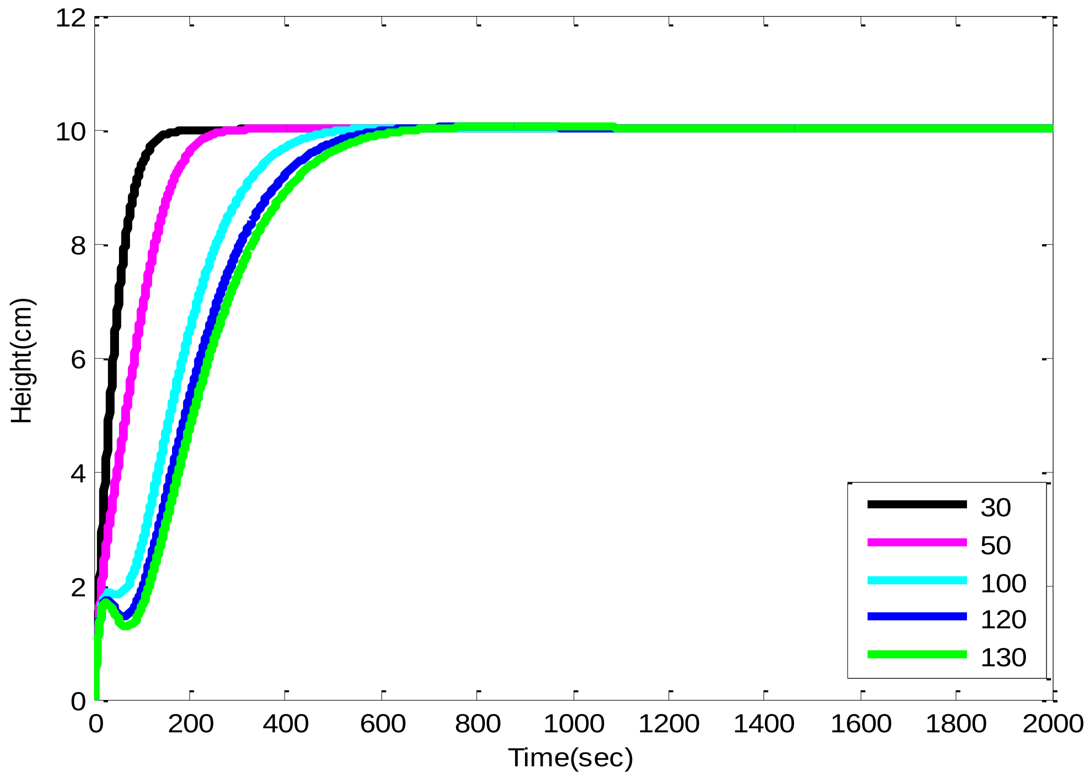

Figure 4.14 Effect of filter coefficient variation on primary tank

It is clear from figure 4.14 that λ=30 is producing the fastest response and λ=50 is also producing a quick response while other values of λ are producing slow response. For λ=100,120 and 130 a peak is observed at lower portion of response. This peak is due to the action of feed-forward controller. The reason behind the occurrence of this peak is that: As the value of λ increases the response becomes slower. So at lower values of λ the response is so fast that feed-forward controller comes in action at the last stage of response but for higher values of λ the response is slow and feed-forward controller starts working at the initial stage of the response. That is why this peak is observed for large values of λ. So from this figure only two values of λ are selected i.e. λ=30 and λ=50.

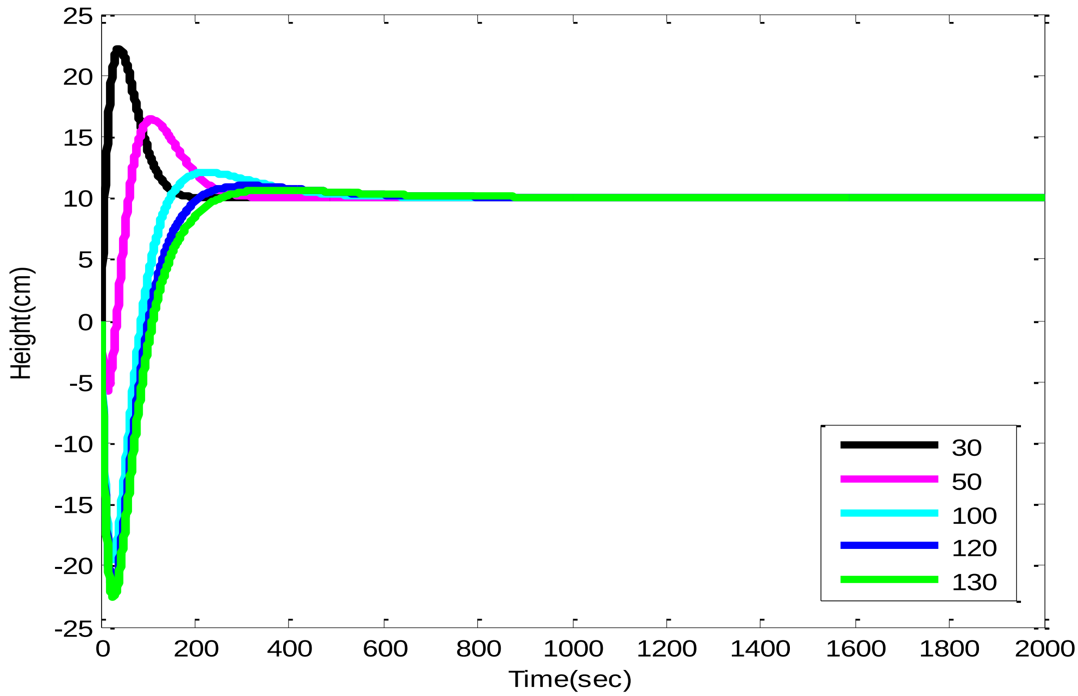

Figure 4.15 Effect of filter coefficient variation on secondary tank

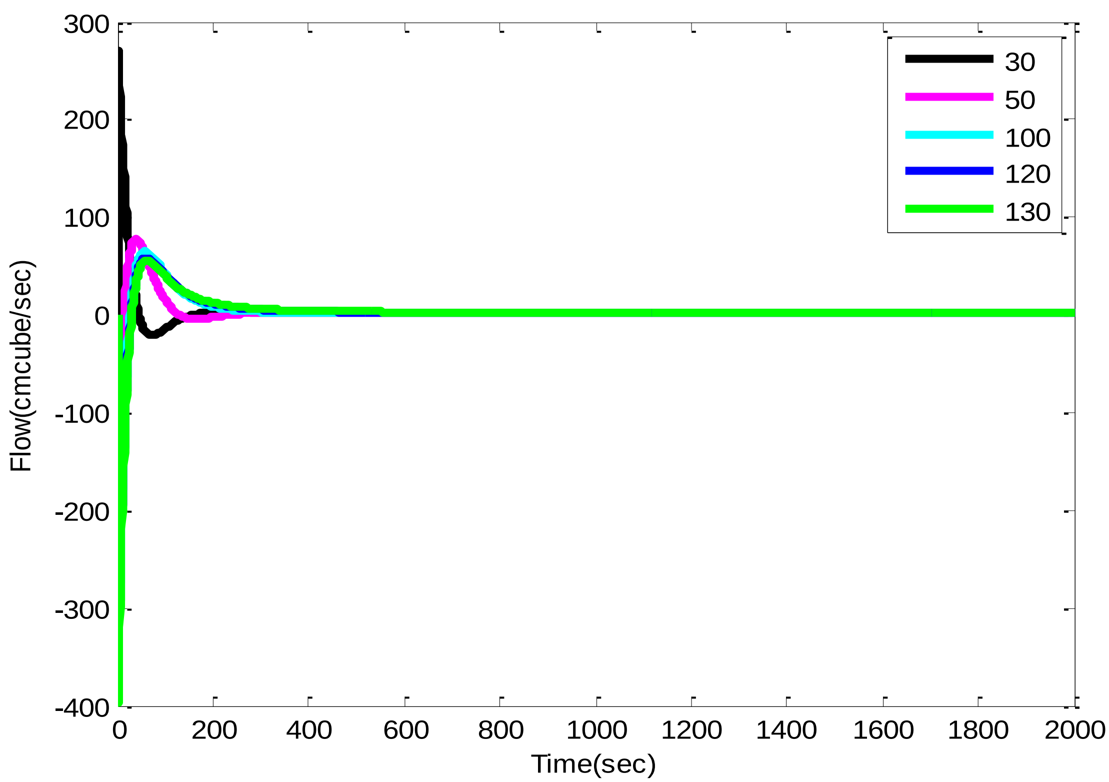

Figure 4.16 Effect of filter coefficient variation on manipulated variable

Figure 4.15 shows the effect of filter coefficient variation on secondary tank. It is evident from the figure that at λ= 50 the response is becoming negative which is not possible. So λ=50 is rejected and now the optimal value of λ is 30 for two tank interacting system.

Figure 4.16 shows the effect of filter coefficient variation on manipulated variable. This figure also suggests that the optimal value of λ is 30 for two tank interacting system because for all other values of λ the manipulated variable is becoming negative.

Figure 4.17 shows the effect of filter coefficient variation on disturbance rejection. From figure 4.17 it is clear that λ= 30 is taking least time to settle and to reject disturbance. Therefore this figure also justifies why λ=30 is the optimal tuning parameter.

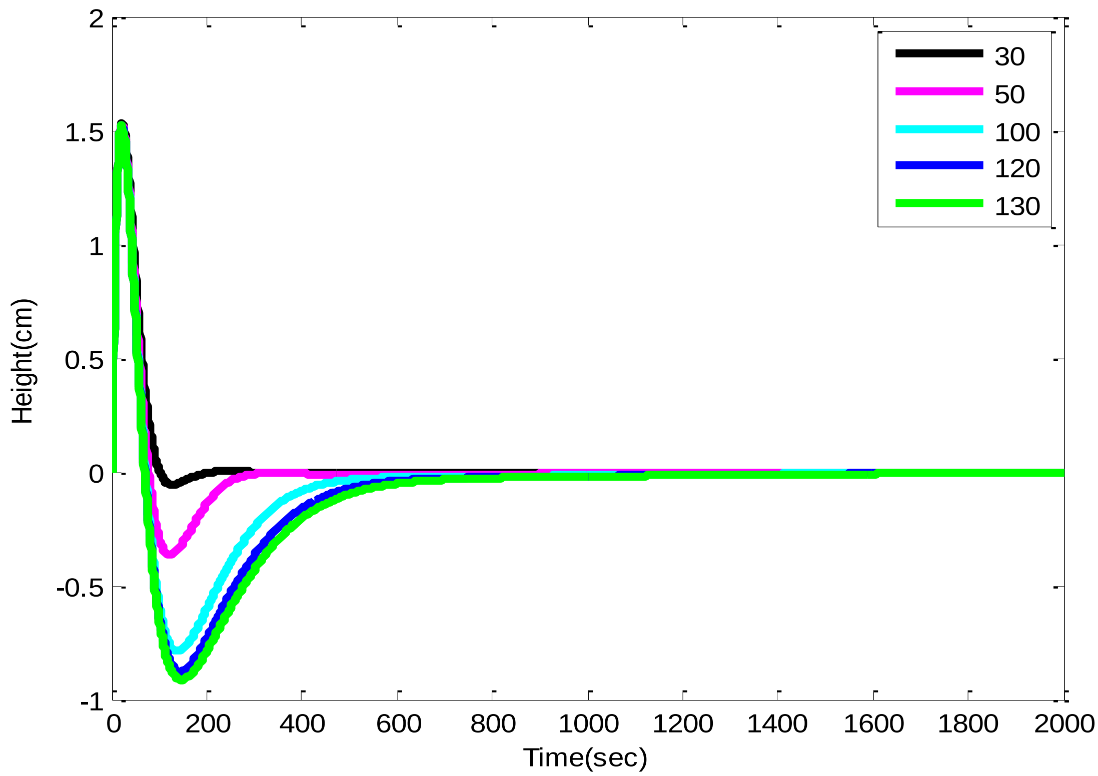

Figure 4.17 Effect of filter coefficient variation on disturbance rejection

The value of various performance indices like rise time, settling time, percentage overshoot and peak time are calculated and given in Table 4.3. This table shows that λ=30 is having minimum performance indices among all the values ofλ. So this table also supports λ=30 for optimal filter coefficient choice. One more thing that can be observed from the table is that peak overshoot is zero for all values ofλ. This is the biggest advantage of IMC-FF over all the controllers, especially over PID.

	λ=30	λ=50	λ=100	λ=120	λ=130
Rise Time(sec)	81	155	310	372	403
Settling time(sec)	132	226	432	515	557
Percentage Overshoot	0.0	0.0	0.0	0.0	0.0
Peak time(sec)	0	0	0	0	0

Table 4.3 Comparison of performance indices for different values of λ

4.3.2.2 Disturbance Variation and Set-point Tracking:

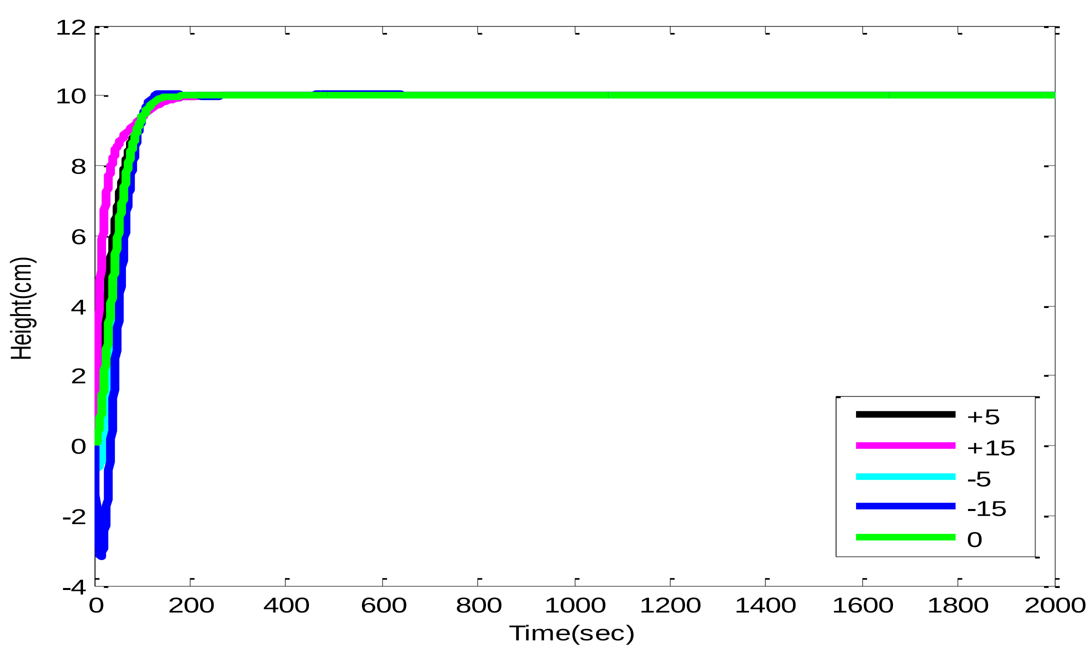

Figure 4.18 Set-point tracking with varying disturbance rejection

Figure 4.18 shows the set-point tracking of IMC-FF with varying disturbances. The transfer function of IMC is given below:

$$G_c(s) = 0.83\frac{76000s^2 + 800s + 1}{(30s + 1)^2} \tag{4.19}$$

The transfer function of the feed-forward controller used is given here under:

$$G_{ff}(s) = -\frac{G_d(s)}{G_p(s)} = -0.83\frac{76000s^2 + 800s + 1}{729s^2 + 54s + 1}$$

Figure 4.18 tells that the different values of disturbance do not affect the response of IMC-FF. It is because of Feed-Forward controller. It can be seen in figure 4.18 that all the responses are taking nearly same settling time to settle.

4.3.2.3 Comparison of Various Controllers with IMC-FF:

In this section the response of IMC-FF is compared with the responses of PID, PID plus Feed-Forward and IMC. Figure 4.19 shows the comparison of different controllers. The various performance indices are calculated for different controllers and listed in Table 4.4.

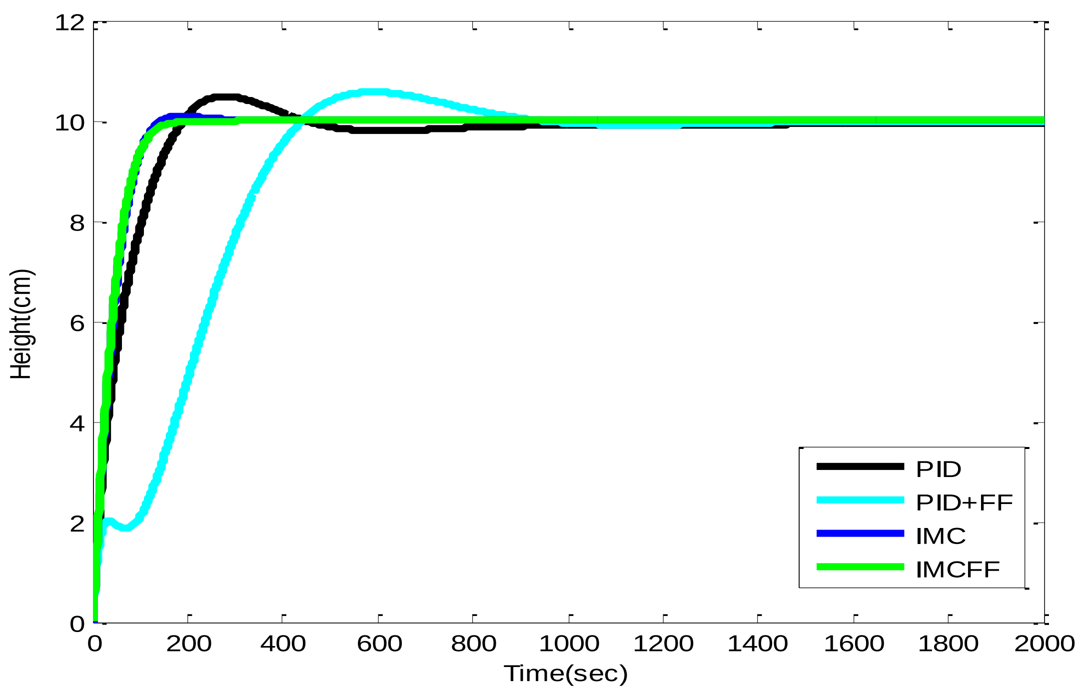

Figure 4.19 Comparison of various controllers with IMC-FF for Two-Tank Interacting System

	PID	PID+FF	IMC	IMC-FF
Rise Time(sec)	129	355	83	81
Settling time(sec)	405	820	125	132
Percentage Overshoot	5.4	5.9	1.0	0.0
Peak time(sec)	282	592	189	0

Table 4.4 Comparison of performance indices for different controllers

Table 4.4 shows that percentage overshoot and peak time is zero only for IMC-FF. IMC-FF has the least rise time and settling time among all of them. That is why IMC-FF is the best controller for two tank interacting system under the assumptions taken in this thesis.

4.3.3 Three-Tank Non- Interacting System:

Now Three-Tank Non-Interacting system is considered for showing the performance of IMC-FF. The transfer function of the single tank equation is given by equation (3.5):

$$\frac{1.572}{277s+1}$$

So the transfer function for the three tank non-interacting system will be given by equation (2.20)

$$\frac{H_3(s)}{Q_i(s)} = \frac{R_3}{(\tau_1 s+1)(\tau_2 s+1)\ (\tau_3 s+1)}$$

After putting the values of all the variables the transfer function becomes:

$$\frac{H_3(s)}{Q_i(s)} = \frac{1.572}{21253933s^3+230187s^2+831s+1} \tag{4.20}$$

The IMC transfer function for this system will be:

$$G_c(s) = 0.83\frac{17576000s^3 + 202800s^2 + 780s + 1}{(\lambda s + 1)^3} \tag{4.21}$$

The transfer function of Feed-Forward Controller will be:

$$G_{ff}(s) = -\frac{G_d(s)}{G_p(s)} = -0.83\frac{17576000s^3 + 202800s^2 + 780s + 1}{19683s^3 + 2187s^2 + 81s + 1} \tag{4.22}$$

4.3.3.1 Variation of Filter-Coefficient:

Now the value of λ is varied as 30, 50, 70 and 100 and the responses are plotted in figure 4.20. The various performance characteristics are also calculated for different values of λ and listed in Table 4.5

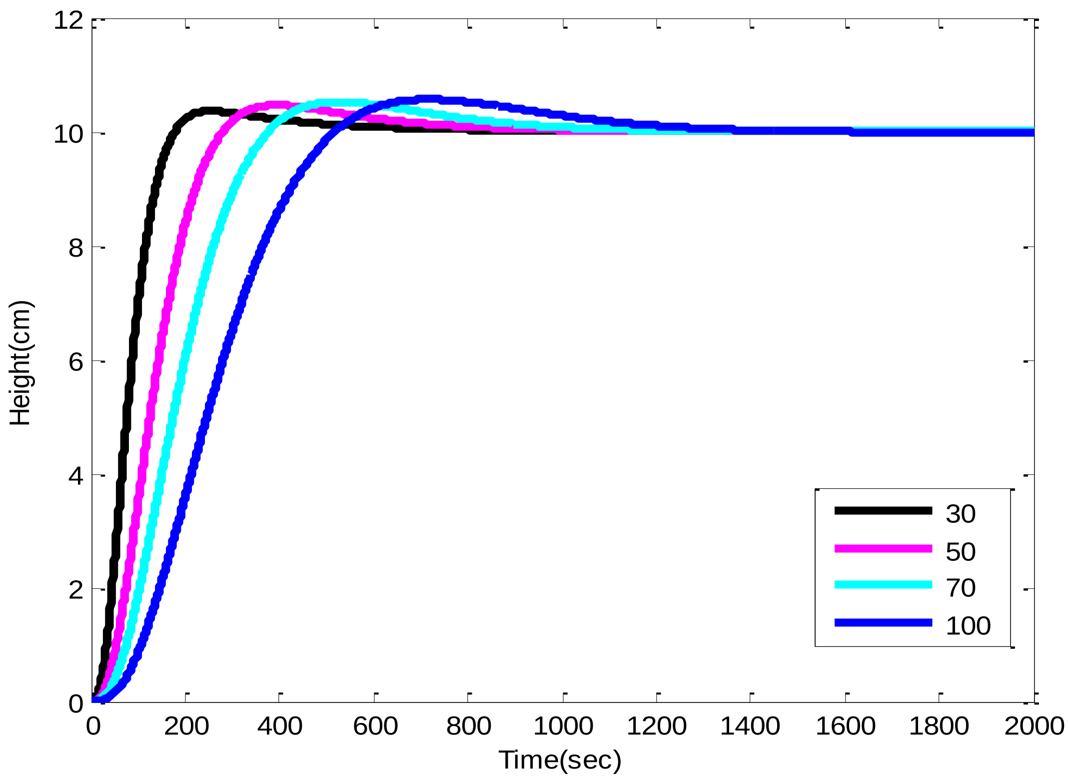

Figure 4.20 Variation of Filter coefficients in IMCFF for three tanks Non-interacting system

From the figure 4.20 it is clear that λ=30 will be the optimal value for three-tank non-interacting system because at λ=30 the fastest response is obtained and λ=30 has the least performance characteristics among all the other values ofλ.

	λ=30	λ=50	λ=70	λ=100
Rise Time(sec)	104	167	228	317
Settling time(sec)	414	638	826	1084
Percentage Overshoot	3.6	4.6	5.2	5.6
Peak time(sec)	255	397	529	718

Table 4.5 Comparison of performance indices for different filter coefficients

4.3.3.2 Comparison of IMC-FF with Feedback plus Feed-Forward:

In this section IMC-FF is compared with Feedback plus Feed-Forward controller (FBFF) in set-point tracking and disturbance rejection. The set-point tracking comparison of both the controllers is shown in figure 4.21 and specifications are listed in Table 4.6. IMC-FF is performing far better than FBFF in set-point tracking. Now it can be generalized that the set-point tracking of IMC –FF is best among all the controllers.

Figure 4.22 compares the disturbance rejection of IMC-FF and FBFF. Again IMC-FF is performing lot better than FBFF. The settling time taken by both the controllers is listed in Table 4.7. FBFF is taking 2600 seconds to settle while IMC-FF is taking only 1051 seconds to settle which is below 50% of settling time of FBFF.

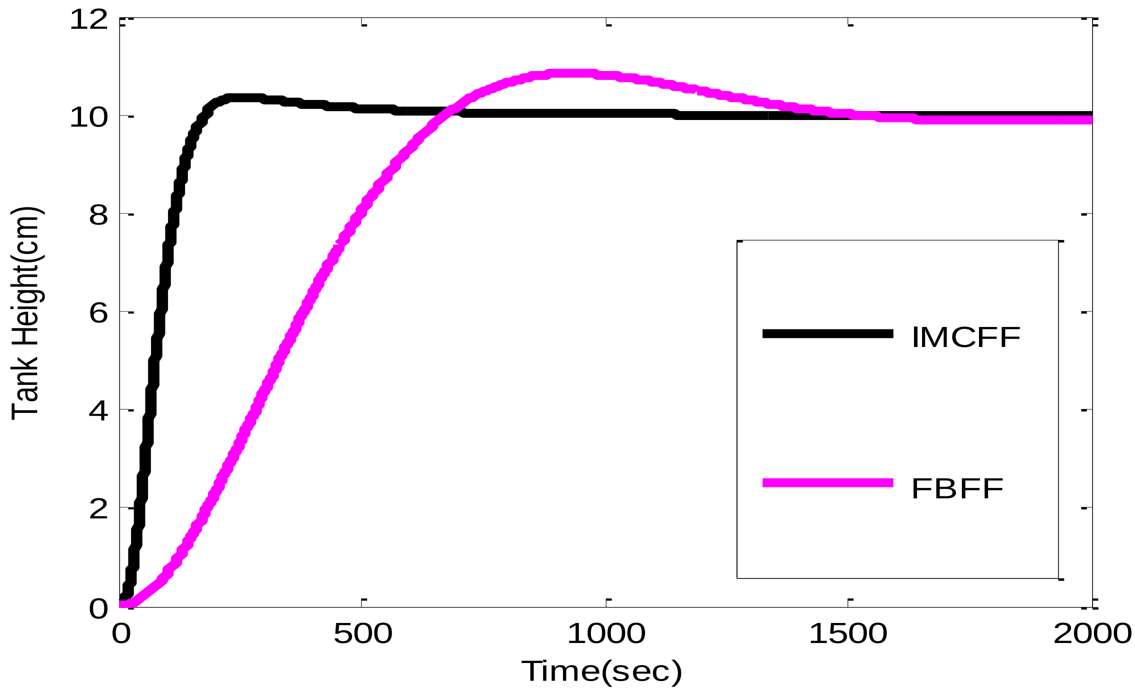

Figure 4.21 Comparison of Set point tracking of IMCFF and PID plus FF

Controller	Rise Time (sec)	Settling time (sec)	Percentage Overshoot	Peak time (sec)
IMC-FF	104	414	3.6	255
FBFF	441	1419	9.3	937

Table 4.6 Comparison of performance indices of IMC-FF and FBFF in set-point tracking

Controller	Settling Time (sec)
IMC-FF	1051
FBFF	2600

Table 4.7 Comparison of Settling Time of IMC-FF and FBFF for disturbance rejection

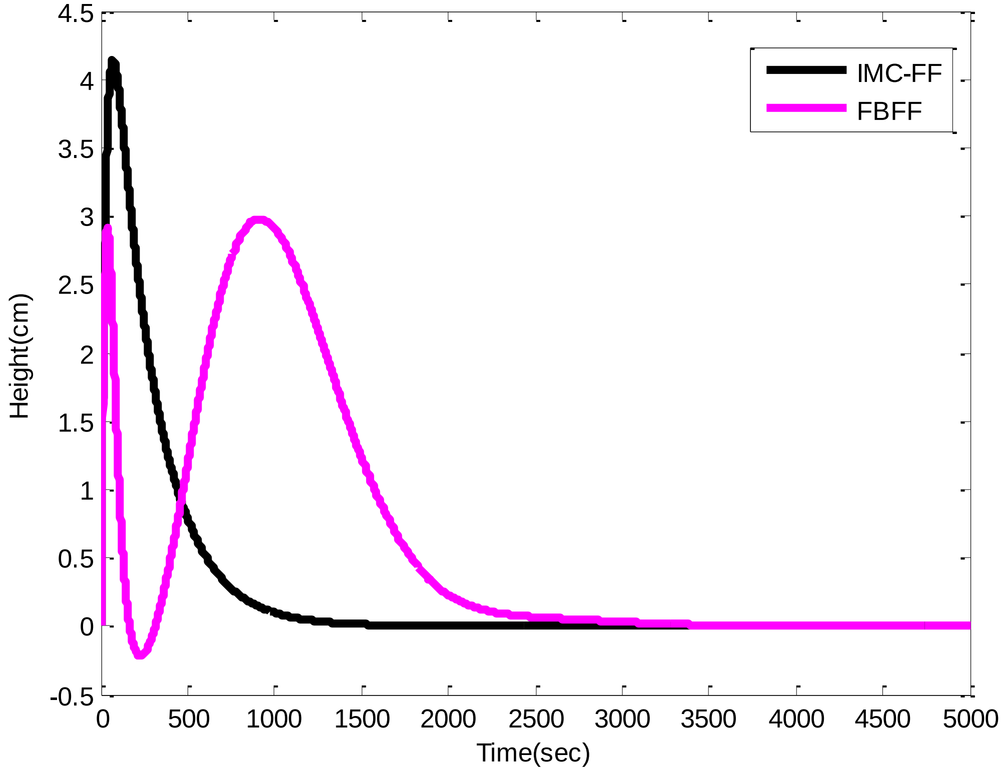

Figure 4.22 Comparison of IMCFF and FBFF in disturbance rejection

4.3.3.3 Empirical Formulae:

Variation of rise time (t_r) with filter coefficient λ is shown in the figure 4.23:

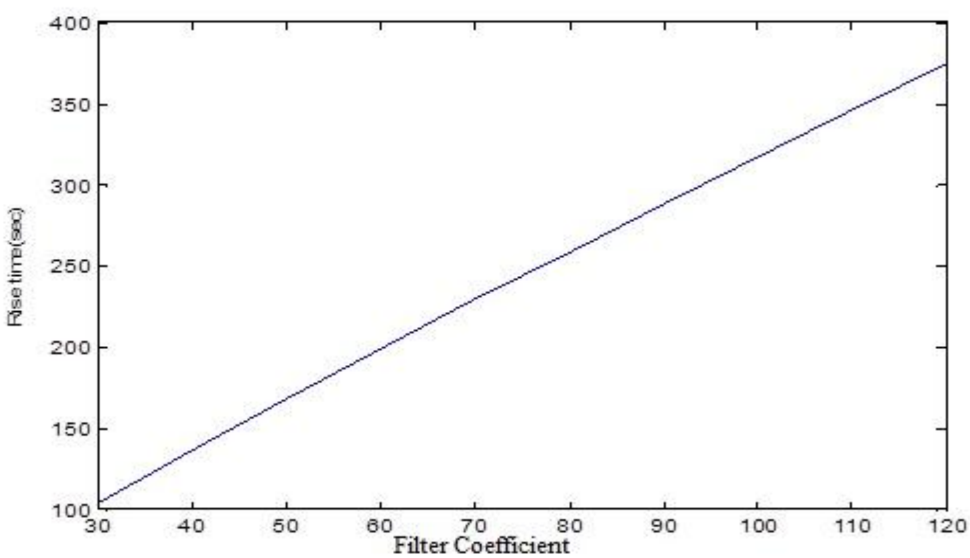

Figure 4.23 Variation of rise time with filter coefficient

The empirical formula for rise time can be written as:

$$t_r = -0.0023\lambda^2+3.3391\lambda+6.1633 \tag{4.23}$$

Variation of settling time with filter coefficient is shown in figure 4.24:

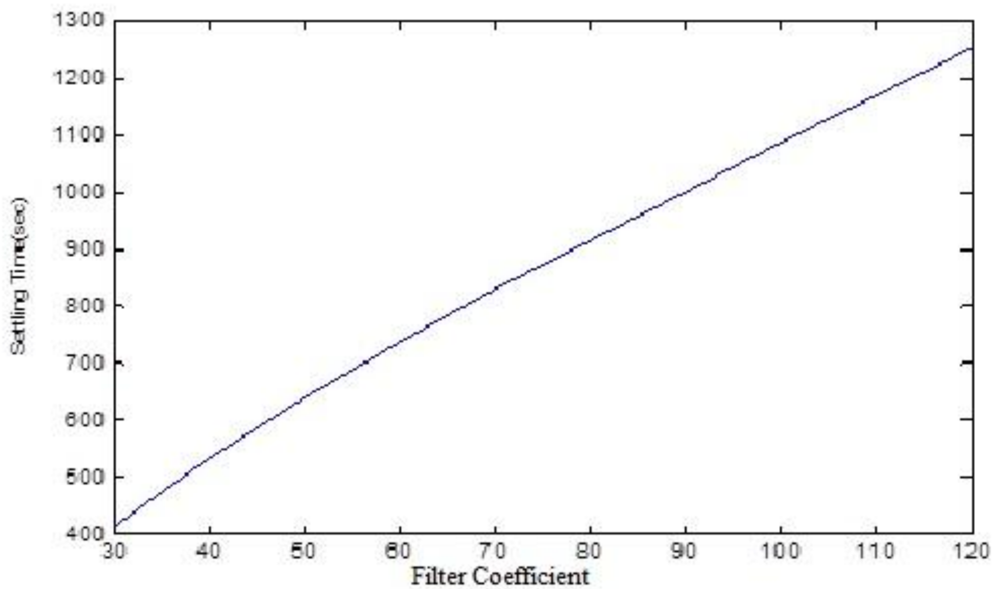

Figure 4.24 Variation of settling time with filter coefficient

The empirical formula for settling time can be written as:

$$t_s = -0.0191\lambda^2+12.0091\lambda+79.2 \tag{4.24}$$

Variation of percentage overshoot with filter coefficient is shown in figure 4.25 and the empirical formula for percentage overshoot can be given as:

$$M_P = -0.000287\lambda^2+0.0668\lambda+1.95 \tag{4.25}$$

Variation of peak time with filter coefficient is shown in figure 4.26 and the empirical formula for percentage overshoot can be given as:

$$t_P = -0.0067\lambda^2+7.47\lambda+38.63 \tag{4.26}$$

These empirical formulae will be helpful when desired performance characteristics have to be achieved then by using these formulae the value of filter coefficient is calculated and accordingly Controllers are designed to achieve desired performance characteristics because it is clear from discussions that for controller designing all we need is optimal filter coefficient.

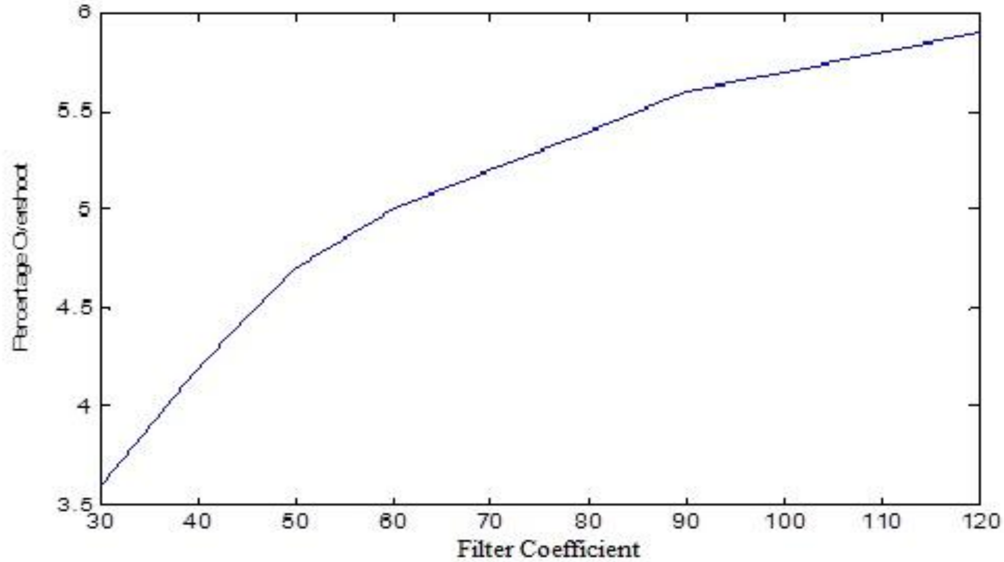

Figure 4.25 Variation of percentage overshoot with filter coefficient

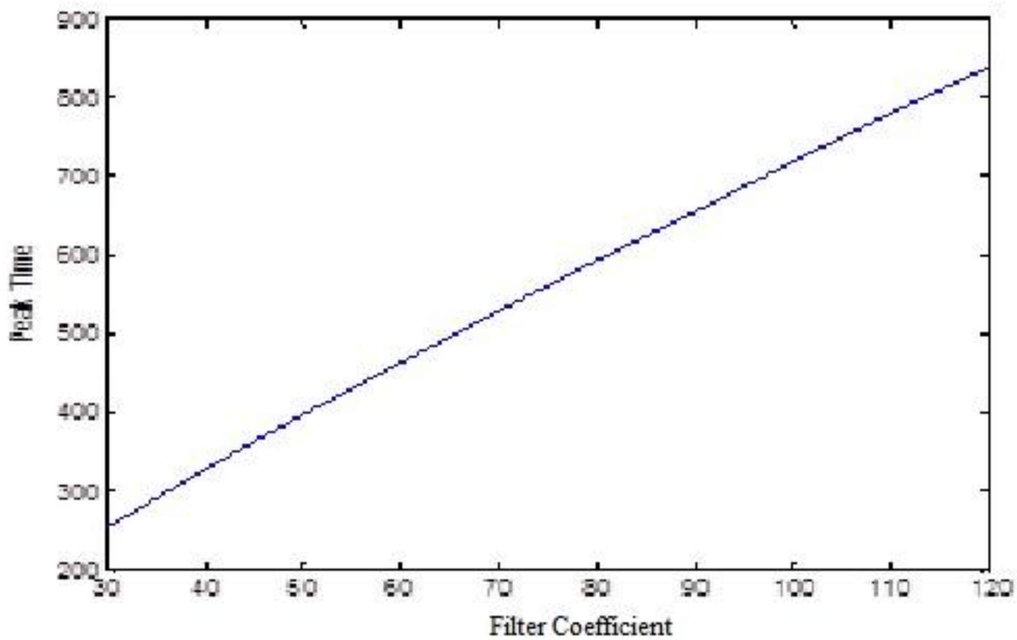

Figure 4.26 Variation of peak time with filter coefficient

4.3.4 Single Tank:

In this section the response of various controllers are compared with IMC-FF for a single tank system. Single tank transfer function is given by equation (3.5):

$$G_P(s) = \frac{1.572}{277s + 1}$$

The transfer function of the disturbance can be given as:

$$G_d(s) = \frac{1}{27s + 1}$$

The transfer function of the IMC controller will be:

$$G_c(s) = 0.83\frac{260s + 1}{30s + 1} \tag{4.27}$$

The transfer function for the feed-forward controller will be:

$$G_{ff}(s) = -0.83\frac{260s + 1}{27s + 1} \tag{4.28}$$

The comparison of various controllers with IMC-FF for a single tank system is shown in figure 4.27. In this figure it is observed that the performance of IMC and IMC-FF are nearly same for single tank system.

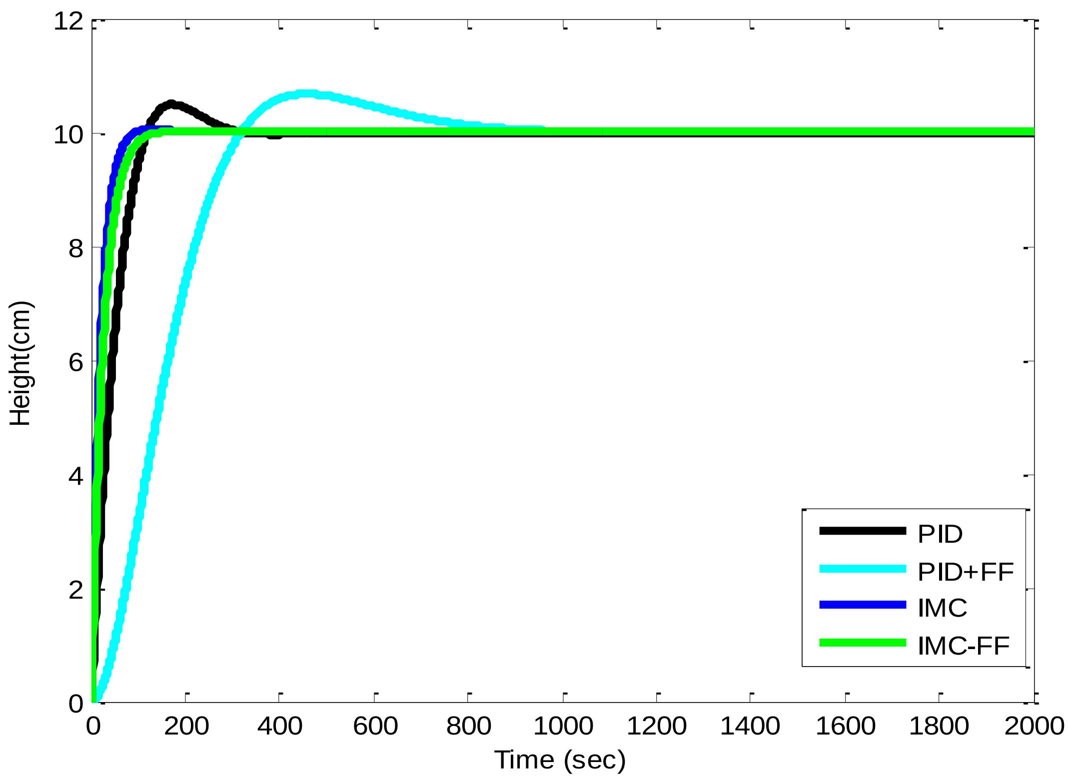

Figure 4.27 Comparison of various controllers with IMC-FF

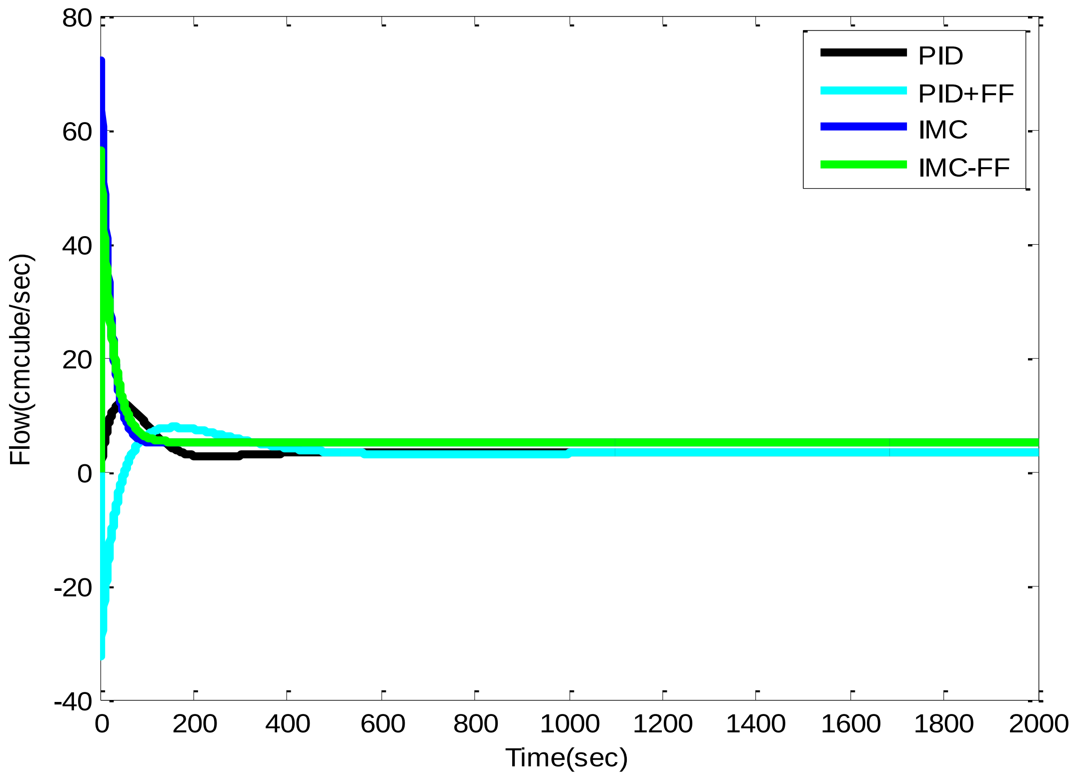

Figure 4.28 Comparison of manipulated variable of various controllers with IMC-FF

	PID	PID+FF	IMC	IMC-FF
Rise Time(sec)	82	209	43	48
Settling time(sec)	256	742	72	79
Percentage Overshoot	5.0	6.7	0.0	0.0
Peak time(sec)	175	460	0	0

Table 4.8 Comparison of performance indices of various controllers with IMC-FF

Figure 4.28 compares the manipulated variable for different controllers. This figure suggests that IMC-FF is better than IMC because IMC-FF requires less magnitude of manipulated variable for achieving same performance as IMC. The other controllers are nowhere in comparison with IMC-FF. IMC-FF is far better than PID and PID plus Feed-Forward.

Actually PID plus Feed-Forward performs better than PID when the disturbance is negative in nature but here the disturbance is considered as additive in nature. So performance of PID plus Feed-Forward is worse than PID alone.

Table 4.8 compares the various performance indices for different controllers. It is noticeable that the value of overshoot and peak time are zero for both IMC and IMC-FF and there is a very less difference between rise time and settling time of IMC and IMC-FF. That is why it is said earlier that IMC and IMC-FF are performing equally for single tank system.

CHAPTER-5
CONCLUSION

5.1 CONCLUSION

In this thesis the work done can be listed as below:

a) The mathematical modeling of Single tank, Two-tank Non-Interacting, Two-Tank Interacting and Three Tank Non-Interacting is done.

b) The experiments are performed on a practical set-up and transfer function of Single tank is determined.

c) This transfer function is used to determine the transfer function of various configurations listed in point (a).

d) After that IMC is designed for Single Tank, Two-Tank Non-Interacting and Two-Tank Interacting system.

e) The Optimal value of filter coefficient λ for IMC in case of a single tank system is 30, for two-tank non-interacting system is 50, for two-tank interacting system is also 50.

f) After IMC, IMC-FF is designed for single tank, two-tank non-interacting, two-tank interacting, three tank non-interacting system.

g) The Optimal value of filter coefficient λ for IMC-FF in case of a single tank system is 30; for two-tank non-interacting system is 30, for two-tank interacting system and three tank interacting system are also 30.

h) Empirical formulae of rise time, settling time, percentage overshoot and peak time are derived for three-tank non-interacting system. These empirical formulae will be helpful when the values of these performance indices will be given and IMC-FF has to be designed to achieve those fix performance indices.

i) Performance of IMC-FF is compared with PID, PID plus feed-forward and IMC. IMC-FF performs better than all these controllers.

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