CERTIFICATION OF APPROVAL

Advanced Process Control of a Flotation Column

By

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHD FAIRUS BIN MOHAMED RAMLEE

ABSTRACT

Flotation cells a solid-solid separation process based on the physical and chemical properties of the mineral particle surface. The process is widely used in the mineral processing industry for a low grade and finely disseminated ores to recover the valuable mineral. It is also applied in recycling and solvent extraction process. These are several problems associated with this process namely:

a) Poor product recovery due to inconsistent froth stability
b) Low product grade attributed to recover of undesired hydrophilic particles
c) High energy and maintenance cost of mechanical agitator
d) Poor control of the cell's level.

The main objective of this research project is to study a possible control type to improve the level control mainly in advance control process. It definitely will enhance the recovery and purity of precious mineral from the ores. There were 5 control types being evaluated in this study which are feedback, feed-forward, cascade, smith predictor and fuzzy logic control.

The research work began with developing model of the flotation column process using simulink toolkit within MATLAB software. It is succeeded with development of the abovementioned controller onto the process model. For those control that uses conventional PID algorithm, similar tuning constant were applied. Each of the control types were subjected to set point change on the level and disturbance (.i.e. ratio of valuable and waste within the feed). The performance for every control type was evaluated and trends were compared.

In conclusion, cascade control provides best performance both performance in set point change and rejecting disturbance.

ACKNOWLEDGEMENTS

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CHAPTER 1
INTRODUCTION

1.1 Background

Cell flotation is a solid-solid separations process based on the physical and chemical properties of mineral particle surfaces. It is a widely used in the mineral processing industry process by the concentration of low grade and finely disseminated ores. Generally the froth flotation is a unit operation for separating selected solids from aqueous suspensions by the introduction of air bubbles with adequate chemical and hydrodynamic condition. The feed to the process is mineral solid/water slurry which also contains a small amount of frother. Air is introduced into the cell through the agitator shaft to generate small bubbles. Minerals rise to the pulp (top) of the cell assisted by a proper hydrodynamic condition achieved through contacting and adhering of hydrophobic particles with the air bubbles. The minerals / air froth formed at the top of the cell finally flows to a launder.

Flotation cells although used extensively in the mineral processing industry have some inherent drawbacks. The product recovery is usually low and recovered solids grade is poor. The main cause for low recovery and poor grade are poor froth stability and a significant recovery of undesirable hydrophilic particles referred to as gangue respectively. Other disadvantages of the flotation cells are poor process controllability and high energy and maintenance costs due to mechanical agitation.

1.2 Problem Statement

Explicitly, the concern of this project is to conduct modeling work and analysis of selected control type for the flotation column. In detail, the concern is to simulate the flotation dynamic control process by applying five control methods. These control types are feed forward control, feedback control, cascade, smith predictor and fuzzy logic control. Fuzzy logic is introduced as the one advance process control to simulate its behavior regarding to the flotation process. Thus, in order to condone the task, it is fundamental to equip basic knowledge of the process dynamic and controls in the minerals industry particular on froth flotation column. The recommended control strategies can be a reference in future for further enhancement of the system involving flotation column.

1.3 Significant of the Project

By identifying and analysis of the selected advance process control for flotation column, a stable process can be accomplish through the automatic control of process variable involve. Subsequently, it would also allow better understanding of the dynamic model control behavior for the process. The dynamic model is developed by using simulink in Matlab software. Basic tuning also has been condoning in order to get initial basic value for further simulation.

1.4 Objective and Scope of Study

The objectives for this research comprise in the following;

1. To study the behavior of a flotation process.
2. To built simple model of dynamic flotation process
3. To add and improve the existence dynamic flotation model by applying a selected advance process control.
4. To initiate the tuning process then applies by using advance process control.

The scope of the studies is to enhance the control system of the flotation. The main criteria monitored when controlling the flotation is the level. This can be done by applying the advanced control strategies. In this study, the Advanced Control Strategies adapted are as follow:

- Feedback Control System
- Feedforward Control System
- Cascade Control
- Smith Predictor Control Method
- Fuzzy Logic System

CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1 Control process of a flotation

In the case of the column flotation process, the main control objective is the optimization of the metallurgical performance so as to guarantee that the column operation reaches the reference values necessary for the desired recovery and grade of the concentrate stream. To achieve this goal, it is first necessary to stabilize the process thus minimizing the number and severity of the erratic operations. Under these conditions, one of the specific control objectives is to maintain at pre-specified values variables such as froth layer height, air holdup in the recovery zone and bias, by manipulating the air, the wash water and the non-floated flow rates. These variables are indirectly related to the recovery and to the concentrate grade. Figure 2.1 show the process diagram of flotation column.

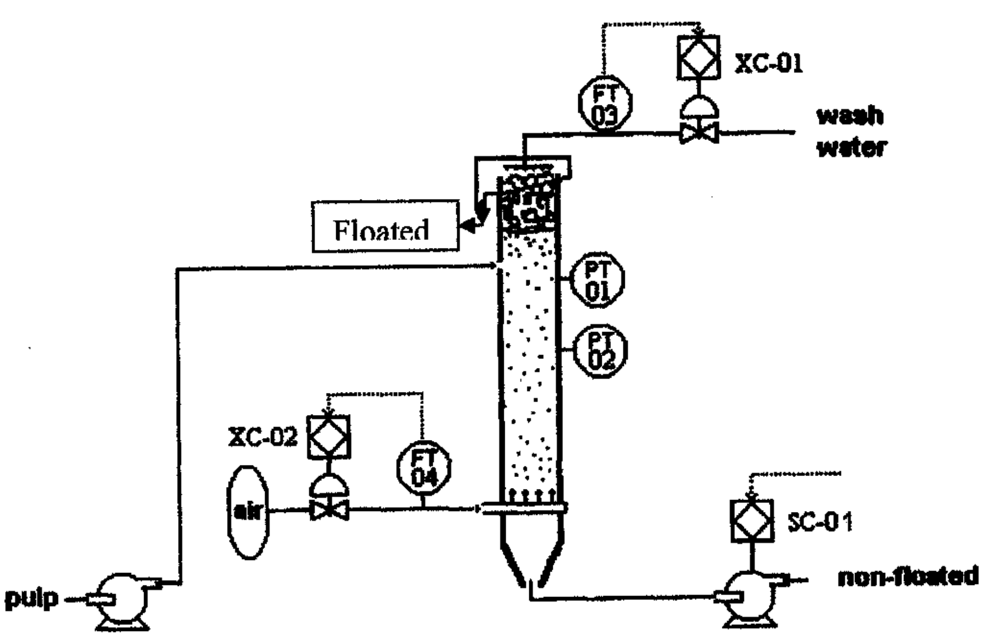


Figure 2.1: Schematic Diagram of a Flotation column

To implement a predictive controller for a coal flotation column, Pu *et al.* (1991) developed a model in which the controlled variables are the froth layer height and the air holdup in the recovery zone, the air flowrate and the non-floated flowrate being the manipulated variables. Bergh and Yianatos (1995), describe a discrete time model for a pilot-scale column operating in a two-phase system. The model describes the relationships between the froth layer heights, the air holdup in the recovery zone and the bias (defined as the difference between the non-floated flowrate and the pulp feeding flowrate) with the wash water flowrate and the percentage of aperture of the valves that control the non-floated flowrate and the air flowrate. However, the relationship between the froth layer height and the percentage of aperture of the air control valve has not been determined; Del Villar *et al.* (1999) present a continuous time model relating the froth layer height and the bias with the non-floated flowrate and wash water flowrate. Their objective was to implement a multi-loop control strategy.

In this work, a complete model describing all the interactions between the manipulated and the controlled variables is presented. The model, derived initially from the mass and energy balance equations of the process has been specifically developed to emulate multivariable control strategies. In this case, the true physical variables are used in the modeling process and the model validation is accomplished using data gathered from a pilot-scale column equipped with sensors and actuators similar to the ones used in industrial plants (figure 2.1).

2.2 The dynamic model for a flotation

The assumption is to consider only two components into the flotation, which are the valuables and waste. The agitator suspends in the flotation cell the component are perfect mixing. The rate equation for the model is independent of temperature, which the rate is constant. The valve equation is controlled at the tails of the flotation.

The dynamic behavior of the sump is as follows:

$$\frac{dM_v}{dt} = F_v - T_v - C_v \tag{2.1}$$

$$\frac{dM_w}{dt} = F_w - T_w - C_w \tag{2.2}$$

$$\frac{M_v}{M_w} = \frac{T_v}{T_w} \tag{2.3}$$

F is the mass flow rate in the flotation cell, T is the tails flow rate out from the flotation and C is the concentrate out from the flotation. The subscript v and w denotes the valuables and waste respectively.

$$T_v + T_w = C_v x \sqrt{\rho g h} \tag{2.4}$$

$$C_v = k_v M_v \tag{2.5}$$

$$C_w = k_w M_w \tag{2.6}$$

$$\%\,Level = 100 \times \left[\frac{M_v}{\rho_v} + \frac{M_w}{\rho_w}\right] \times cell\ height \div Area \tag{2.7}$$

k is the rate constant, C_v is the valve sizing, x is the valve opening, ρ is the density. The square root for the tails equation are related by the following equation:

$$T_v + T_w = C_v x \sqrt{\frac{g(M_v + M_w)}{Area}} \tag{2.8}$$

where $Area$ is the cross sectional for the flotation cell.

The overall equation for the mass flow for the valuables and waste are as follows:

$$\frac{dM_v}{dt} = F_v - k_v M_v - \left[\frac{M_v}{M_v + M_w}\right] C_v x \sqrt{\frac{g(M_v + M_w)}{Area}} \tag{2.9}$$

$$\frac{dM_w}{dt} = F_w - k_w M_w - \left[\frac{M_w}{M_v + M_w}\right] C_v x \sqrt{\frac{g(M_v + M_w)}{Area}} \tag{2.10}$$

The dynamic modeling mass balance is an ordinary differential equation (ODE). The equation is modeled in Matlab simulink. The valve-sizing coefficient was determined as 30 $m^3/hr\ Pa^{1/2}$. The volume for the flotation used is 60 m^3. The rate constant for the valuables is 0.01 hr^{-1} and for the waste is 0.001 hr^{-1}. The total flow in the flotation is maintained at 100 tonnes/hr. The density for the valuables and the waste is 2.65 and 1.00 tonnes/m^3 respectively.

CHAPTER 3
METHODOLOGY AND PROJECT WORK

Initially the methodology of this project involve of four steps. From the literature review said that the dynamic of flotation process is derived from the pilot-scale model. But in this project the behavior of cell flotation is determined by derived equation from dynamic behavior of sump where the level (controlled variable) are determined by valuable and waste flow rates respectively. This equation is developed by author supervisor where the research is done for further analysis especially to look its control behavior regarding to dynamic of flotation process. In doing so, the project work has a several steps which are:

1. Identify the process variable and assumptions for a flotation system
2. Develop the flotation dynamic equation
3. Establish a Flotation tank circuit in MATLAB simulink as a subsystem
4. Develop closed loop control for respectively control strategies by MATLAB simulink

3.1 Identify the process variable and some assumptions

As the first step in determining the level behavior of flotation column, some variable need to identify. The controlled variable introduce in this system is l*evel* meanwhile the manipulated variable is valve opening at the tail of the cell. Valuable flow rate and waste flow rate is acting as the feed assumption flow into the cell. Basically the ratios of valuable and waste flow rates are given as 50-50%, 60-40% and 80-20%. Other assumptions that need to be considered are:

1. The process is always in ideal condition
2. The process is independent from the temperature change.

3.2 Develop the dynamic behavior of flotation column.

The dynamic behavior of flotation column is determined by the equation from section 2.2. All the equations are developing by sump equations which finally give the level in the column. The equation for all the functions is as follows:

$$ratio\ of\ the\ tails\ valuables\ \ to\ tails\ waste = \frac{mass\ of\ valuables}{mass\ of\ waste} \tag{3.1}$$

$$\%\ Level = 100 \times \left[\frac{mass\ valuables}{density\ valuables} + \frac{mass\ waste}{density\ waste} \right] \times cell\ height \div Area \tag{3.2}$$

$$Tails\ valuables = \left[\frac{mass\ valuables}{mass\ valauble + mass\ waste} \right] \times C_v x_v \sqrt{\frac{g(mass\ valuables + mass\ waste)}{Area}}$$

$$Tails\ waste = \left[\frac{mass\ waste}{mass\ valuables + mass\ waste} \right] \times C_v x_v \sqrt{\frac{g(mass\ valuable + mass\ waste)}{Area}}$$

3.3 Establish a flotation tank circuit in MATLAB simulink as a subsystem

After the equation is developed, the dynamic equation was modeled in the Simulink as subsystem. First, the equation of flotation system is translated into the circuit by using MATLAB simulink. Figure 3.1 shows the detail circuit created for this sytem. The input for the subsystem is the feed of the valuables, the feed of the waste, cell height, the rate constant for the valuables and the waste, cross sectional area for the flotation cell, valve sizing coefficient and the valve size opening.

From the circuit, the function 2 is the tails of the valuables, function is the ratio of the mass valuables to the mass of the waste, function 1 is the equation for the percentage level in flotation and function 3 is tails of the waste. The integrator is the initial condition for the mass of valuables and the integrator one is the initial condition for the mass of waste.

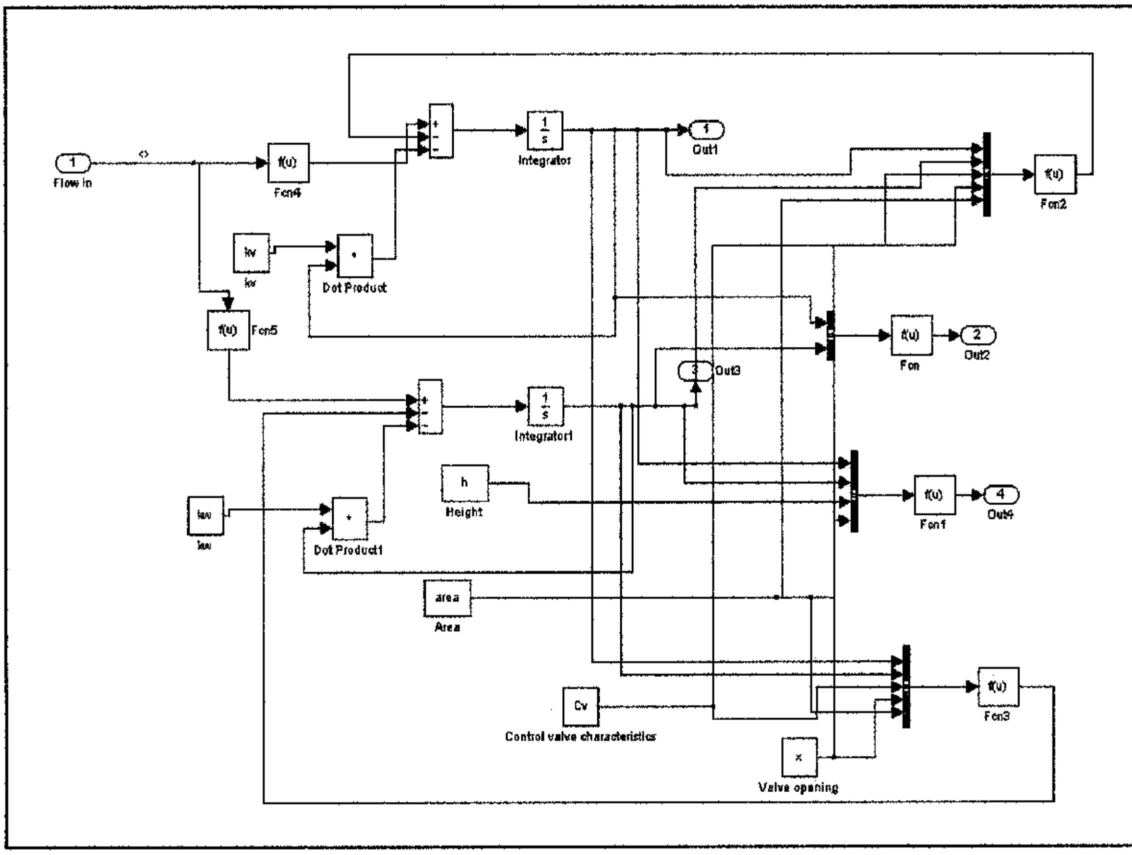


Figure 3.1: The detail circuit of flotation column

Finally the circuit is then comprised to one block process which is called as a subsystem.

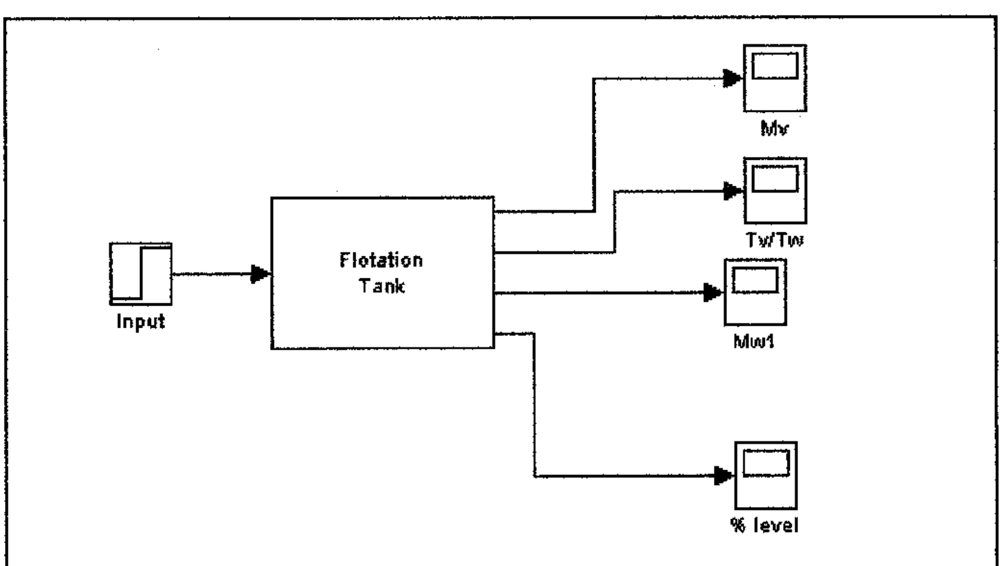


Figure 3.2: Subsystem of Flotation Column

3.4 Develop closed loop control for respectively control types by MATLAB simulink

Finally the subsystem is analyzed for five control method. Basically the first two type of control method is the basic controls which are feedback and feed forward control. Then the work is proceeded to determine the flotation control system acting in advance process control such as fuzzy system. Basic value is important to gain in order basic behavior can be completed. All the circuit is perform an open loop tuning to PI controllers which finally give a better result of performance. The flotation block diagram was used in all control loops in order to study its behavior. All the detail circuits for respectively control types can be viewed at the result and discussion section.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Feedback Control

The principle of feedback said that increase the manipulated variable when the process variable is smaller than the set point and decrease the manipulated variable when the process variable is larger than the set point. This type of feedback is called negative feedback because the manipulated variable moves in opposite direction to the process variable. This control was designed to response the error (process variable-set point) in reverse. i.e. the control will increase against negative error and vice versa.

4.1.1 Simulation of Feedback control

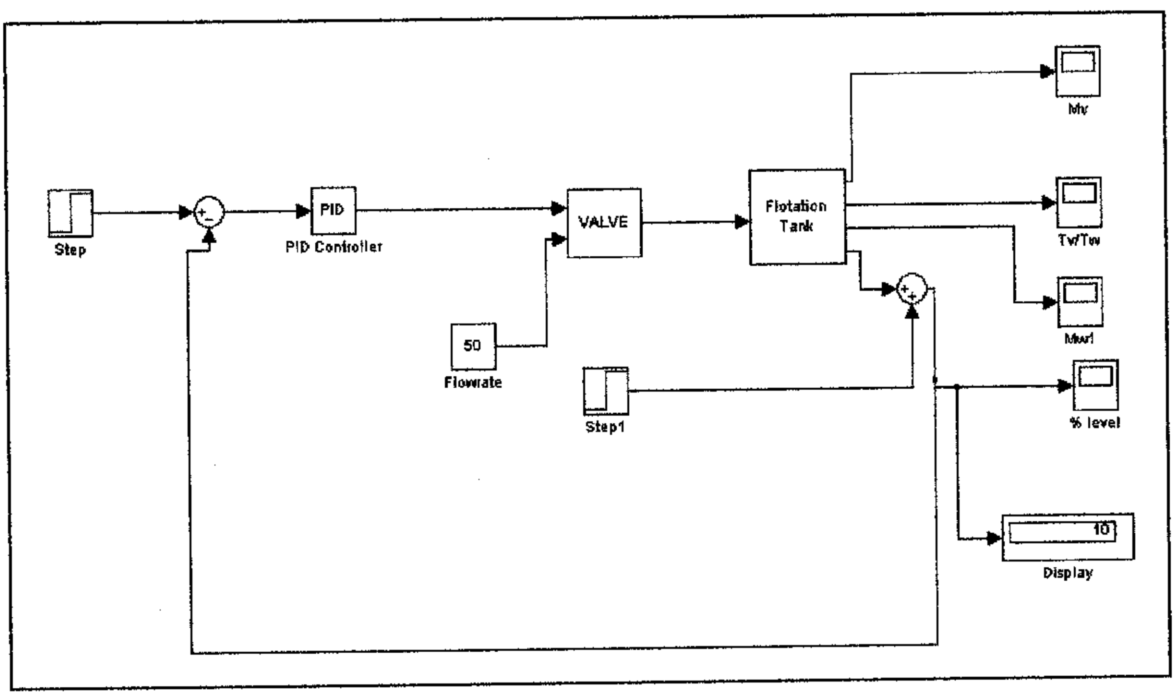


Figure 4.1: Block diagram of feedback control loop for flotation column in Matlab

In simulation generated from Matlab, the response is built base on simulink tool. The diagram above show the typical block simulink which can be used as flotation feedback control as the advance process control application. Valve opening is set to 0.15 with 100% flow rate in flotation column (50% of valuable flow rate and 50% of waste flow rate).

4.1.2 Results

From the result found that feedback control created for flotation column is significant to control. The tuning process is established base on continuous cycling method that was published by Ziegler-Nicholas in 1942. The continuous cycling has also been referred to as loop tuning or the ultimate gain method. To determine the best value of PI controller, the first step is to experimentally determine K_{cu} (ultimate proportional gain). The K_{cu} value is pre-determine by trial and error until oscillatory between the set point is gained. Increase the controller gain K_c by small increment until continuous cycling occurs after a small set point or load change. Meanwhile the period of the resulting sustained oscillation is referred to as the ultimate period P_u. Then the PID controller setting are calculated from Kcu and P_u using Ziegler-Nicholas tuning relation in table 13.1 (refer to appendix I for tuning relation table)

From the tuning result (refer to appendix II) obtain that tuning 5 give the best response with small overshoot and fast response. As we can see at appendix II that the percentage level in the flotation column is maintained at constant 10%.

Comparison is made between the tuning where the result have small an overshoot and oscillations. K_{cu} and P_u value is determined by figure 4.2 which the response is extensively oscillate and not stable. Initially the level response has greater overshoot value and it reducing until at the end of the process. The response is not stable because it has higher upper dead time and lower dead time. From table 13.1 the ultimate Kcu is reducing by 45%. The graph obtained has less oscillation but higher in time settling. The new K_c reducing again by 45% from first tuning which result stable process but not in a good response. It shows that the process response likely generate more oscillation response compare to tuning 1. The number of oscillation also increases after reducing the value of K_{cu}. But the number of oscillation will reduce back same like tuning 1 and tuning 3. Decreasing again K_{cu} by 45 % will result of less overshoot area and oscillation which finally result tuning 6 will give best response of flotation feedback process. (Refer to appendix III).

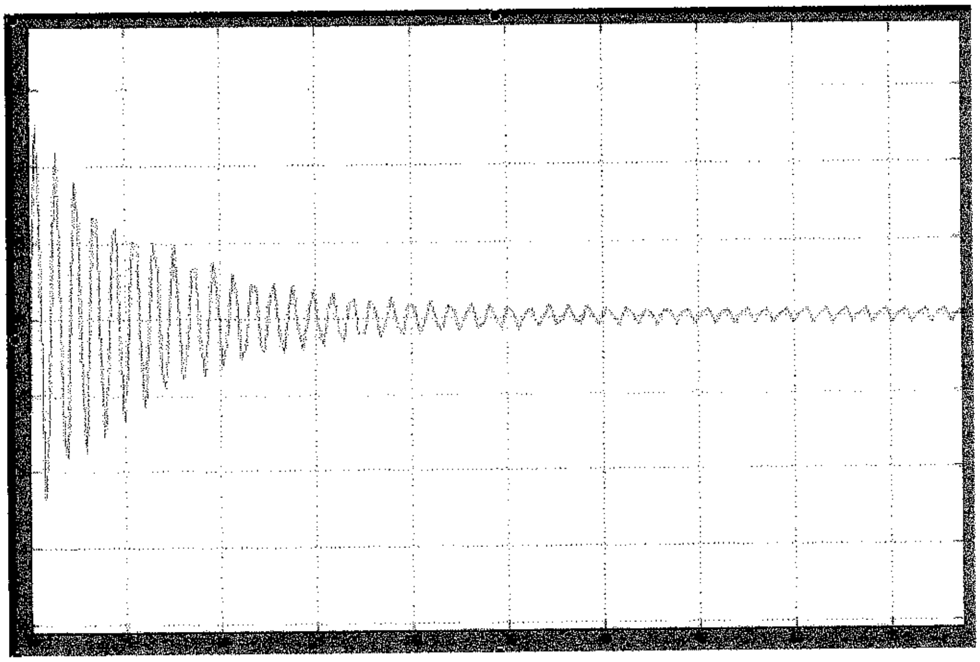


Figure 4.2: Process response for ultimate gain (K_{cu}) and ultimate period (P_u)

There have some disturbance at the output process. The disturbance introduced significantly generates small effect to flotation process response. Other than that the process is not suitable if feedback function, delay time and saturation introduced in the flotation feedback process loop. This is because these functions will give poor performance in the control process.

4.2 Feedforward- Feedback Control

With the feedforward control the basic idea is to measure important variable and take corrective action before they upset the process. In contrast a feedback controller does not take corrective action until the disturbance has upset the process and generated an error signal. From the diagram below there have 2 types of PID controller which are PID feedback controller and PID feedforward controller. These two identical controller is located at different manner which main PID controller need to be set up is PID feedback controller. With 100 tonnes/hr and friction valve opening with two disturbance introduced the loop is modified by adding PID feedforward controller to measure and correct load disturbance measurement.

4.2.1 Simulation of Feedforward-Feedback Control

First the PID value used in this feedback-feedforward control loop is base on tuning made from manual mode of flotation model. There have several values determine from the IMC method calculation. Below are the value of Kc and Ki that make the process is available for best response.

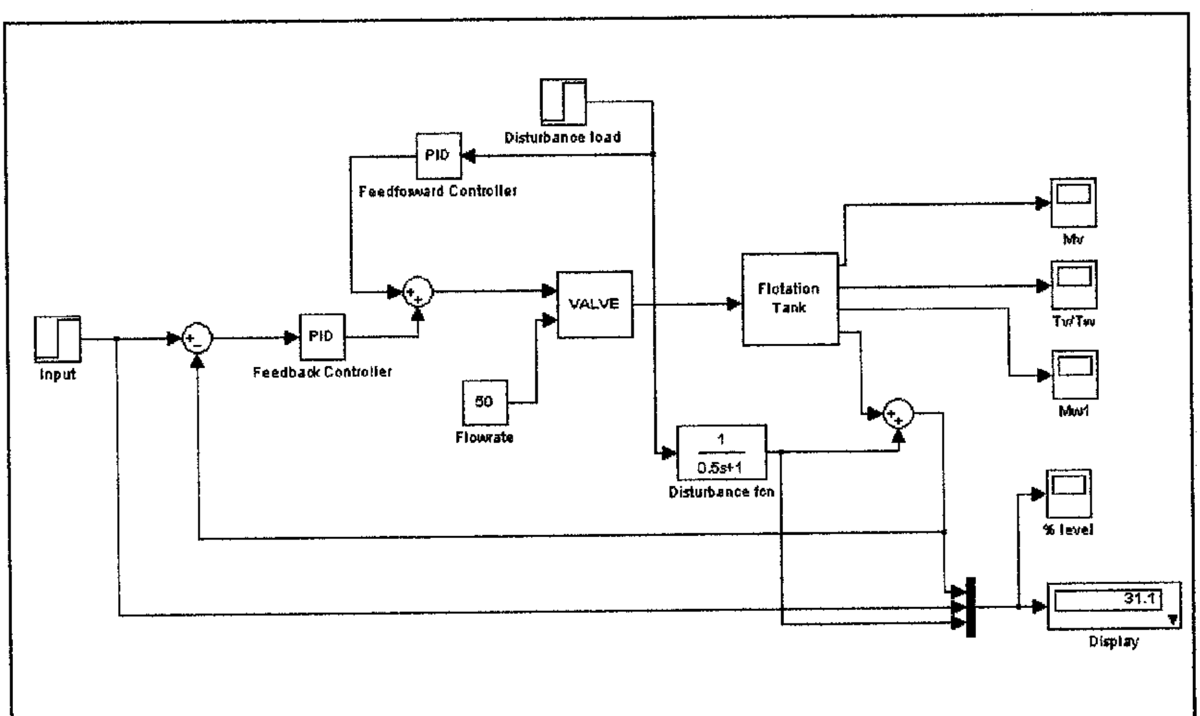


Figure 4.3: Block diagram of Feedforward-Feedback control loop for flotation

4.2.2 Result

Table 4.1: Tuning value from IMC method (from manual mode into auto mode)

Tuning 1	Kc	1/Ki
1	-0.1086	-8000
2	-0.0953	-6000
3	-0.0906	-5500
4	-0.0833	-5000
5	-0.07088	-4650
6	-0.05574	-5800
7	-0.0540	-5650
8	-0.05854	-6000

By referring table 4.1 value the graphs obtain shows result of stability and performance with respect to time which quantifying control performance of the flotation process response.

The result is compare by setting up the valve opening which are the manipulated variable of the control valve. By setting up the valve opening less than 0.25 (Valve opening $\leq$ 0.25) the response show is very unstable because the overflow is happen. (Percentage of level in flotation column exceeds 100%). The graph of all tuning for valve opening 0.25 can be referring to appendix IV

By manipulated the opening valve for above than 0.25 shows that the response for each tuning is very stable to apply. The response is very fast toward constant level at which there is not in overflow manner. No oscillation is present. The graph of all tuning for the valve opening 0.50 can be referring to appendix V

The result show for above tuning is the values that give stability and performance % level also can be applied from simple auto mode to advance process control like feedback-feedforward control loop. These values is like kind of uncontrolled level which it's only depend the manipulated variable which is valve opening from the tail of the column. By looking into the pervious tuning for feedback control loop mode, the value of feedback control loop is tune base on continuous cycling method. Base on that value, the percentage of the level can be set at desired value with good performance. Base on the tuning from continuous cycling method the best value for PID feedback controller is conclude by the table below:

Table 4.2: Tuning value from Feedback control loop

Tuning	Kc	Ki
1	-0.04887	-0.8333
2	-0.05000	-0.5
3	-0.04887	-0.5
4	-0.02199	-11.25
5	-0.009896	-2.416

In the case of PID value of feedforward controller, the best value of its controller is determined by trail and error process. From this process the best Kc and Ki of feedforward controller are -0.01 and -0.0105 s. Figure 4.4 result for advance process control particular in feedback-feedforward flotation control process for final value of 30%;

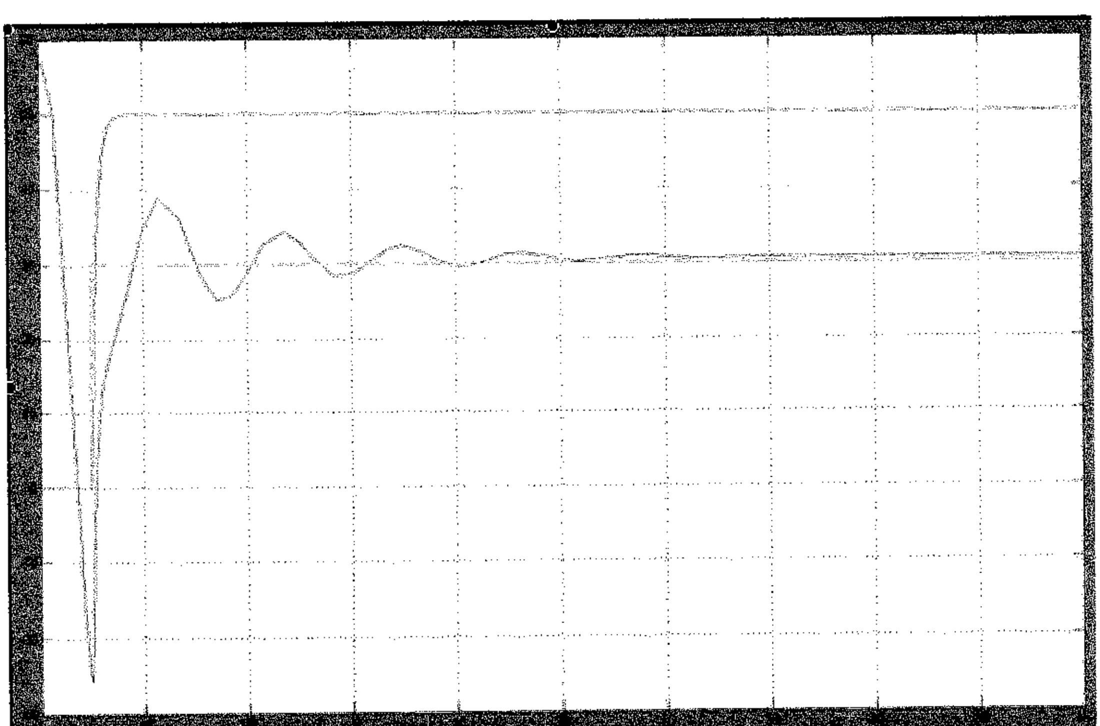


Figure 4.4: Level response of feedforward control loop

The feedback controller used are Kc= -0.04887 and Ki= -0.8333 and it was set to 5 hr step size of time. By referring to the graph the load disturbance is introduced at step size of 5 hr which the performance of the response will corrected effectively to constant level after several hours.

For further analysis we change the load disturbance time for final value of 20 s. The graph is show below:

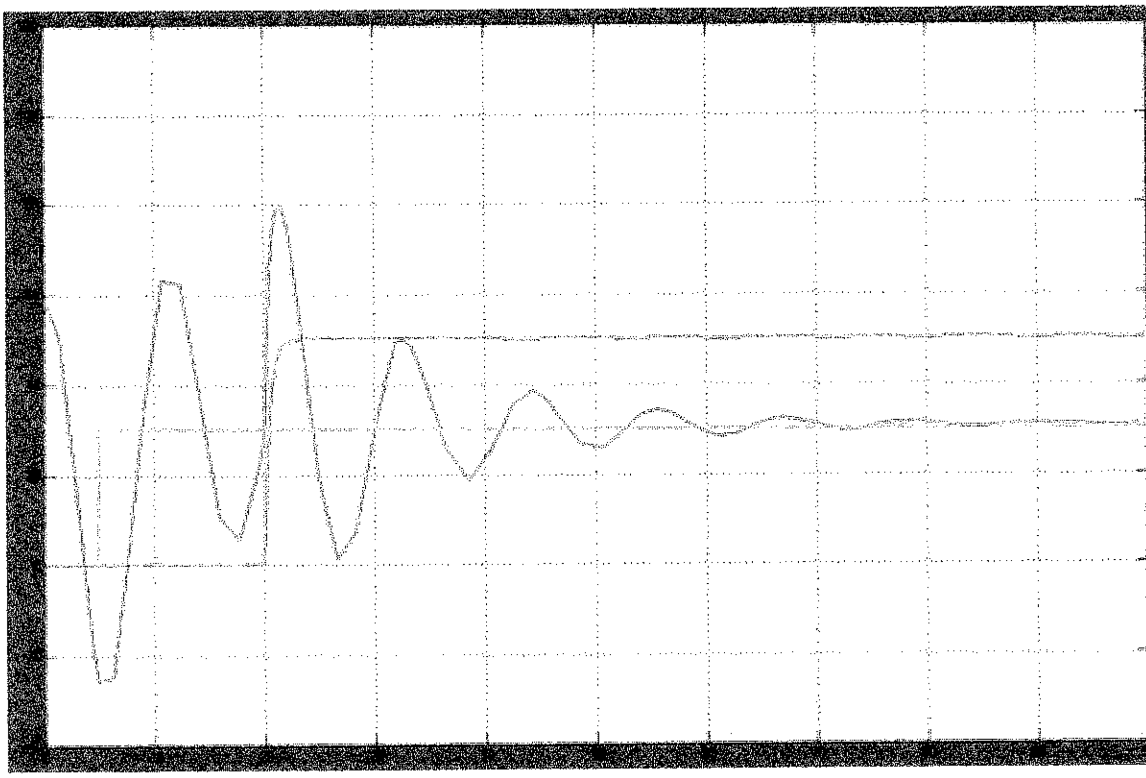


Figure 4.5: Level response of feedforward control with load disturbance change

The load disturbance will result of some overshot and oscillation response that make the process sluggish to become stable. The final value is also have an offset which give an error The load disturbance step size at t= 20 s will generate larger upper and lower dead time of oscillation which it conclude have a greater value of IAE. In order to reduce the dead time of the response the proportional value of PID feedforward controller can be increase to its maximum value which is 1.5. Below are the graph for the model of Kc= 1.5, Ki = -0.0105 s;

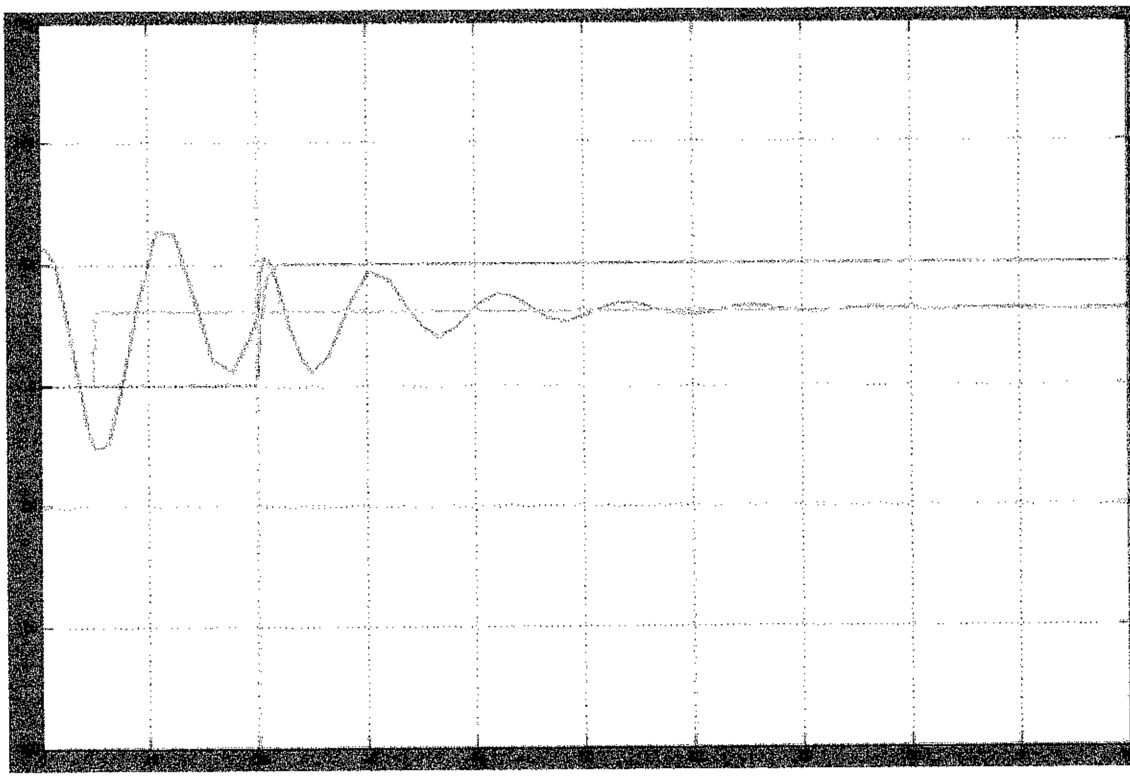


Figure 4.6: Level response with Kc= 1.5, Ki = -0.0105

Beside that the time delay, feedback function and saturation is not suitable for this model of control loop process. It is because the existing of these functions will generate instability of the control loop process.

4.3 Cascade Control

Cascade control application is advance controls strategies used that provide improved process control beyond what can be obtained with conventional PID controller. In the flotation process in order to control percentage level of froth layer inside the column is depend on 3 manipulated variable which are wash water flowrate , air flowrate and non-floated friction flowrate which it directly proportional to the mass flowrate of valuable and waste. By assumption of these manipulated variables the process variable which is the froth layer height can be determined. In real condition process, to determine the actual layer height at constant level for the separation process of solid-liquid phase by surface tension principle is very hard to control. It is because the load disturbance is always to introduce into the system such as variety of wash water, air and non-floated fraction flowrate of the system. Thus the stability of the process control needs to stress on load disturbance change over the time continuously. Therefore cascade control is introduced into the system in order to manage the load disturbance effectively.

A disadvantage of conventional feedback control is that corrective action for disturbance does not begin until after the controlled variable deviates from the set point. As previously look into the feedforward control system offers large improvements over feedback control for processes that have stability of the level height percent. However feedforward control requires that the disturbance be measured explicitly and the model is available for calculating the controller output. Other alternative approach which improves the dynamics response to load change is to use a secondary measurement point and a secondary feedback controller. This secondary measurement point is located so that it recognizes the upset condition sooner that the controlled variable but the disturbance is not necessarily measured. This approach utilizes multiple feedback loops and is called *cascade control.*

4.3.1 Cascade Simulation

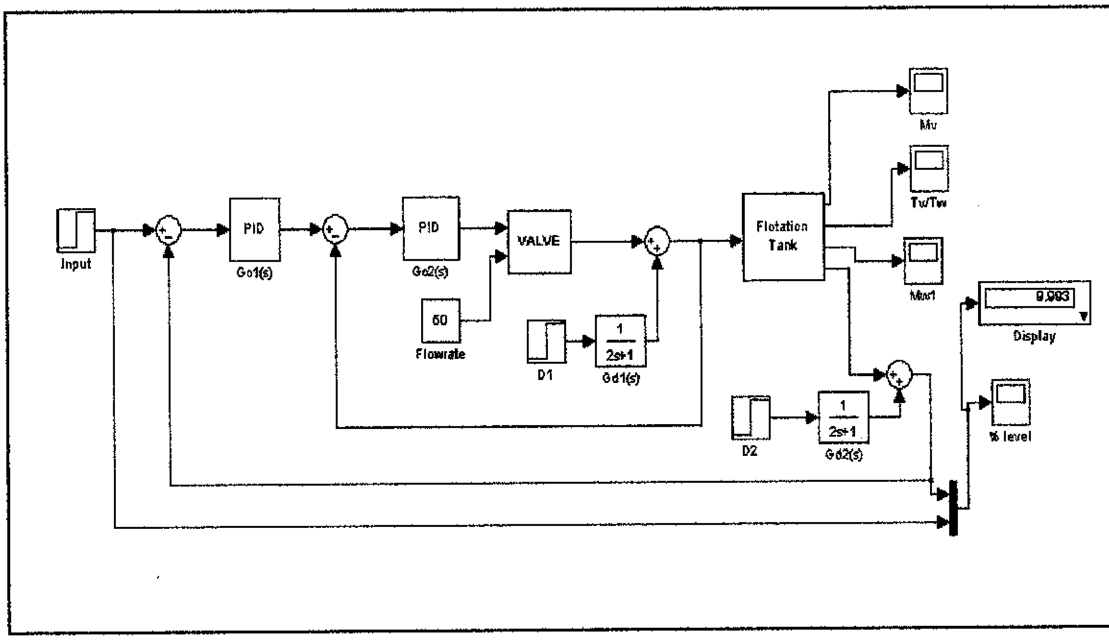


Figure 4.7: Block diagram of Cascade control loop for flotation column in Matlab

The simulation of the flotation cascade control is done by simulink in Matlab software. The simulink interface is used to show how the flotation control process is control. By referring to the diagram above step input is used as the initial input for the system and also the disturbances (D_1 and D_2). Meanwhile the transfer function for the disturbances is also be done by setting up the Kc = 1 and Ti = 2. In the flotation tank processes the constant values involve are;

- Valuable rate constant , 0.01 hr^{-1}
- Waste rate constant, 0.001 hr^{-1}
- Volume of the column , 60 m^3
- Valve sizing coefficient, 30 $m^3/hr\ pa^{1/2}$

However the valve opening is a manipulated variable that control the total flow inside the column. Initial valve opening used is 0.15. By controlling the level of flotation the output of this process comprise of percentage level inside the column, ratio of the tail valuable to tails waste, tails valuable flowrate and waste valuble flowrate.

4.3.2 Result

Cascade control system particular in flotation level control is designed to handle a total flow rate of valuable and waste more effectively. A secondary loop is sued to adjust the regulating valve and thus manipulate the total flowrate of valuable and waste. The primary loop sends its signal in term of desired level to the secondary loop which is flow controller by valve. In essence the signal from the primary loop is the set point of the secondary controller.

In designing the PI controller for the multi loop control process has several setting that need to be done in order the response will give better performance. For primary control loop the value of PI controller used are;

Table 4.3: Feedback control loop tuning

Tuning	Kc	Ki
1	-0.04887	-0.8333
2	-0.05000	-0.5
3	-0.04887	-0.25
4	-0.02199	-11.25
5	-0.009896	-2.416

This result is base on PI tuning by continuous cycling method by Ziegler-Nicholas tuning. However the best performance value that give smooth response in this primary loop for flotation cascade control is tuning 3 which is Kc = -0.04887 and Ki= -0.25. Meanwhile for PI secondary control loop values are determine by trial and error method which the response is advance in multiple control loop in order to eliminate offset from load disturbance introduced. From the 8 tuning that have been made, all the value is available to used in order to manipulated the disturbance occur between the system.

For further analysis the performance of the flotation cascade control value of PI controller for primary and secondary control loop is tested by;

1. Primary control loop ; Kc = -0.04887 and Ki = -0.25 s
2. Secondary control loop; Kc = -1.5 and Ki = -0.4 s

By applying these PI value with the step time of 5 s and there is no load disturbance entered which the final value setting is 50%; the graph is shown as below;

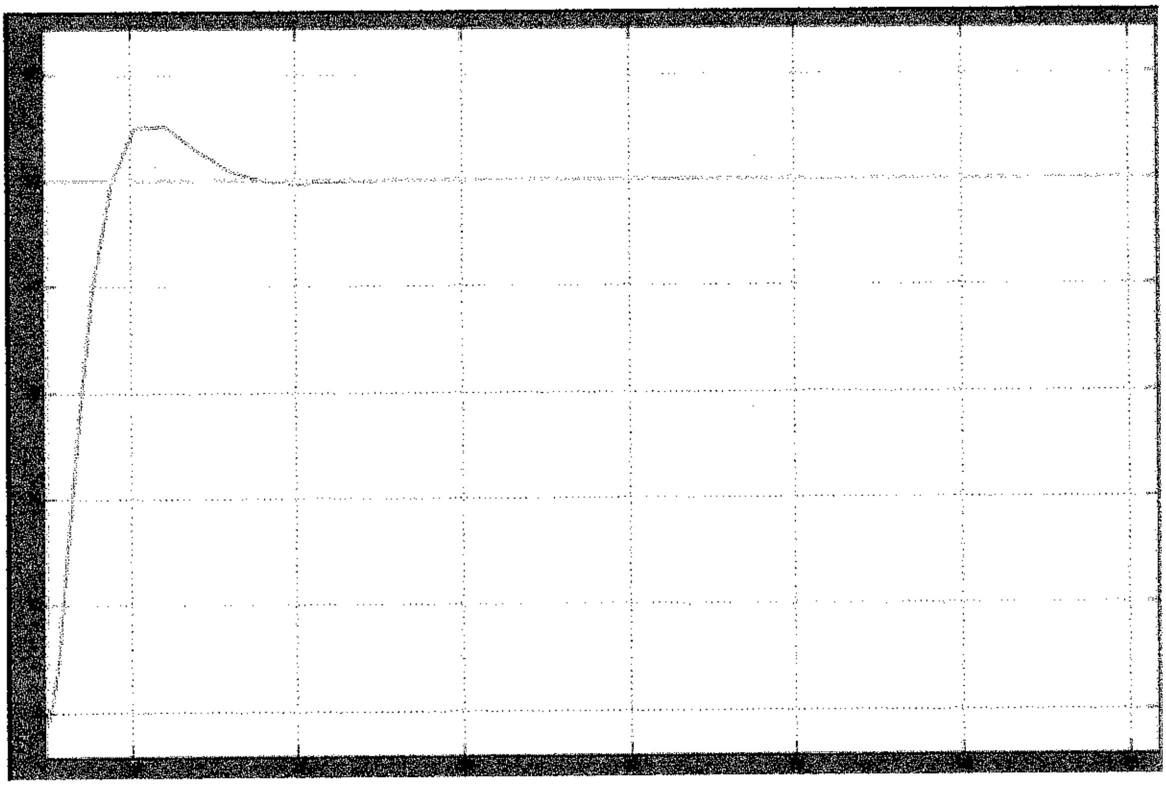


Figure 4.8: Cascade control loop with no disturbance

The graph shows that the response of process variable is faster with only small value of oscillation. The upper and lower dead time is also been reduced by cascade control loop. In this case there is no load disturbance introduced to the system. There are also no offset with final value entered to the system at which 50%.

Time delay function

From the analysis of the flotation cascade control found that the system is not appropriate if the function of feedback measurement done by any measurement transfer function or time delay. It is because the systems will generate unstable response with higher value of percentage level. Thus overflow will happened and it does not meet the objective of the control flotation system. Other than that the quality of the metallurgical metal in flotation separation process will result of low quality.

Load disturbance

The main objective in introducing cascade control of flotation process is the effectiveness of the system to correct load disturbance change. Basically the flotation process has inconsistently of level height in the column. This is happen because of flowrate of wash water, air and non-floated friction is fluctuating over the time. Thus by applying advance process control with multiple control loop the measurement of the load change (disturbance) can be improve.

By setting the same PI controller value for both controllers, two load disturbances are introduced by the disturbance function. First disturbance is measure before the flotation tank meanwhile the other is measure after the flotation tank First disturbance has a step time of 40 s which locate inside the secondary loop meanwhile the second disturbance has a step time of 80 s inside the primary loop. The result can be view as graph below;

Figure 4.9: Cascade control loop with 2 disturbances

4.4 Smith Predictor Controller Method

Theoretically the Smith Predictor Control Method is a special control strategy that is best to be used in order to improve the performance of time delay systems. Time delays commonly occur in the process industries because of the presence of distance velocity lags, recycle loops and the dead time associated with composition analysis. The presence of time delays in the process limits the performance of a conventional feedback control system. From a frequency response perspective, time delay add phase lag to the feedback loop, which adversely affects closed-loop stability. Therefore flotation column level response depends on valuable and waste flowrate which from assumption its may have one of the cause that generate lags for feedback process loop. Thus the model is developing in order to maintain the level if time delay is present in flotation control process.

4.4.1 Smith Predictor simulations

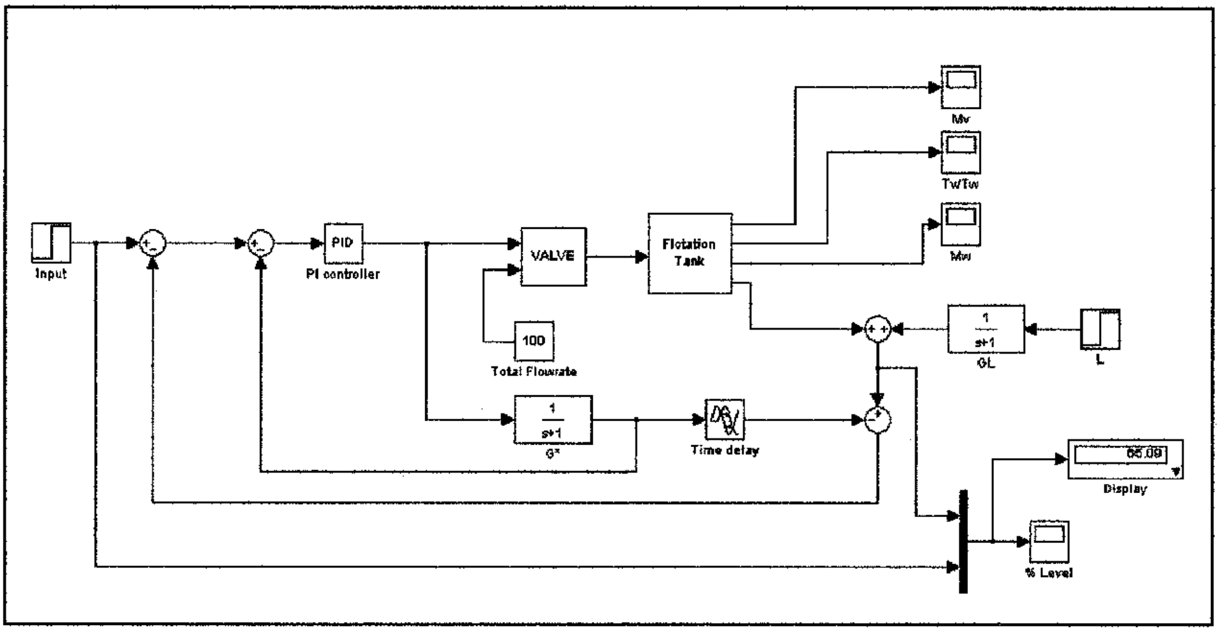


Figure 4.10: Block diagram of smith predictor control loop for flotation column in Matlab

The comparison is made between the different of valuable and waste flow rate into the column. Figure 11 above illustrate the flotation system where the Smith Predictor Controller Method is applied. The step size is 5 % of total flow in with step time of 5 hours. The value for the PI controller used is Kc = -0.04887 and Ti = -0.10. These values are referring to feedback control loop tuning. Then the valve friction opening is set to 0.25. Meanwhile the initial value of valuable and waste flow rate analysis is shown in the table below:

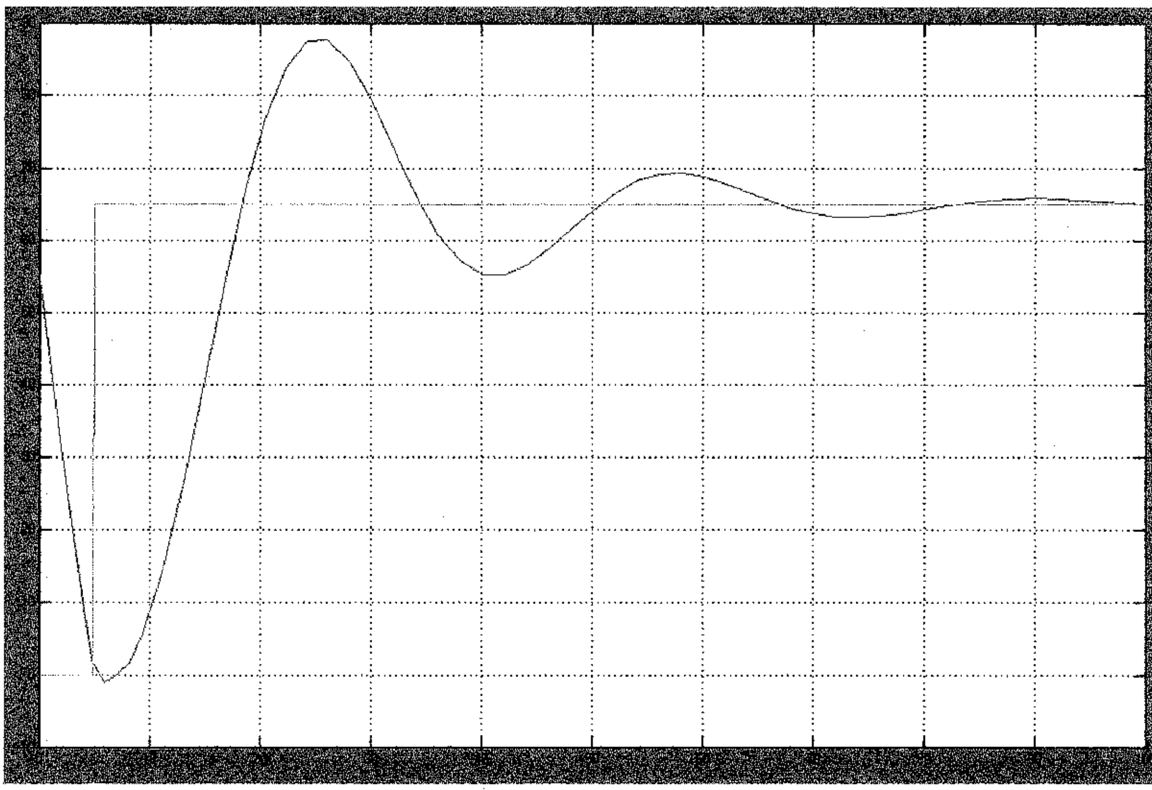
Table 4.4: Ratio of feed flow rate

Parameters	Valuable Flow rate (tones/hr)	Waste Flow rate (tones/hr)	Total Flow rate (tones/hr)
Set 1	50	50	100
Set 2	60	40	100
Set 3	80	20	100

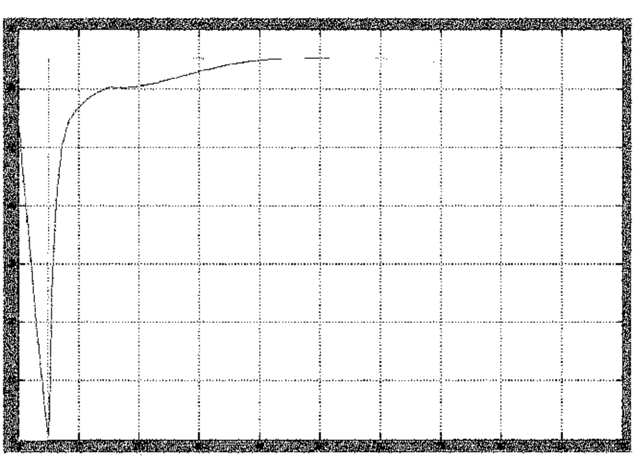
Base on the modeling control loop, the graph is obtained for each set. Time delay is introduced into the system for each set. The value of time delay used is in the range 1-3 s. This range is used as the maximum time. This is because the system become unstable with $0<Td<3$. Beside that disturbance function is assume with Kc=1 and Ti =1 s. The step size input is use as the load disturbance. In this case 60 are used as the disturbance final value with 5 hr step time. It represent of any changes that influence the percentage level inside the flotation column. For example is tail flow rate is not constant or variation of total flow rate in the system.

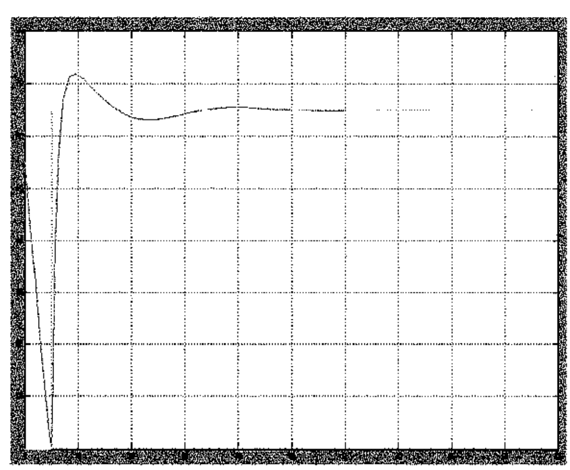
4.4.3 Result

For flow of feed valuables and feed waste is at 50 and 50 tonnes/hr, the response is shown below;



a

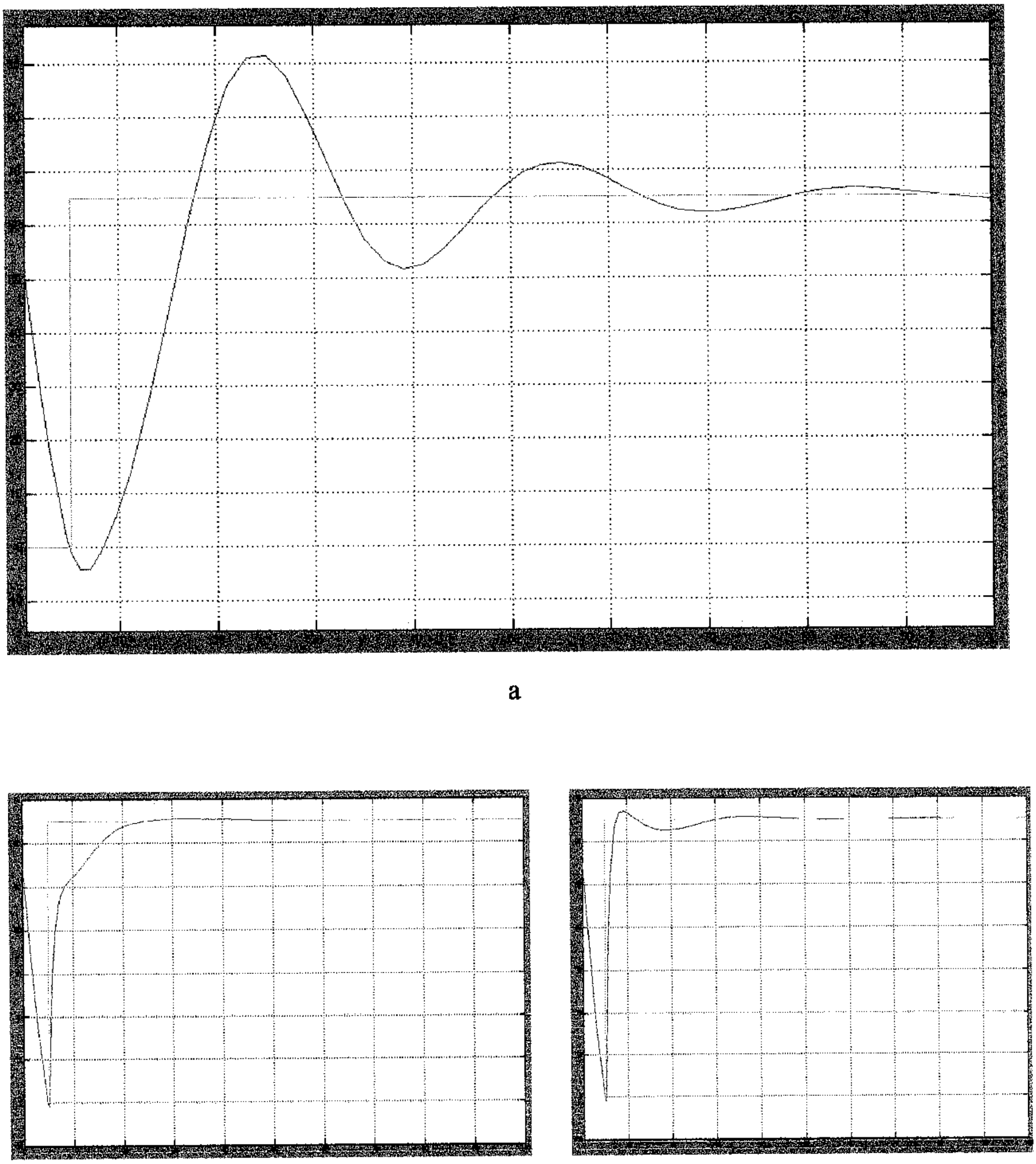




b c

Figure 4.11: a) The level response of 50-50 tonnes/hr with respect to time delay value of 2 hr. b) Load disturbance introduced below the set point. c) Load disturbance introduced above the set point.

For flow of feed valuables and feed waste is at 60 and 40 tonnes/hr, the response is shown below ;



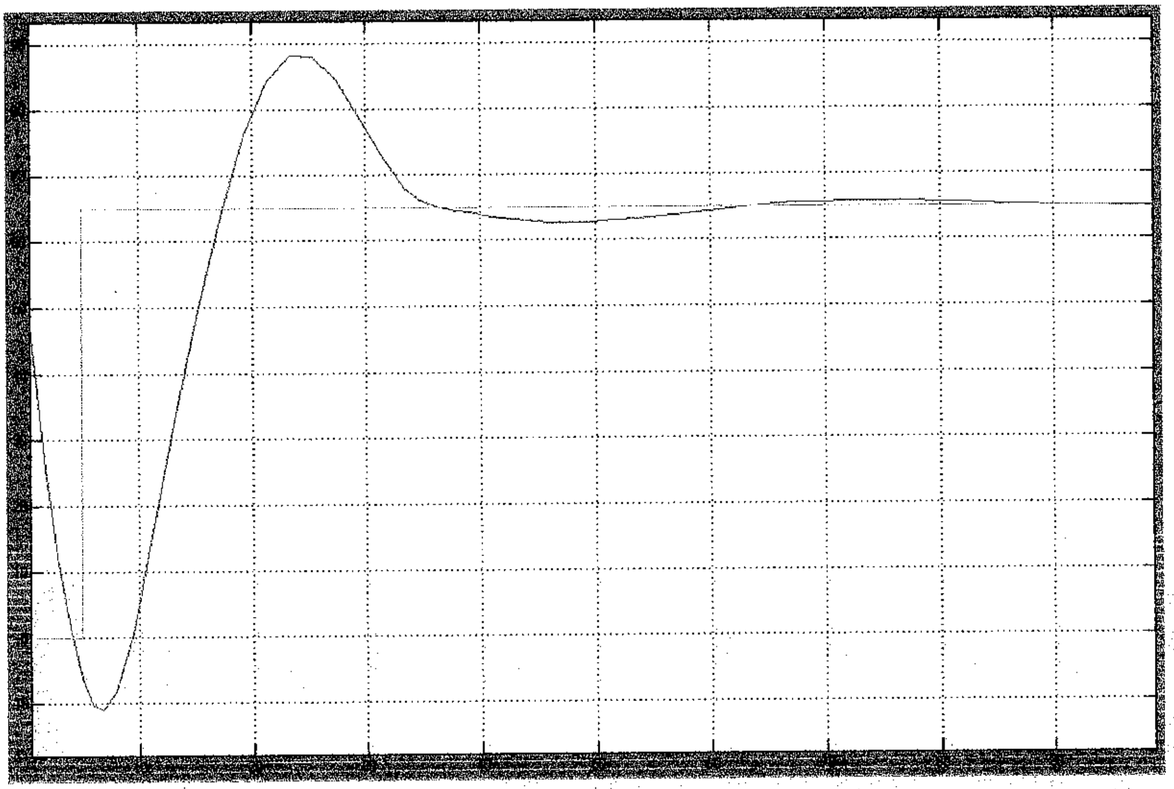
a

b

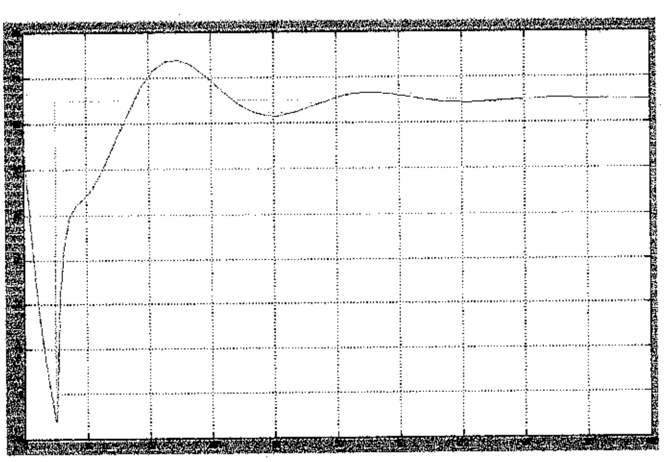
c

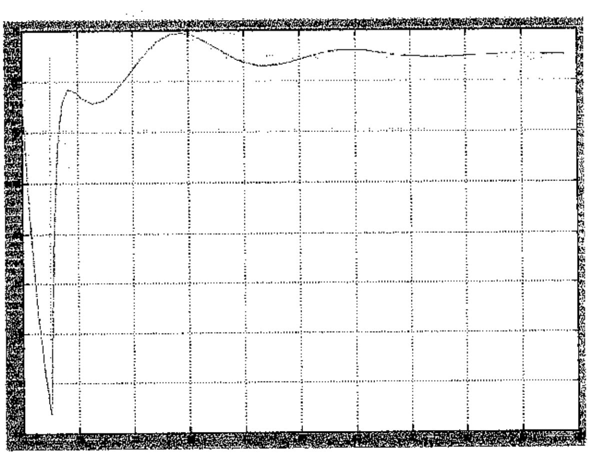
Figure 4.12: a) The level response of 60-40 tonnes/hr with respect to time delay value of 2 hr. b) Load disturbance introduced below the set point. c) Load disturbance introduced above the set point.

For flow of feed valuables and feed waste is at 80 and 20 tonnes/hr, the response is shown below



a





b c

Figure 4.13: a) The level response of 80-20 tonnes/hr with respect to time delay value of 2 hr. b) Load disturbance introduced below the set point. c) Load disturbance introduced above the set point.

From the graph obtained, the response is slight different as the ratio of valuable and waste flow rate is change. Initially 50 to 50 valuable and waste flow rate is investigate by using smith predictor controller method. As mention earlier the control loop introduce into the control process is to eliminate any lags of response due to time delay inside system. Base on figure 12, the response of level response for 50-50 has a higher overshoot with large upper and lower dead time. It same goes for 60-20 and 80-20 ratio of valuable and waste flow rate. The response shown is drive with time delay of 2 s. When the disturbance is applied (step size of 5 with final value 60) the responses are slow and sluggish. However as the step input of load disturbance is increased to 80 of final value, the control loop is corrected faster with little oscillation. It shows that the disturbance introduces for all ratio of valuable and waste flow rate has better stability in maintaining level inside the flotation column. As in feedback, feedforward and cascade process loop, the time delay introduced will disturb greatly of level performance in the flotation column. By using smith predictor control loop, the model is construct to provide time-delay compensations. The performance of time delay system is modeled with double feedback control loop where it determine by corrected time delay input into the stable parameter in control process. Thus the existence of time delay into this system has small impact in performing of better level percentage. Thus it was prove that the performance of time-delay system is improve and can be applied to the flotation model process.

4.4 Fuzzy Logic Control

4.4.1 Fuzzy system

To overcome the difficulties in the development of phenomenogical models, the development of empirical model which base on experimental data is used. The empirical model used is defined as dynamic modeling build for controlling system. However in fuzzy control process, the dynamic modeling is developing mutually with several constraints which its development will toward to better performance.

Fuzzy control can be applied to situations where the information source can be interpreted only on qualitative or inexact form avoiding the need for a time consuming task of construction on mathematical models that can be used in the synthesis of a controller. In this perspective fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multi valued logic. But in a wider sense, which is in predominant use today, fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with unsharp boundaries in which membership is a matter of degree.

Fuzzy logic system is applied into the flotation column. There involve 3 major step which determine the system can be run with fuzzy system;

1. Fuzzification (using membership function to graphically describe a situation)
2. Rule evaluation
3. Defuzzifications (obtaining the crisp result)

There are specific components characteristic of a fuzzy controller to support a design procedure. In the block diagram in Figure 15, the controller is between a preprocessing block and a post-processing block. The following explains the diagram block by block.

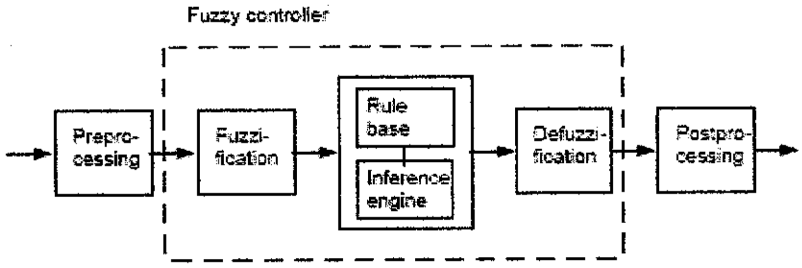


Figure 4.14: Block of fuzzy controller

4.4.2 Simulation of Fuzzy Logic Control

Basically the modeling of simulation is done by simulink in Matlab software. Below are the flotation model constructed in simulink interference.

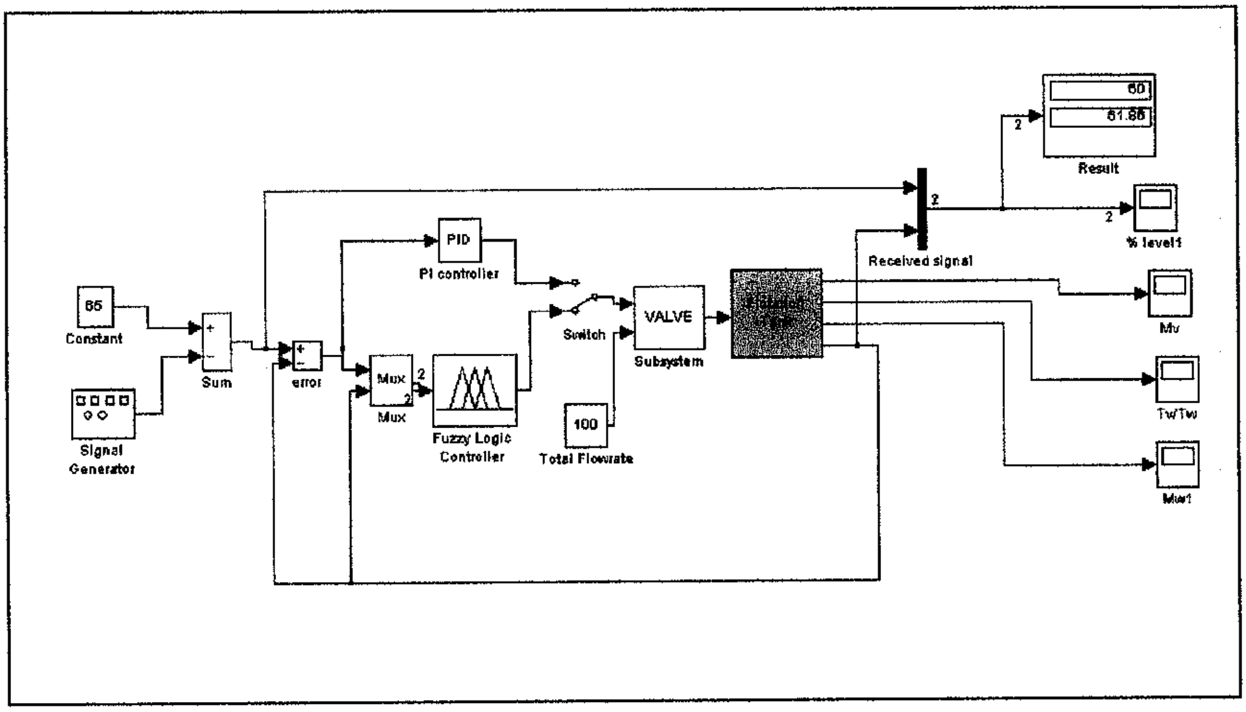


Figure 4.15: Block diagram of Fuzzy Logic control loop for flotation column in Matlab

The diagram above shows flotation column is control by fuzzy logic controller. However it has two way of controllability system which it can be switch manually with PI controller as well. The reason is the comparison between these controllers can be analyzed.

The system of flotation fuzzy structure has internal parameter that it needs to set. Therefore the circuit is built same as PI control loop which the overall circuit is based on the controllability of desired output. The volume used for this column is 60 m^3. Total flow rate is set to 100 tonnes/hr which 50-50 of valuable and waste flowrate. The valve opening for the valve block has an initial value of 0. By maintaining other constant parameter level performance is observe as a major output. Therefore mass of valuable, mass of waste and ration of valuable tail and waste tail are side output which generated from flotation column. By using feedback loop, the percentage level of flotation system will iterate within the system until the result will constant at desired value.

To determine the parameter within the fuzzy system, trial and error method is used as the tuning process. The fuzzy controller has a *Mamdani* type structure with linguistic rules antecedents and consequences. The value is gained by assuming the process is in ideal condition where there is no load disturbance. Beside that the circuit has a signal generator which generates an input continuously. The output is record by the scope function.

Generally 3 steps are required to manage the fuzzy controller system. Below are the detail descriptions for each step.

4.4.2.1 Fuzzification

Fuzzification procedure is involves the definition of the number of linguistic term that characterize input and output variable and the mathematical model of the membership function. The number of term determines the granularity of the linguistic characterization of the variable. In what regards input variable, the term number determines as well the dimension of the problem because the number of input variable term determines the number of rules in the rule base. As the rule base was heuristically defined a large number of terms would not reflect an actual knowledge and therefore only 3 terms per variable is considered which is low, medium and high

The linguistic term for flotation model are mathematically modeled by sinusoidal functions (Gaussmf type). Generally these functions have 3 parameter that can be adjusted according to the knowledge of the variable. The graphs also represent type of reaction that will be response from the controller. More open curve means that the knowledge about the variable is vaguer and the controller permits the variable under control goes far from the set point, before the controller acts vigorously. Meanwhile the less open curve is defined as approximation to on-off controller. In this project two input and one output is used as the variable function in controlling the system. The parameter of the mathematically function for each input and output of flotation column used are shown in table 5 and 6.

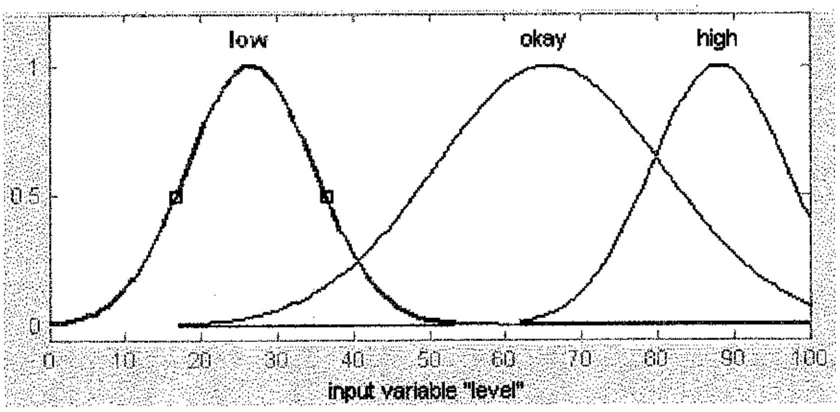
Table 4.5: Membership function parameter of controlled variable

variable	Linguistic term	Parameters		
		a	b	c
Level (%)	Low	1	25	50
	Normal	40	65	80
	High	80	90	100
Rate	Positive	-10	-4	0
	Normal	-4	0	-4
	Negative	-4	8	10

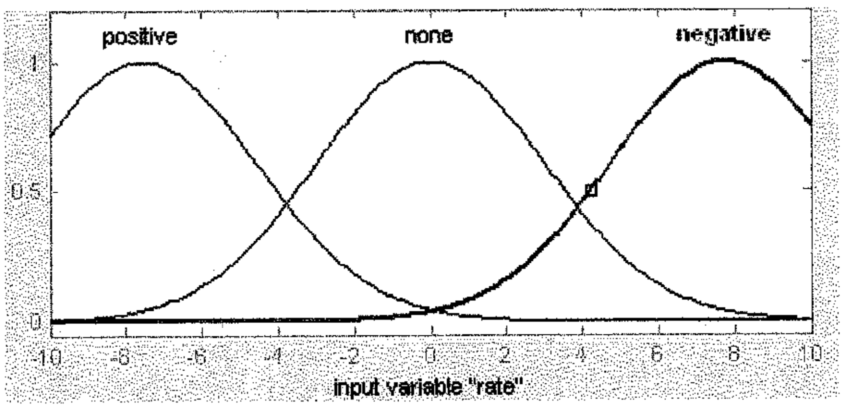
Table 4.6: Membership function parameter of manipulated variable

variable	Linguistic term	Parameters		
		a	b	c
Valve opening	Close fast	0	0.05	0.1
	Close slow	0.2	0.25	0.3
	No change	0.6	0.65	0.7
	Open slow	0.7	0.75	0.8
	Open fast	0.9	0.95	1.0

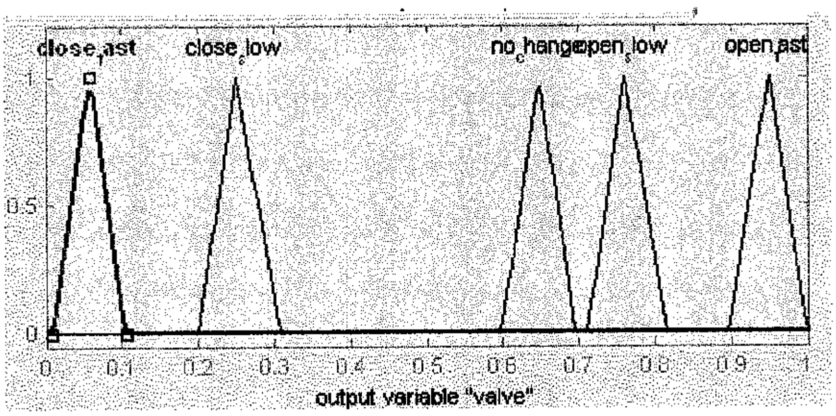
The membership for each variable is assigned into the fuzzy tool in Matlab software where the result is gained. Below are the membership used in Matlab software;



a



b

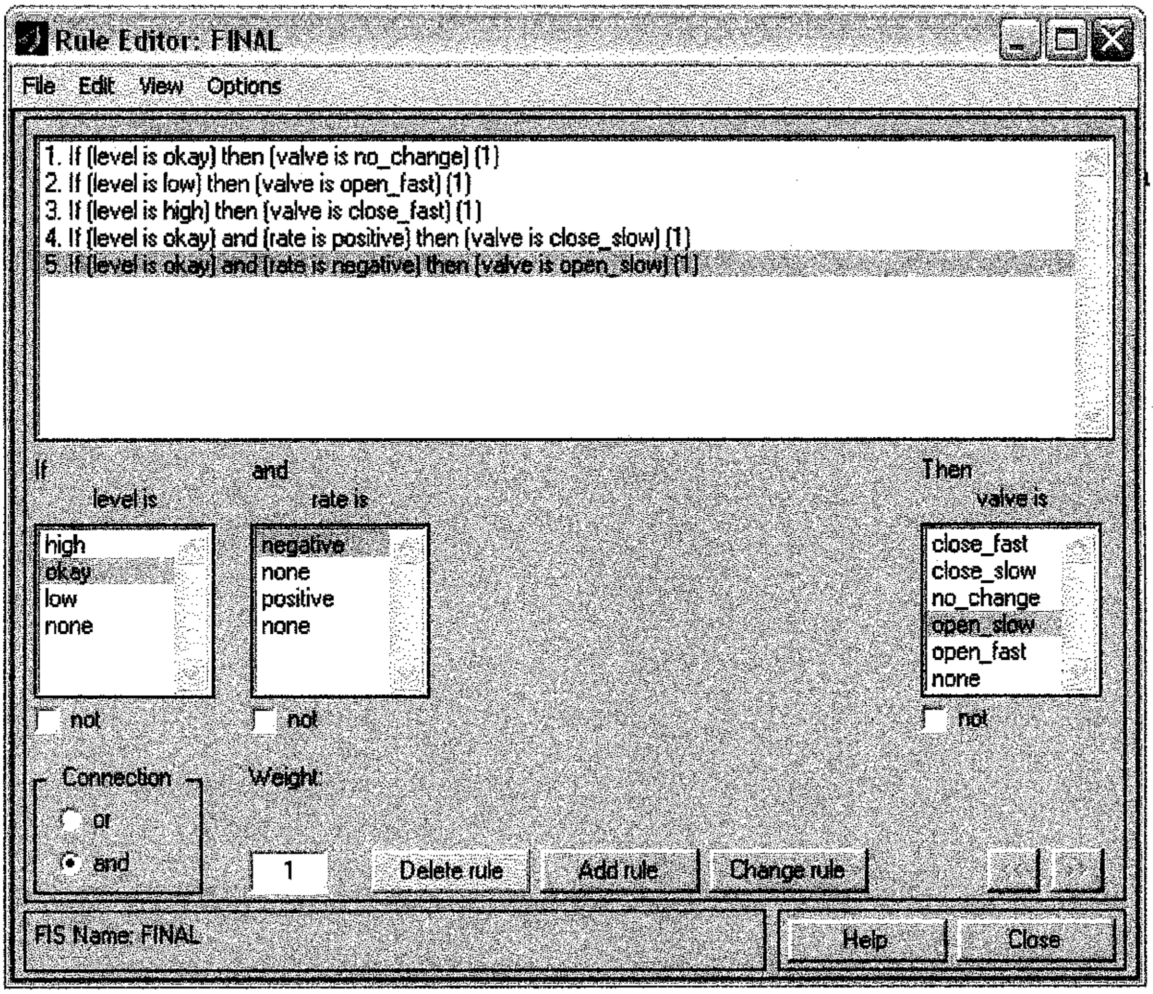


c

Figure 4.16: a) Sinusoidal of percentage level in membership function. b) Sinusoidal of Rate in membership function. c) Valve opening of membership function.

4.4.2.2 Rule evaluation

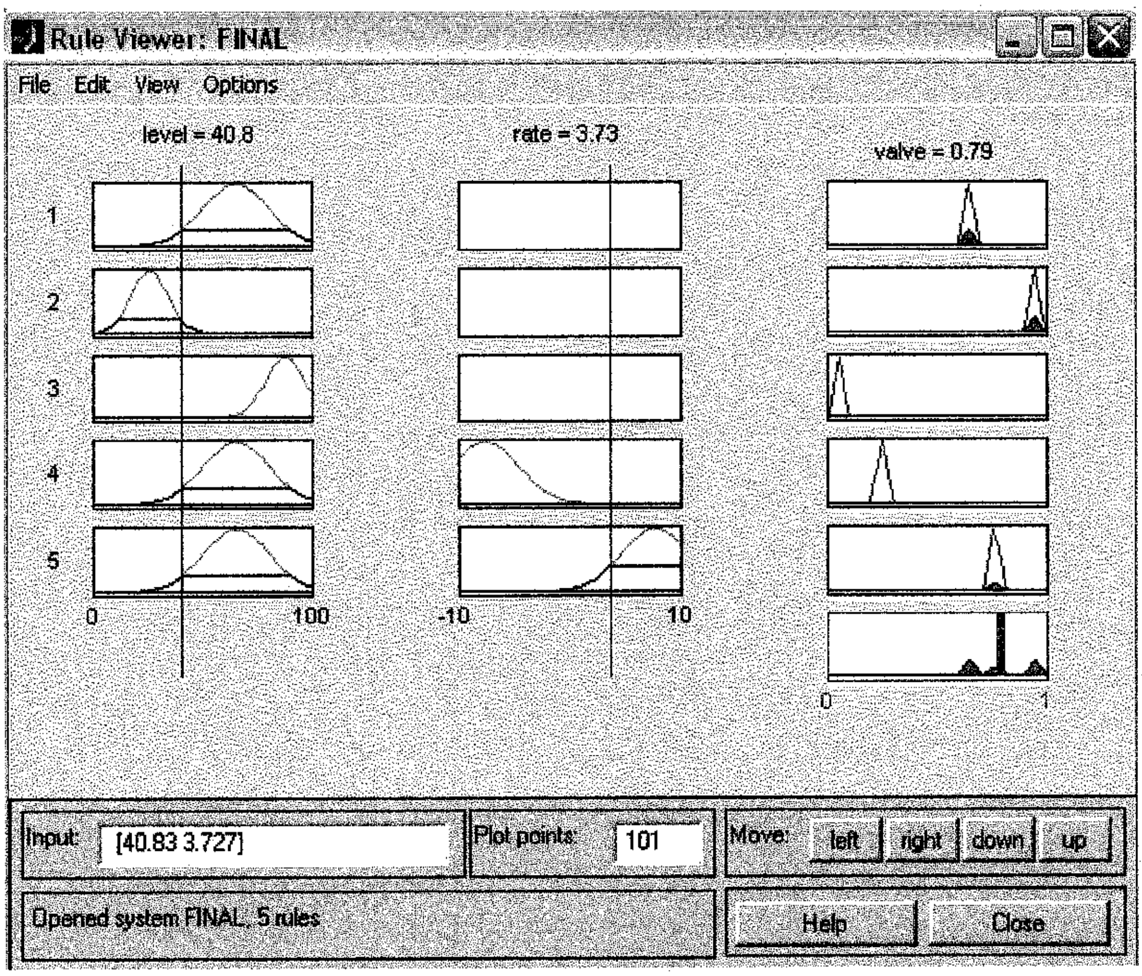
The rule base contains the heuristic qualitative knowledge interaction between input and output variable. Flotation column base rule used is;



There are 5 type of rules used into the system. Figure above illustrate that the interconnection between the variable is used mathematical logic which it define the actual response that need to be done. The rules relate the states of the input and output variable in logic expression that resemble the knowledge of an expert in the operation of the process.

4.4.2.3 Defuzzifications

After the inference process which the evaluation of rules, the process will define the output value as a combination of linguistic attributes. It means the inputs will translate to output in real value of the processes. From the flotation fuzzy system, as the level high with normal rate of flow rate ,it stimulate of valve opening to be fast close at this condition. The rules viewer below will summarize the modeling condition at which the inputs generated into the system will generate all output bases on rule (mathematical logic equation) in order to stimulate valve opening (manipulated variable) to be at constant level.



4.4.3 Result

The modeling is run without the disturbance circumstances. This is because the assumption has made in order to gain basis fuzzy control system of flotation control process. The signal generator is used as the input generator with the frequency of 0.1 rad/s and its amplitude is 5. The structure of response is illustrates as the square form. It is because the system can be analyzed by various input parameter. With constant value of 65 (Indicate percentage at desired constant level) the response of flotation column with respect to time is determined. Below are the graph obtained from the flotation fuzzy simulation system by different ratio of valuable and waste flow rate.

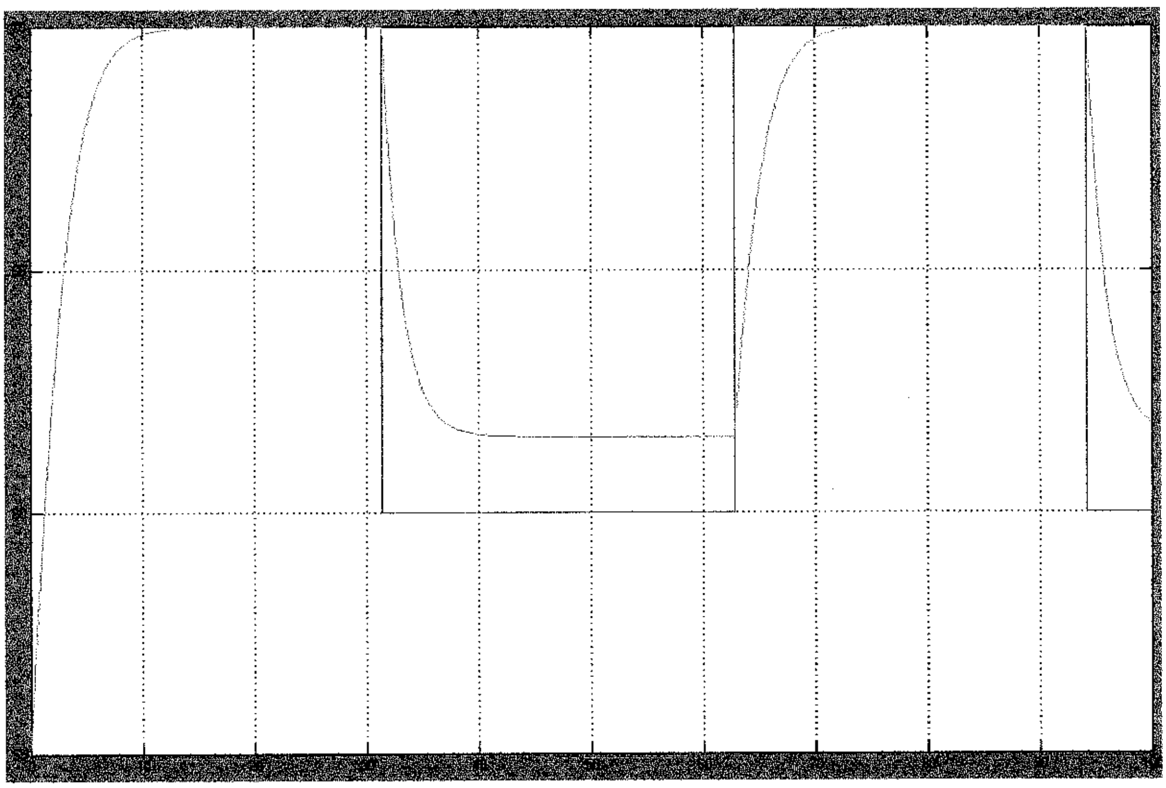


Figure 4.17: Level response for feed flow of the valuables at 50 % and waste at 50% in Fuzzy controller

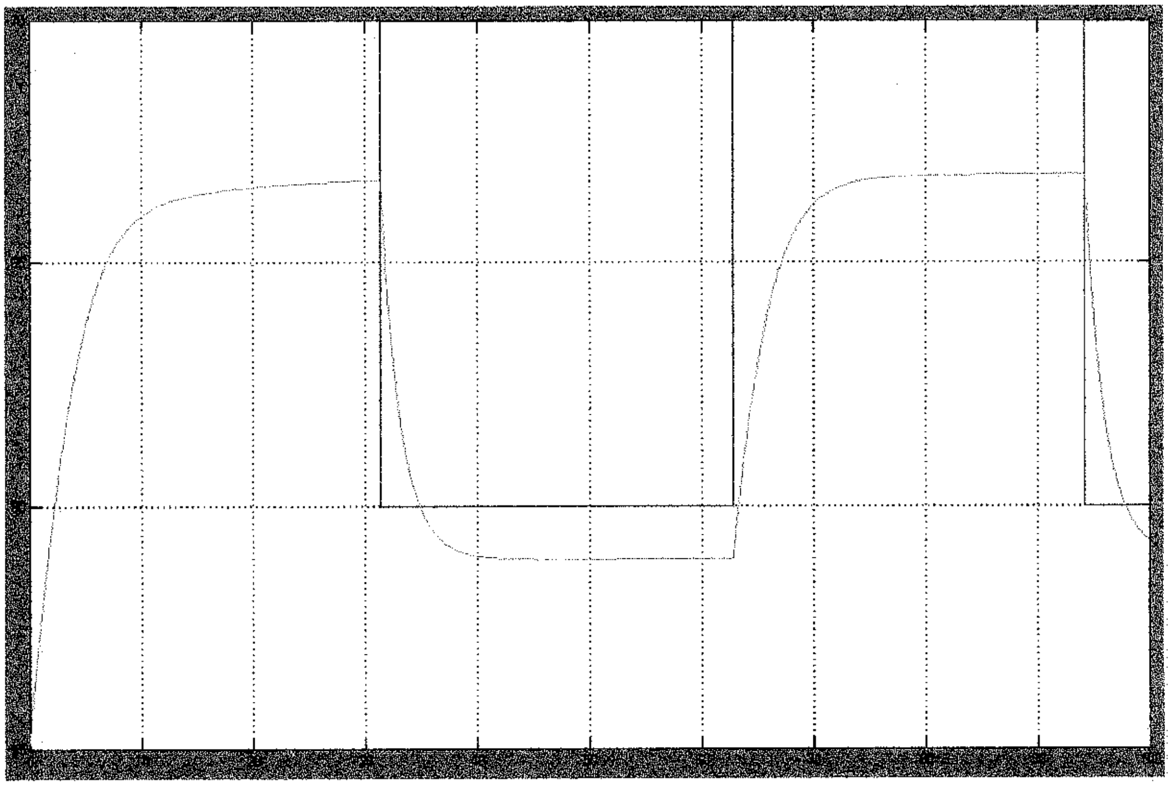


Figure 4.18: Level response for feed flow of the valuables at 60 % and waste at 40 % in Fuzzy controller

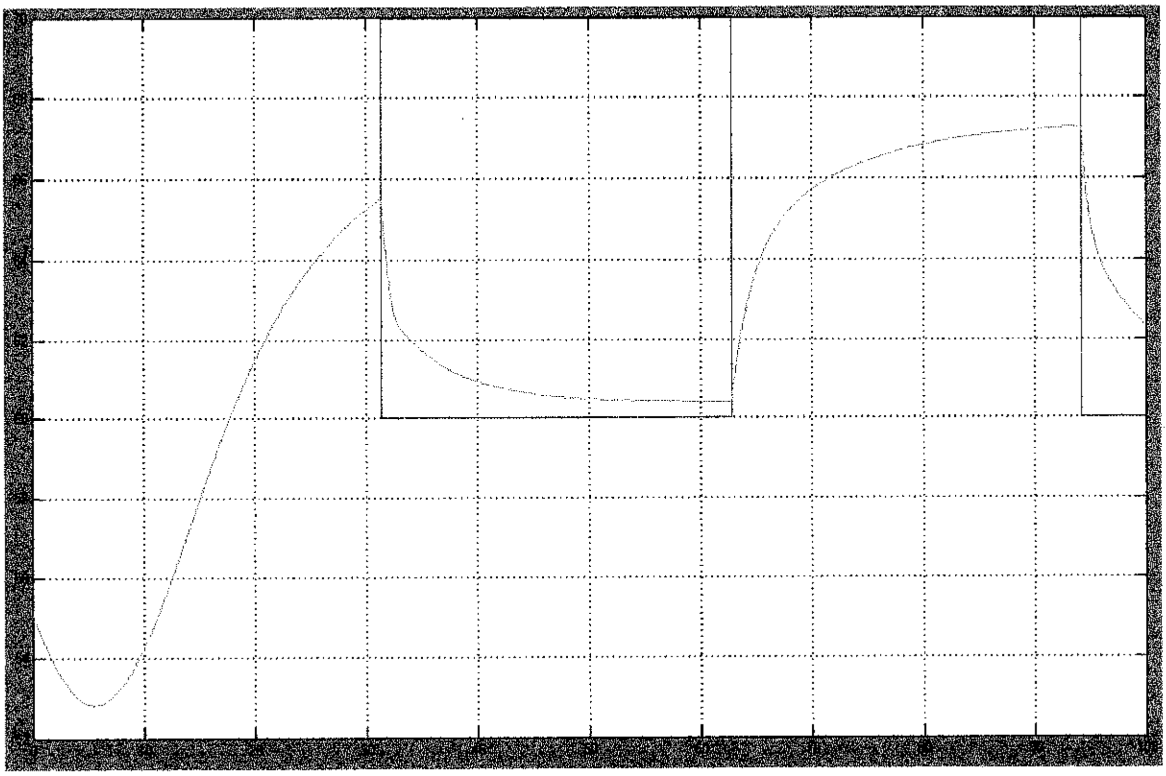


Figure 4.19: Level response for feed flow of the valuables at 80 % and waste at 20 % in Fuzzy controller

Base on the graph above different in ratio of valuable and waste flow rate result in different response of control process with respect to time. The behaviors of each response have an error between the set point. The error is due of each ratio of flow rate need to have respectively parameter inside fuzzy controller. The error is determined by initial and final value of the response. By setting up the same parameter for all type ratio flow into the flotation column, different behavior is gained. However the controlled variable trend has consistent response by introduce step square input frequency. It can be show by the response will generate same form base on input from the signal generator.

Valve opening is the manipulated variables which have five linguistic form in fuzzy controller. The characteristic is determined by an experience and logic approach. When the level is high, valve opening will result to close and vice versa. Therefore rate input represent the rate of level increasing or decreasing with respect to time. When the level is high with positive rate, the valve will act to close fast. But if the level is high but in negative rate, the valve will act to close slowly. But if the level is normal (65%) there are no change of valve opening.

The different form of graph for different type of feed ratio of flow rate determine absolutely have similar stability response. It can be seen that the response have consistent increasing and decreasing value constantly without having noise or great amplitude. For 50-50 and 60-40 flow rate ratios the graphs have the same pattern but different in error contribution. However for 80-20 flow rate ratio has some inconsistent initial response which it took long time to settle at set point.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

As a conclusion the value of PI controllers is a forward acting. This is because the K_P and K_I all negative. The comparisons of behavior are made in the initial amount of the valuables and waste in the flotation which is the ratio of feed flow rate. All control loops is used PI controller because it said to control the level in the flotation from overflow and to make sure that the flotation level maintains at a constant level. Therefore the integral action is used to eliminate offset. The disadvantage of the integral action is that the responses will start to be oscillatory and reduce system stability. By using the PI value it was further used in advance process loop which give better result of performance. Feed forward and cascade control has multiple loops which eliminate the existence disturbance and make the process response faster. Meanwhile smith predictor method is used as an advance process to overcome the time delay system. Fuzzy logic control is used in order to define the capability of processes with linguistic term method. It shows that flotation system has a higher potential to be advance controlled by using fuzzy system which it provide efficient performance. It proves by the result which fuzzy system is appropriate to apply in flotation process. Further modifying should be done in order fuzzy logic controller will be perfectly applied into the flotation control process. In conclusion, cascade control provides best performance both in set point change and in rejecting disturbance.

For recommendation, the flotation level control need to be implement in neural network system in order to look the behavior of the process with hybrid system approach. By using advance technique strategies the flotation level control will further improve in order to achieve higher product recovery from the column. Beside that in order to apply the modeling constructed is ideal with actual condition, the modeling should have raw data from actual unit in order to determine the comparison between simulation and actual operation parameter. Thus from the comparison made the dynamic modeling can be improve by time to time heuristically.

6.0 REFERENCES

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7.0 APPENDIXES

Appendix 1 ; Table of continuous cycling tuning

Table 13.1 Ziegler–Nichols Controller Settings Based on the Continuous Cycling Method

Controller	K_c	τ_I	τ_D
P	$0.5K_{cu}$	—	—
PI	$0.45K_{cu}$	$P_u/1.2$	—
PID	$0.6K_{cu}$	$P_u/2$	$P_u/8$

Appendix II: Feedback control tuning value

Feedback Loop tuning

Setpoint of level (%) 15%

Mass of valuables (tonnes)	**150**
Mass of waste (tonnes)	**150**

Fv (tonnes/hr)	50
Fw (tonnes/hr)	50

Density valuable (t/m^3)	2.65
Density waste (t/m^3)	1.00

Volumetric flowrate valuables (m^3/hr)	18.87
Volumetric flowrate waste (m^3/hr)	50.00

Flotation volume (m^3)	60

Total volumetric flowrate (m^3/hr)	68.87

Residence time (hr)	0.87

*Residance time =
(Flotation volume / Total volumetric flowrate)

By zigler-Nicholas through continous cycling method

Kcu	-0.1086
Ti	-100
Pu	1

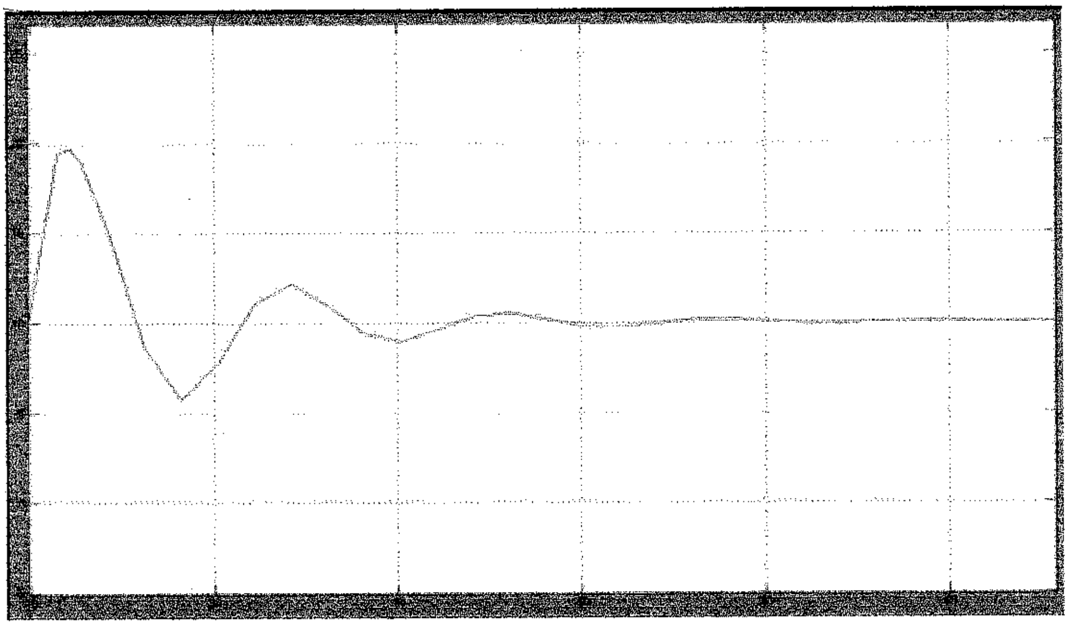
	Tuning 1	Tuning 4	Tuning 5	Tuning 6
Kc	-0.04887	-0.04887	-0.04887	-0.04887
Ti	-0.833333333	-0.5	-0.25	-0.1
Pu	13.5			

Tuning 2

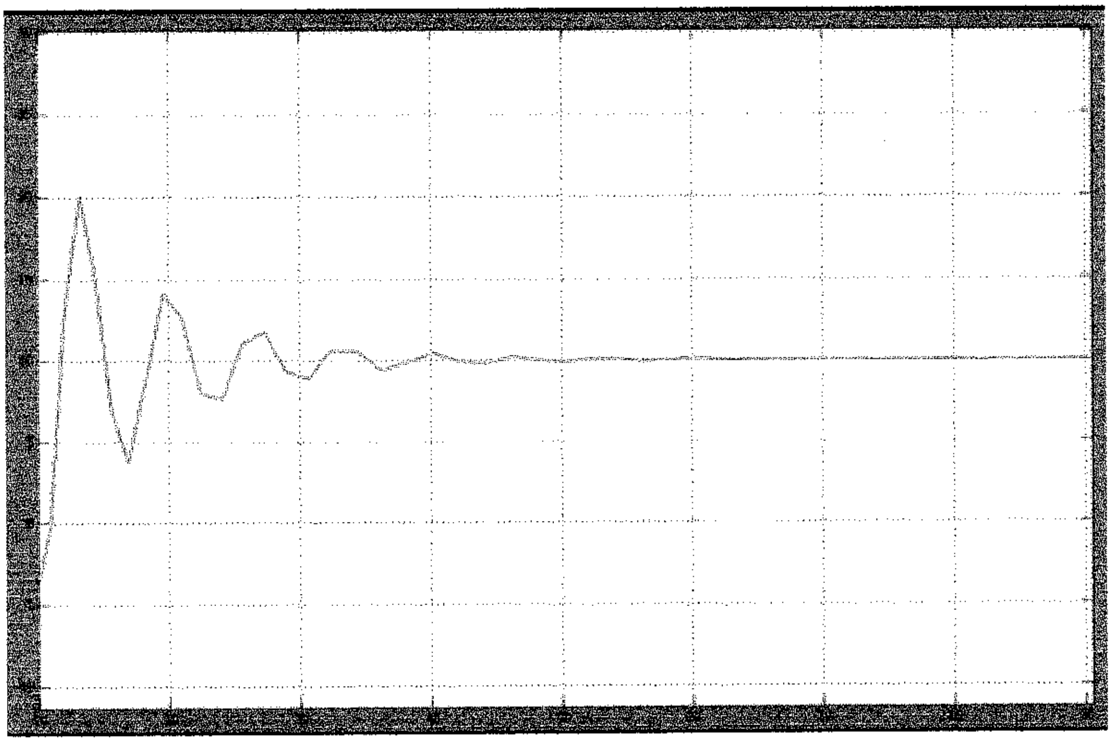
Kc	-0.0219915
Ti	-11.25
Pu	2.9
Tuning 3	
Kc	-0.009896175
Ti	-2.416666667
Pu	7

APPENDIX III

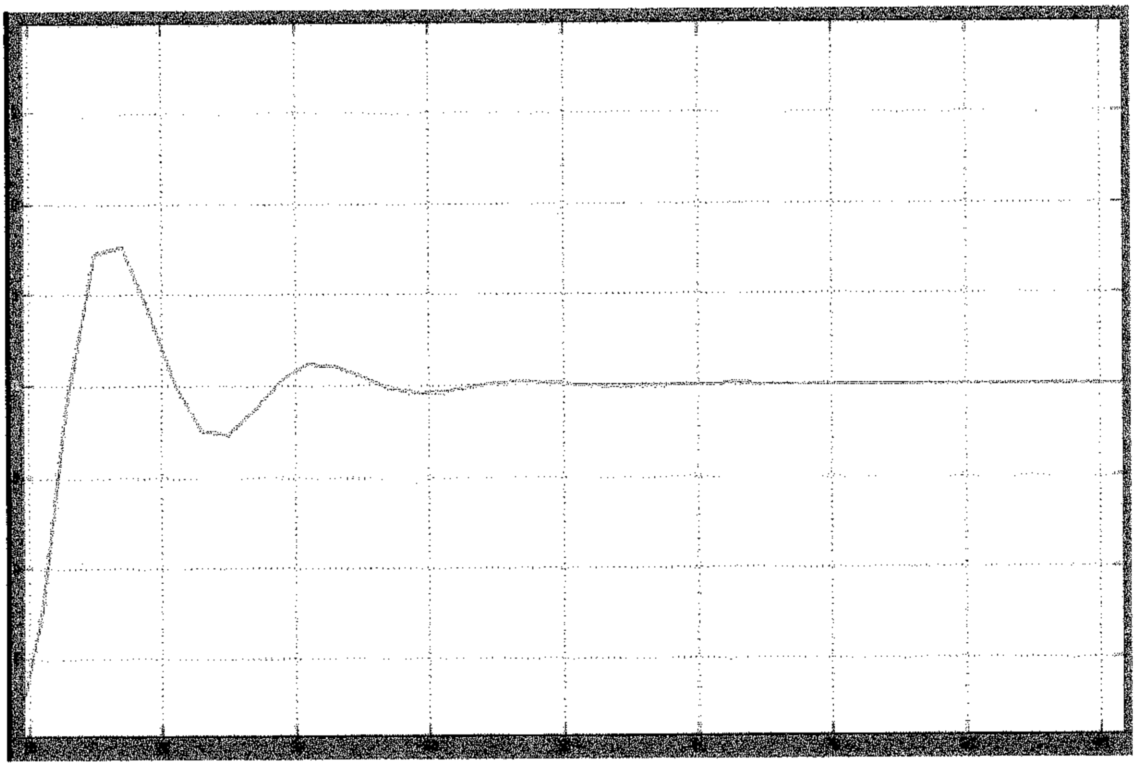
Tuning 2



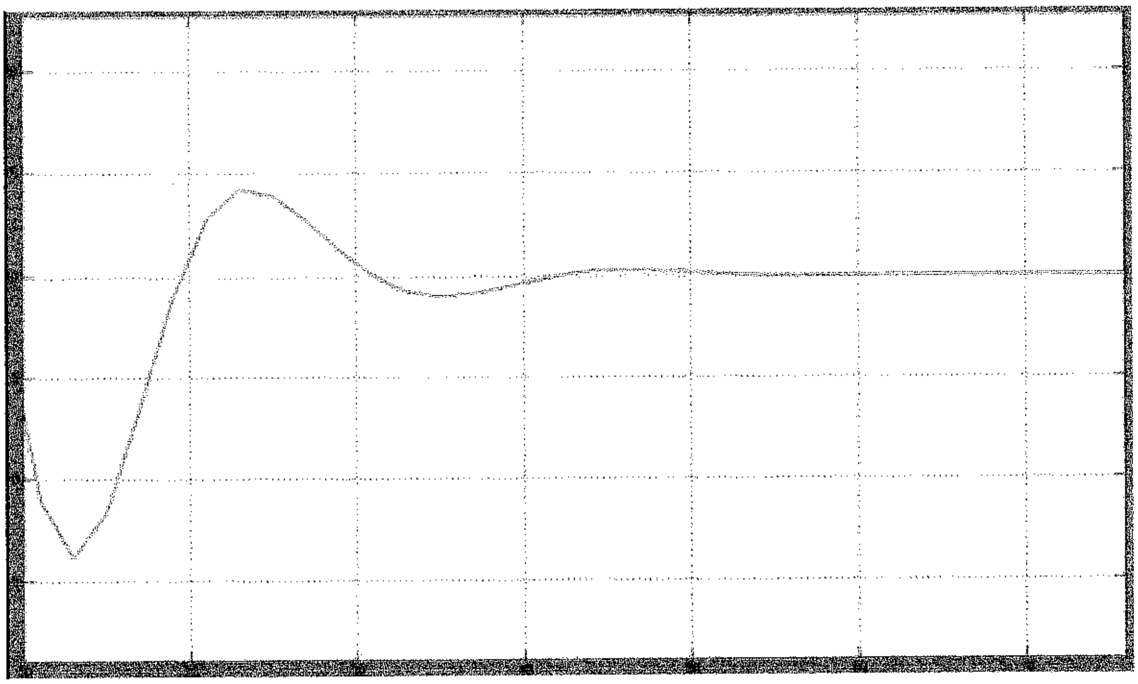
Tuning 3



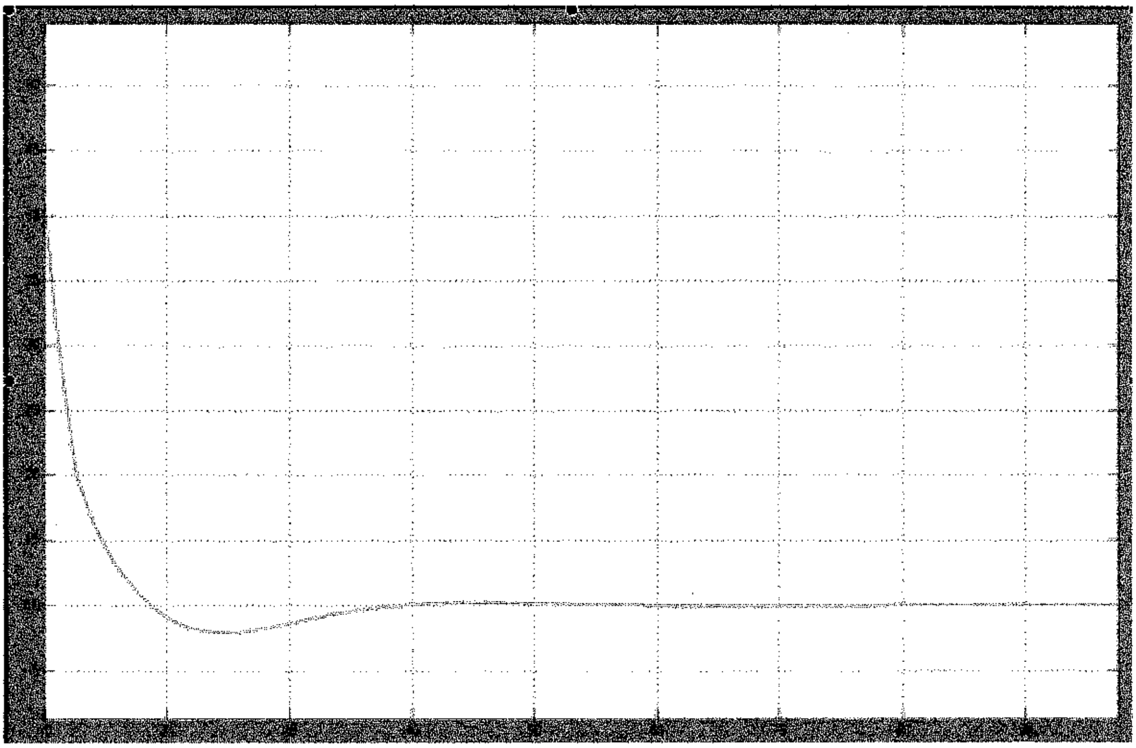
Tuning 4



Tuning 5

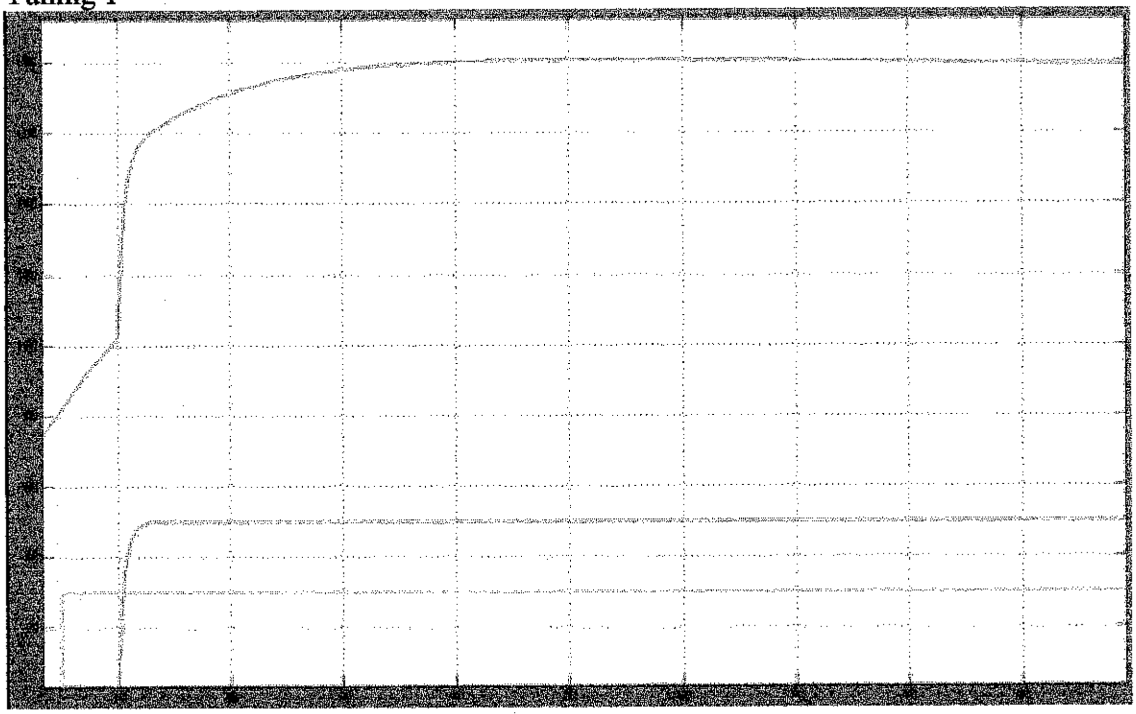


Tuning 6

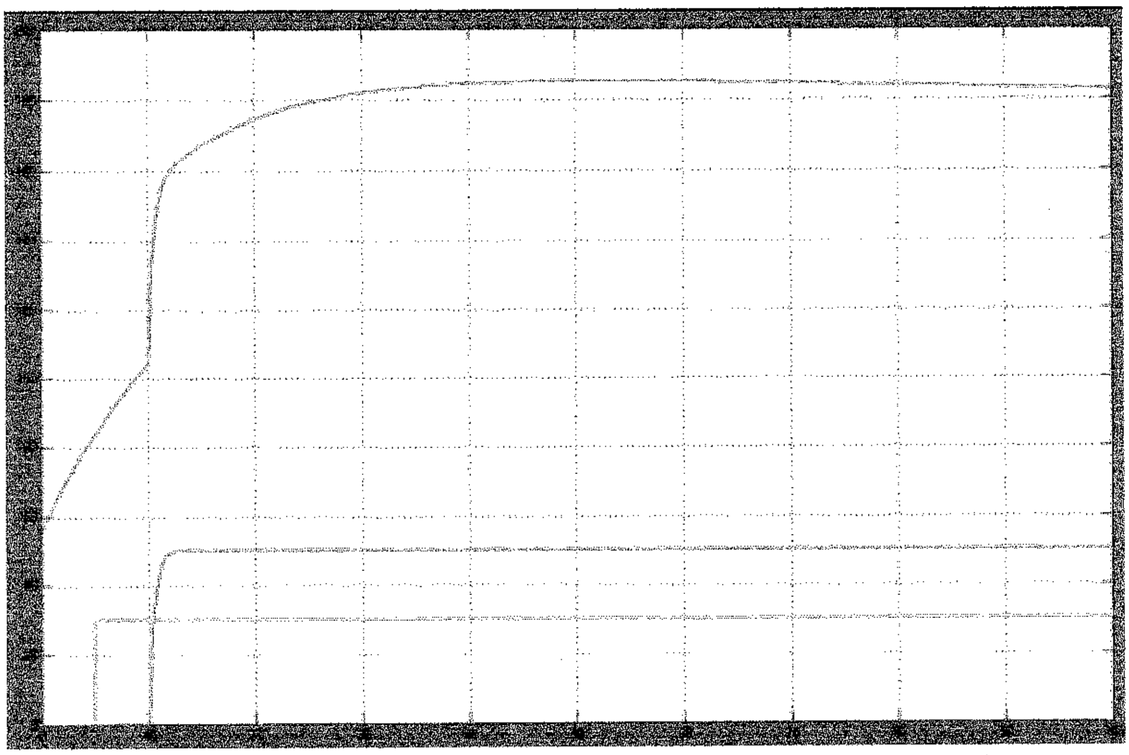


Appendix IV: Graph of level response for value from table 1 with valve opening 2

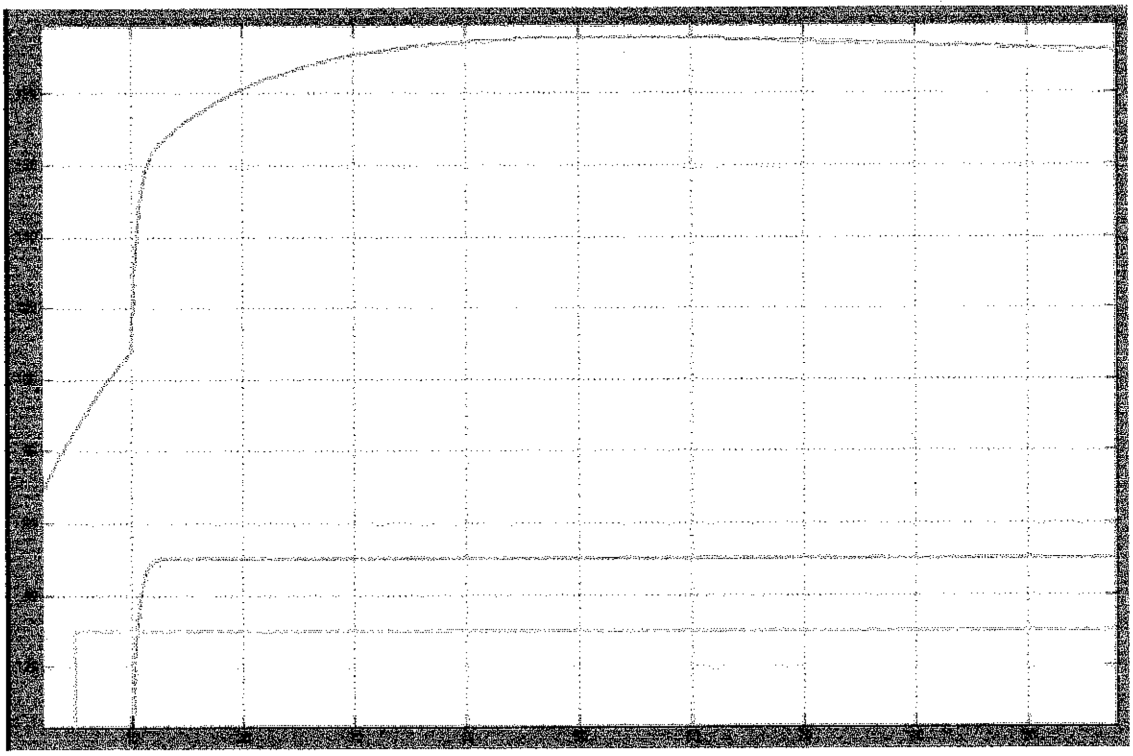
Tuning 1



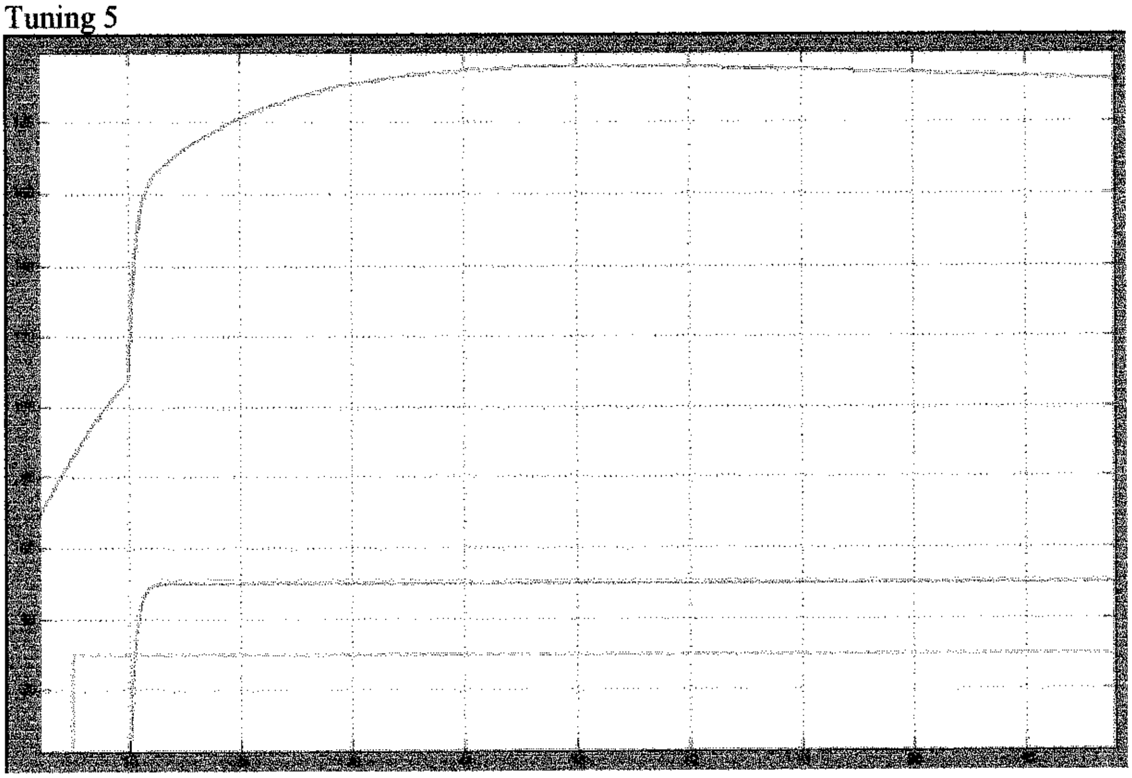
Tuning 2



Tuning 3

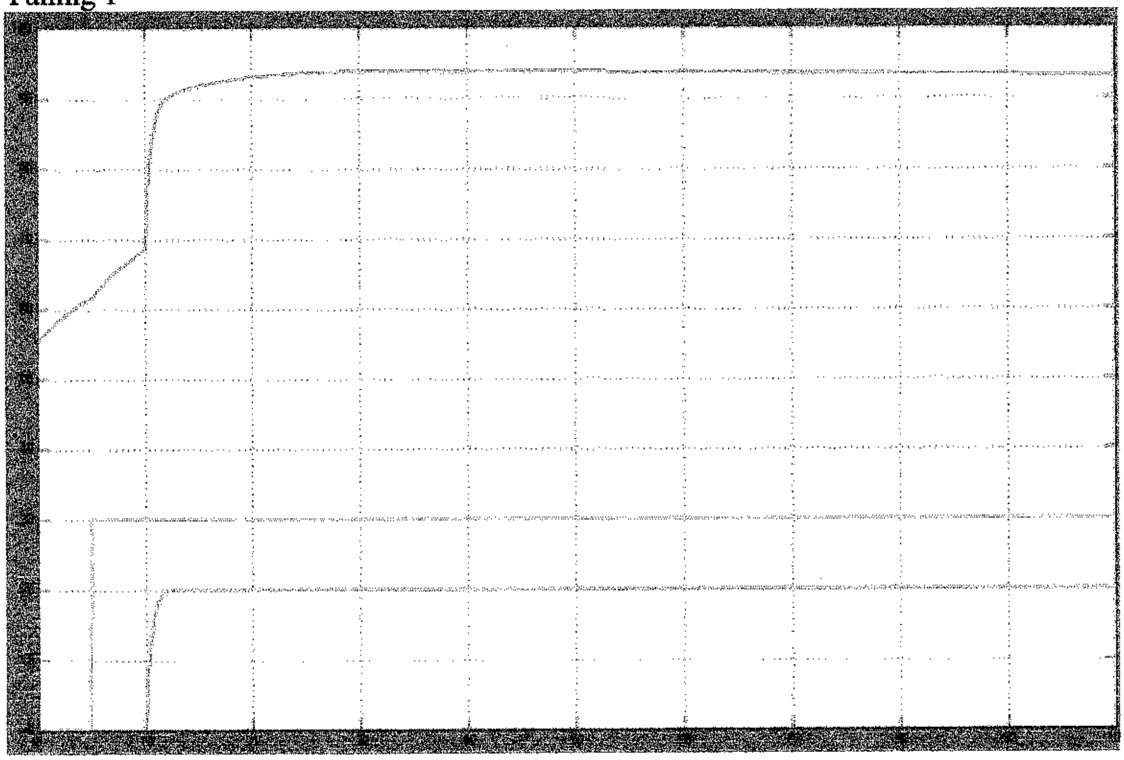


Tuning 5

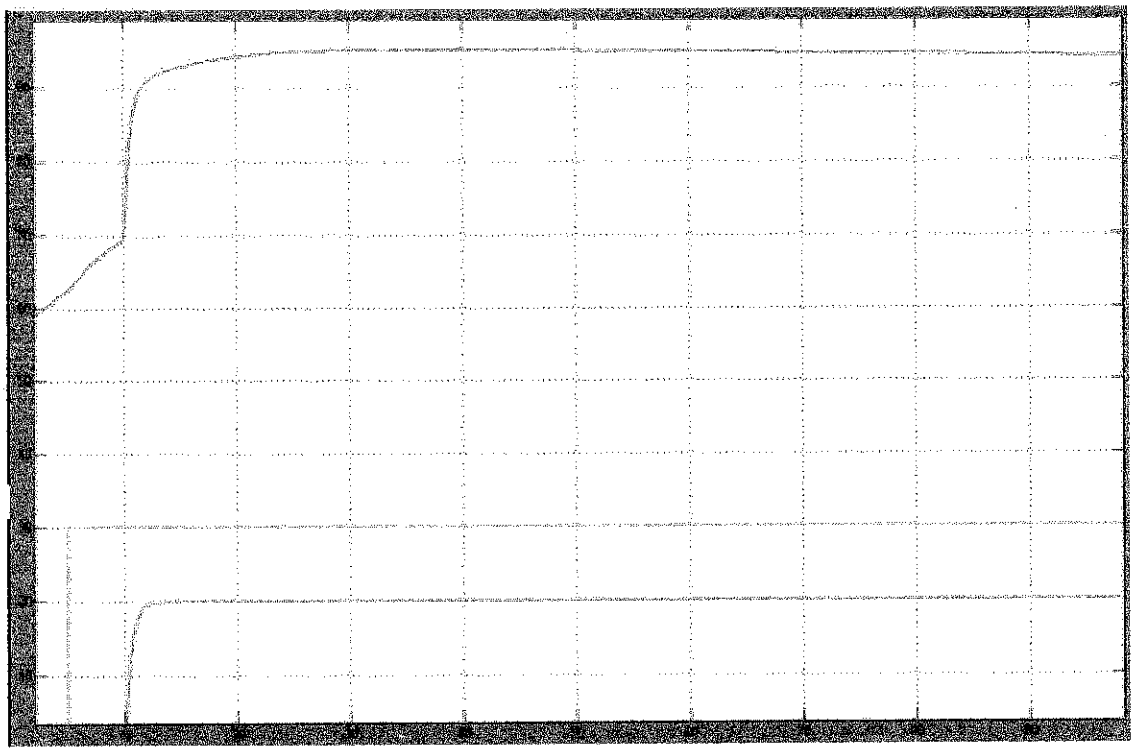


Appendix V: Graph of level response for value from table 1 with valve opening 5.0

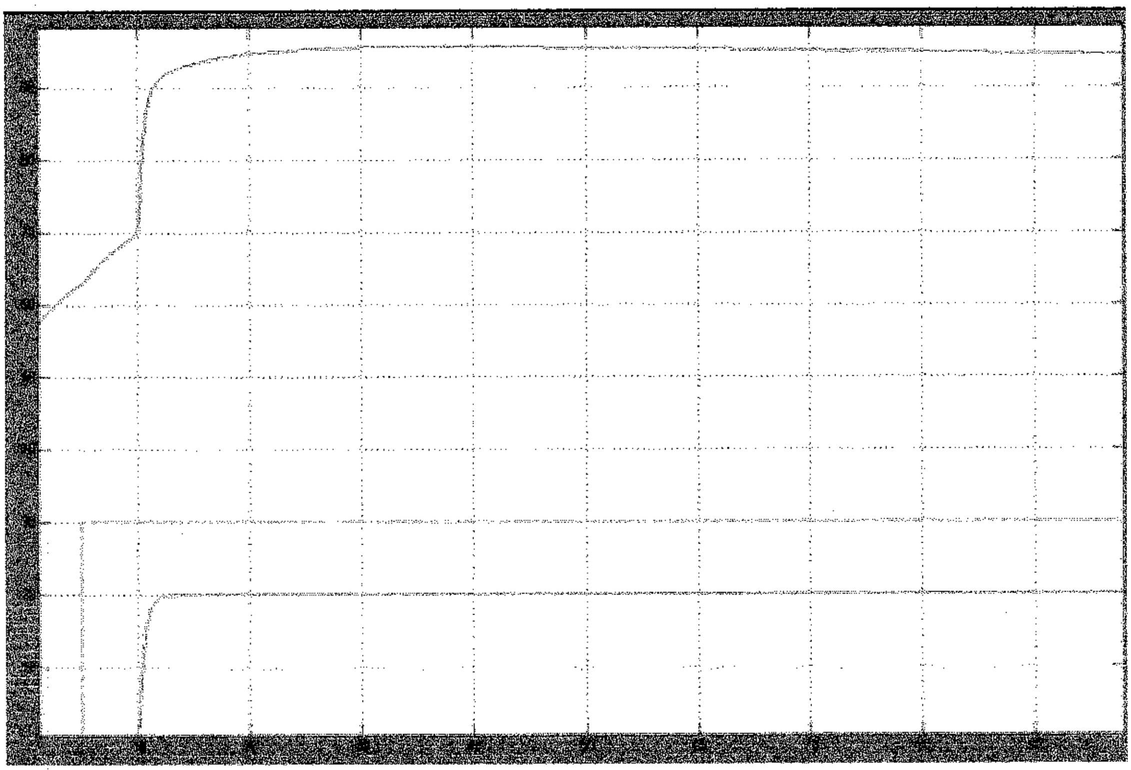
Tuning 1



Tuning 2



Tuning 3



Tuning 4