

Simulation of process identification and controller tuning for flow control system

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Abstract. PID controller is undeniably the most popular method used in controlling various industrial processes. The feature to tune the three elements in PID has allowed the controller to deal with specific needs of the industrial processes. This paper discusses the three elements of control actions and improving robustness of controllers through combination of these control actions in various forms. A plant model is simulated using the Process Control Simulator in order to evaluate the controller performance. At first, the open loop response of the plant is studied by applying a step input to the plant and collecting the output data from the plant. Then, FOPDT of physical model is formed by using both Matlab-Simulink and PRC method. Then, calculation of controller's setting is performed to find the values of K_c and τ_i that will give satisfactory control in closed loop system. Then, the performance analysis of closed loop system is obtained by set point tracking analysis and disturbance rejection performance. To optimize the overall physical system performance, a refined tuning of PID or detuning is further conducted to ensure a consistent resultant output of closed loop system reaction to the set point changes and disturbances to the physical model. As a result, the $PB = 100$ (%) and $\tau_i = 2.0$ (s) is preferably chosen for setpoint tracking while $PB = 100$ (%) and $\tau_i = 2.5$ (s) is selected for rejecting the imposed disturbance to the model. In a nutshell, selecting correlation tuning values is likewise depended on the required control's objective for the stability performance of overall physical model.

1. Introduction

In the new era of technology, most of the controller in manufacturing plants are automated control system. The mentioned control system is extended to various industries such as food processing, refinery, chemical, and power generation plants. The control systems consist of a single instrument or a group of instruments which are designed, developed, installed and operated to control a process.

Control system is suffered with the issues of instability and limited capability to resist external disturbances [1]. It typically requires continuous monitoring and controlling by operators so as to maintain output response of system. Even so, the full-time availability of the operators in the plant is unachievable due to other assigned duties and tasks that need completion as well. Therefore, the idea of utilizing instruments to automate the control system is becoming a popular discussion in many industries.



Bi et al (1999) explains that control loop is exactly a feedback control loop that compares the process variable, PV of plant to its set point, SP . This is followed by generating a manipulated value, MV to drive PV for the new SP . At first, control loop must utilize a sensor to measure PV . Secondly, control loop must have a controller block with an actuator that control parameters of the process. A typical automated control system is depicted in block diagram as shown in Figure 1.

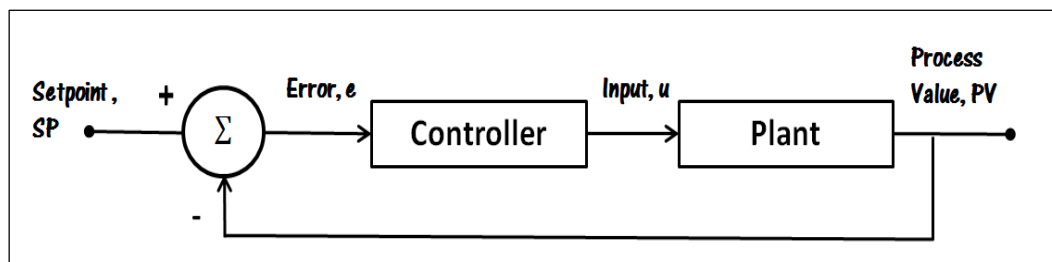


Figure 1. A typical automated control loop.

Plant is the model to be controlled. A plant incorporates a group of physical instruments to produce the products. The plant is inherently fixed and does not react to any changes of process parameters as well as interferences from external environment. PV varies relatively to any changes of parameters in the plant. The imposed changes of PV are feedback and compared at summing point. This is a symbol in the diagram that conceptually adding two or more input signals, and produces a single sum output signal as error e . The e is transmitted to the controller for generating control signals or MV that regulates the initial changes of PV . In a nutshell, the main objective of control loop is to regulate PV close to SP at all times.

A reliable control loop needs a sophisticated controller, which is able to regulate consistently any factor that destabilized PV in the plant. There are various applied control methodologies whereas PID controller is the most widely used [2] because of its flexibility and simplicity to change the settings cope with various requirements in the system. There are elements of control actions for a PID controller [9],[10] comprises proportional action, P , integral action, I and derivative action, D .

1.1. Proportional Action P

Proportional action P is the most common form of control action. It is depended on magnitude of e that is generated after PV is compared with changes of SP . In common, the P is represented as proportional gain K_c which implies the ratio of changes of PV to the changes of SP .

Equation (1) shows that the output of controller, u is equal to multiplication of K_c with e .

$$u(t) = K_c e(t) \quad (1)$$

The greater value of K_c means to more magnificent control actions given for similar amount of e existed in the process. The controller will take greater stage action for just a small amount of PV deviated from SP . It is depicting the purpose of P that improving capability of controller so to reduce steady state error when the PV attains a new steady state condition. Nevertheless, K_c is unable to eliminate steady state error.

There is an applied term that is closely related to K_c , which is known as proportional band, PB . It expresses the gain of the controller as a percentage of the span of the instrument. In mathematical form, PB is reciprocal to K_c as described in equation (2).

$$PB = \frac{100\%}{K_p} \quad (2)$$

The lower value of PB means a greater K_c setting for the controller. In essence, the response is increasingly robust when PB is reduced until the limit and eventually the controller will become over-responsive. At this moment, the controller is reacting as an ON/OFF controller and consequently the action of actuator is limited to fully open and fully closed.

In contract, a greater PB means a smaller K_c and subsequent control actions become ‘inaccurate’ due to a lack of responsiveness to the e . In this extent, the actuator is not responding to minor signal e which is just a tiny parameter change in the process. Therefore, appropriate setting range of PB is important to allow robust and efficient controller.

1.2. Integral Action I

The second term of control action is known as integral action I . It is prominently to govern PV to stay tuned with SP . I reacts by gradually shifting the PV once e existed. The action is tended to eliminate e so that PV will attempt to converge towards SP .

The gain of integration is known as integral gain K_i . It reviews capability of the controller to overcome e versus to the SP setting. The greater the K_i , the controller becomes more responsive to process and typically to produce more oscillatory output response due to changes of PV . Mathematically, I is the sum of the instantaneous e over time and gives the accumulated offset that should have been corrected previously. I responses to changes of e by multiplying K_i with net area of e from time equals to 0. The relationship between the output of the controller, u and the e is described in equation (3).

$$u(t) = \int_0^t K_i e(t) \cdot dt \quad (3)$$

where

$$I = K_i = \frac{K_c}{\tau_i}$$

The drawback of I is associated with a sort of storehouse of remembered past error that can continuously act towards e even after the PV reaches the desired value. As the PV converges back to the SP , the proportional term begins to decrease. But the I is continuing to act because of the stored e under the error curve, even though SP had been reached. I will drives the PV past through SP and to shed its accumulated e and stay continuously away from SP until accumulated e of the opposite direction accumulated and canceling the previous accumulated e . Ultimately, resultant PV is increased oscillatory and gradually contributes to “Integral Wind up”. In dealing with this issue, the controller is recommended to be temporary turned OFF once control element is saturated.

1.3. Derivative Action D

Derivative action D is the third element in PID control system. D reacts to the rate of change of the e at the current time. Mathematically, the derivative of the error e is determined by computing the slope of the e over time and then multiplying the rate of change with the gain, which is also known as derivative gain K_d .

The mathematical representation of D action is described in equation (4).

$$u(t) = K_d \frac{de(t)}{dt} \quad (4)$$

where

$$D = K_d = K_c \cdot \tau_d$$

D provides a sudden shift in output power level as the result of rate changes (the slope of error curve) in measured value. If PV changes, D immediately produces control signal in an attempt to correct the perturbation before the e signal goes too far.

This immediate action reflects high sensitivity of D relatively to the noise, which is considered as drawback of D . Any appeared noises in the process give the slope of error a flip-flop up and down with severe magnitudes, and consequently slight change of D . The flicking control signals of controller drives the final control element vigorously to one direction, and then move to another direction. As a result, PV becomes oscillatory and unstable. In dealing with this issue, e has to be filtered with hardware filter or a software filter prior to be compared with SP .

2. The application of proportional, integral and derivative action

Combination of two or more than two control actions in parallel produces more comprehensive controller such as proportional-plus-integral controller (PI) and proportional-integral-derivative controller (PID). Each respective control action reacts to e . The greater the K_c , the more final controller element moves so as to drive PV to a new steady state condition. However, K_c is unable to get rid of steady state error. This is the reason of I being added to controller so the controller is constantly acting to regulate PV until it achieves SP at the end. Besides, D enables the controller to predict the potential e based on the current trends of process and respond in advance. It sees the e approaching and starts controlling to stop the growth of e before it becomes larger.

2.1. PI Controller

PI controller produces more energized control besides regulating process without steady state error when the controlled system is obtaining new SV . The combined strength of each control element subsequently makes controller attached to the process that requires high speed response without compromising any steady state error. Figure 2 illustrates the close loop process, which constantly compares SP with feedback of PV so to produce e to controller.

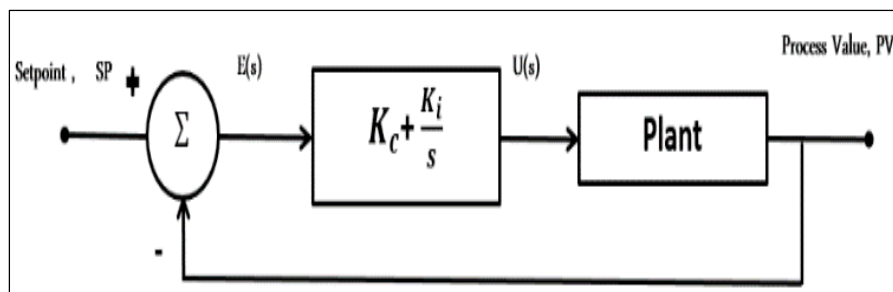


Figure 2. A PI controller in closed loop system.

To increase seems to improve robustness of response by reducing rise time and besides to reduce steady state error as well. Nevertheless, over setting of this element leads to the increase of oscillatory response from controller that destabilizes the process outcome. In essence, the setting of this element must lead to minimum steady state error where oscillatory response will start. Meanwhile, K_i is initiated purposely to eliminate steady state error. It leads to higher controller capability to eliminate the steady state error. Nonetheless, over setting of this element leads to oscillatory response as well.

Mathematically, the PI controller is represented in equation (5).

$$u(t) = K_c e(t) + K_i \int_0^t e(t) dt \quad (5)$$

PI controller is not able to predict the future e thus PI controller is unable to reduce the settling time of process response. Nonetheless, PI controller is still preferably used in industries compared to other controller modes [3]. PI controller is widely applied to system with large capacity where the speed is

not an important tuning criterion but precise control is required such as level control of water in tank. Besides, PI controller is also applied to the process where overall process response is fast comparatively to sensor and controller such as flow control system.

3. Process identification

A proper controller tuning is imperatively needed for satisfactory performance of close loop control system. Nonetheless, the presumed performance is less likely to be achieved without a good approach to identify the dynamic of process behavior. Identifying process behaviour typically describes the relationship in between input and output of process, which is represented in mathematical model. This is also known as process identification through modeling.

Modelling process is not an easy task because of complicated processes in industries and high probability of non-linearity, causes difficulties in tuning the controller. There are quite many literature studies had been undertaken for process identification [4],[6]. Among all the studies, one the most common process identification approach is known as Open loop method [9].

This method identifies process behavior by using Process Reaction Curve PRC method. Data such as process gain, K_p , time constant τ_p , and process time delay, θ_p are to be replaced into first order plus dead time, *FOPDT* model and then to calculate correlation tuning values of controller that gives optimum control to the process.

The *FODPT* algorithm of process is represented in mathematical model shown in equation (6).

$$Y(s) = \frac{K_p e^{-\theta_p s}}{1 + \tau_p s} \quad (6)$$

where

K_p = process gain,

τ_p = time constant and

θ_p = time delay.

There are several stages in applying this method [5 - 7] as described in the following steps:

1. To design an experiment and accumulating input-output process data. Prior to experiment test, *PV* is ensured to be in physically stable and controller is in Manual mode.
2. To impose a small percentage of step change as *MV* and observes the change of *PV*. Transient response of *PV* is recorded and plotted in Process Reaction Curve accordingly.
3. To calculate the K_p , τ_p and θ_p . Replace those parameters into the *FOPDT* expression.
4. To compute the correlation tuning parameters of controller and after that to apply these values to controller. Set the controller to Automatic mode.
5. Evaluate the new process response with another applied step input and performing re-fined tuning accordingly.

Open loop method is prominently used in modeling a process. Most of the higher order and complicated process can be approximated into *FOPDT* method [3],[8]. This is recommended to repeat the similar experiment for several times to get average of process response for analysis. The similar stage will improve reliability of developed *FOPDT* model. Figure 3 illustrates a unit step *MV* applied and *PV* is observed.

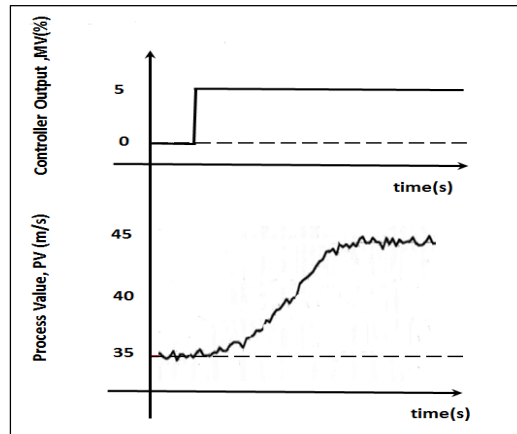


Figure 3. Response of open loop process towards a step change.

3.1. Process reaction curve (PRC)

PRC proposes a set of PV is accumulated from empirical data and plotted in graph by using software program (for instance Microsoft Excel). Graph of respective MV and PV versus time are drawn and compared as illustrated in figure 4.

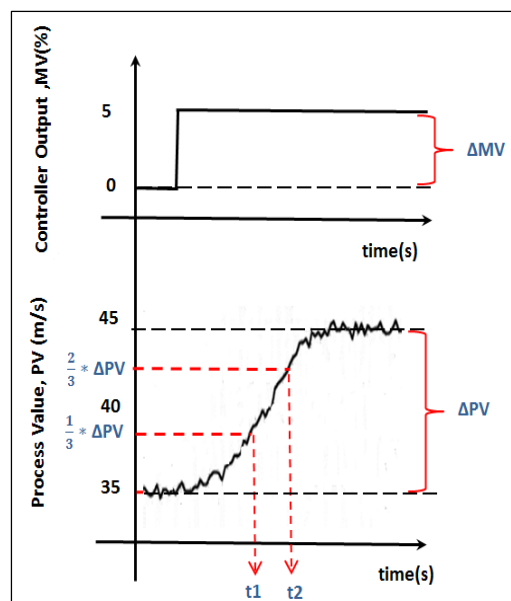


Figure 4. Process reaction curve method.

Determination of all parameters for developing FOPDT model is depicted in equation (7), (8) and (9).

$$\text{Process gain, } K_p = \frac{\Delta PV}{\Delta MV} \quad (7)$$

$$\text{Time constant, } \tau_p = 1.5 (t_2 - t_1) \quad (8)$$

$$\text{Time delay, } \theta_p = 0.5(t_2 - \tau_p) \quad (9)$$

In calculating K_p , the ratio of PV change over MV change is determined. Two points of time scales (t_1 and t_2) are recorded where the PV increases to approximately $1/3$ times and $2/3$ times of its final

steady-state value. Afterwards, the relative *FOPDT* model is developed by computing K_p , τ_p and θ_p with formulas of Cohen-Coon tuning method.

3.2. Cohen-Coon tuning method

Cohen-Coon tuning method is introduced a decade later than the Ziegler-Nichols method. It uses the mathematical equations to determine K_c , τ_i and τ_d . The stages used to determine those parameters are exactly similar to Ziegler-Nichols tuning method. Selecting either one of tuning method is fine as far as the limitation of each tuning method is in considered. In application, Ziegler-Nichols method is more commonly used compared to Cohen-Coon method because this method is superior for higher order system, whereas Cohen-Coon method is only used for single order system. Nonetheless, Ziegler-Nichols method will become less accurate in the process where ratio of θ_p to τ_p is less than 1/2. In contrast, Cohen-Coon method is able to tolerate with ratio of θ_p to τ_p until 3/4 and even can be extended further. That is the reason for Cohen-Coon tuning method to become as dominant method in most control textbooks (Tavakoli and Fleming, 2003).

Calculating K_c and τ_i parameters for a PI controller by using Cohen-Coon's formula (Bi et al, 1999) is illustrated in table 1.

Table 1. Proportional gain and integral time of PI controller (Cohen Coon).

Controller Type	K_c	τ_i	τ_d
PI	$\frac{1}{K_p} \frac{\tau_p}{\theta_p} \left(\frac{9}{10} + \frac{\theta_p}{12\tau_p} \right)$	$\theta_p \left(\frac{30 + 3 \frac{\theta_p}{\tau_p}}{9 + 20 \frac{\theta_p}{\tau_p}} \right)$	-

4. Methodology

4.1. Equipment

In this paper, the Process Control Simulator (Model: 201) is used as physical plant to produce experiment data for analysis as shown in figure 5. The differential pressure value of airflow between both side of orifice plate was measured and converted to electrical signal (mA) by pressure transducer. Furthermore, controller of the simulator is able to control airflow either Manual or Auto mode. The values of all parameters of *SP*, *MV* and *PV* can be recorded and converted to Microsoft excel datasheet for further analysis. This is ideal equipment used to analyze the system response of various PID parameters setting.



Figure 5. Physical plant for experiment.

4.2. Process identification and least square curve fitting

Experiment data was accumulated by using open loop test as depicted in figure 6. A step function (very small % changes for MV) is imposed to the system (showed in the blue line). The resultant output response is likely to be a S-curve. From the graph, the resultant output response is lifted slowly and then gradually speeded up more until it attained the maximum value (approximately 10 seconds), which is also called as new steady state condition.

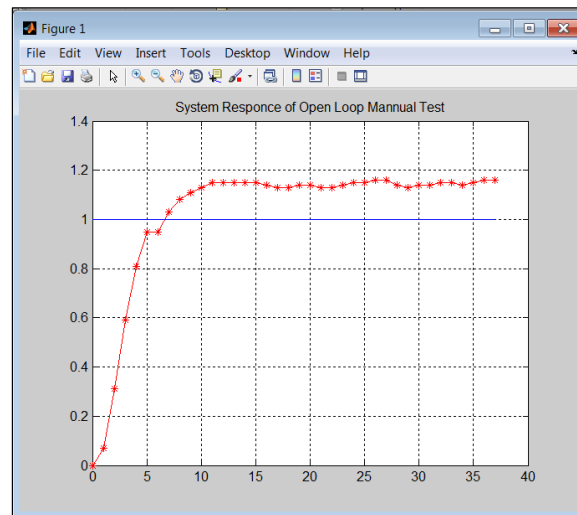


Figure 6. Output response vs unit step input.

The values for K_p is 1.146, τ_p is 2.306 (s) and θ_p of 1.3 (s) are obtained by using *PRC* method. This yields the developed *FOPDT* model as represented in equation (10).

$$G(s) = \frac{1.146e^{-1.3s}}{1 + 1.2306s} \quad (10)$$

Least Square Curve Fitting is applied to validate the reliability of the developed *FOPDT* model. Figure 7 shows graph of *FOPDT* model, which is compared with the experimental data. In essence, the developed *FOPDT* model is fitted to experimental data to prove that *FOPDT* model expresses the approximated dynamic of process.

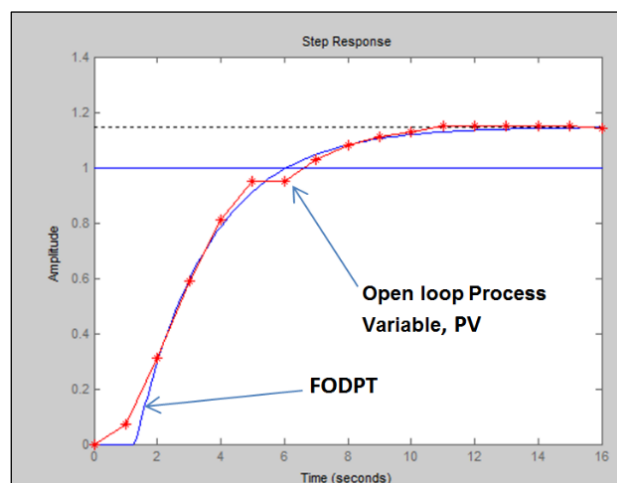


Figure 7. FOPDT and least square curve fitting.

4.3. Flow control diagram with PI controller

A closed loop control diagram is designed and simulated by using Matlab-Simulink as depicted in figure 8. Recall back parameters in FOPDT model, where $K_p = 1.146$ and $\tau_i = 2.306$ (s) and $\theta_p = 1.3$ (s). Replacing those parameters into the formulas of Cohen-Coon tuning formulas yields K_c is 1.5 and τ_i is 2.0 (s). Both K_c and τ_i are set to the PI controller. The result of simulation is generated after RUN button is pressed.

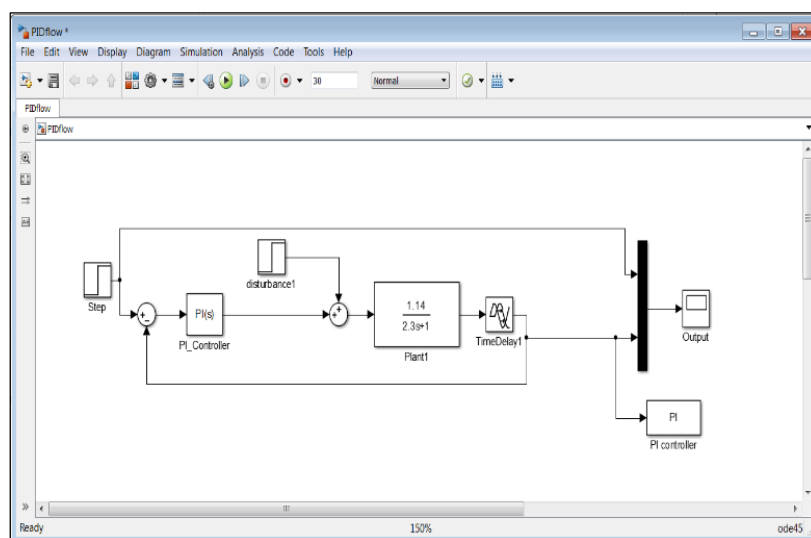


Figure 8. Close loop diagram for flow rate control.

4.4. Comparison of simulation and experimental data

The experimental data from PI controller ($K_c = 1.5$ and $\tau_i = 2.0$ (s)) setting is compared with simulated data as illustrated in figure 9. This is purposely to validate the performed physical system is in line with simulation data. The minor deviation in between simulation data with process data is possibly due to the non-linearity of system or friction of moving part such as motor fan.

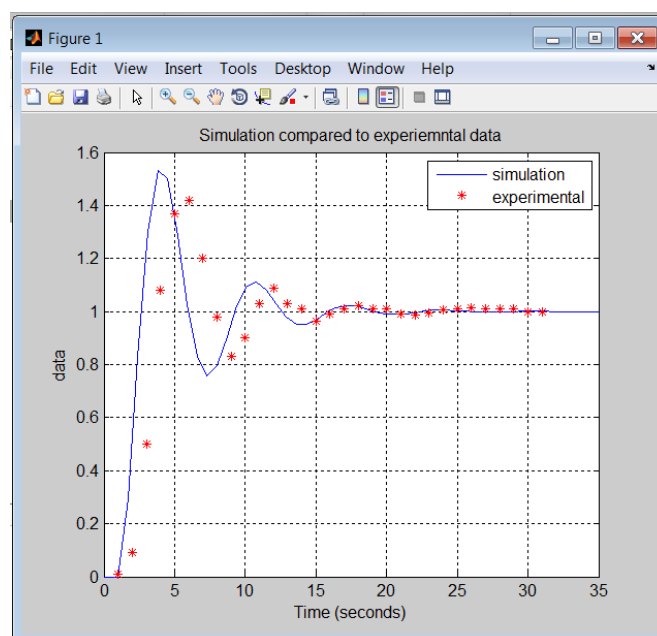


Figure 9. Simulated value vs experimental value.

An optimized control system requires the correlation tuning values for K_c and τ_i to the best fitted for the consistent control response. Ideally, the controller regulates PV aggressively without producing any overshoot [7]. The well-known approach is known as refined-PID tuning. It suggests a minor tuning for K_c and τ_i parameters so as to attain a satisfactory close loop response with minimum overshoot and rise time besides settling time less than 2%. Refined-PID tuning optimizes all features of control actions without deteriorating other features. However, refined-PID tuning might takes minutes or hours for a point setting to produce a stable effect at the end.

5. Analysis for setpoint tracking and disturbance rejection performance

5.1. Set point tracking of flow control system

For a proper controlled system, the output response should be magnificent, and should not oscillate in any new condition of set point or applied disturbance. Robustness of controller response can be enhanced by increasing K_c value which subsequence more oscillatory response as well. In contrast, reducing K_c value reduces oscillatory response. In obtaining empirical result, each correlation tuning values is applied and then followed by a step change for recording output response simultaneously.

After trials on various setting for K_c and τ_i parameters, the selected value for $PB = 100$ ($K_c = 1$ instead of 1.5) whereas the τ_i varies in re-fined PID tuning. The SP change and related output response is illustrated in figure 10, which shows that process response with $\tau_i = 2.0$ (s) is somehow more robust with smaller overshoot incurred. Furthermore, there is no overshoot occurring after τ_i is increased to 2.5 (s). This implies that higher value of τ_i will slow down the system response to the SP change. Therefore, $PB = 100$ (%) and $\tau_i = 2.0$ (s) is preferably chosen.

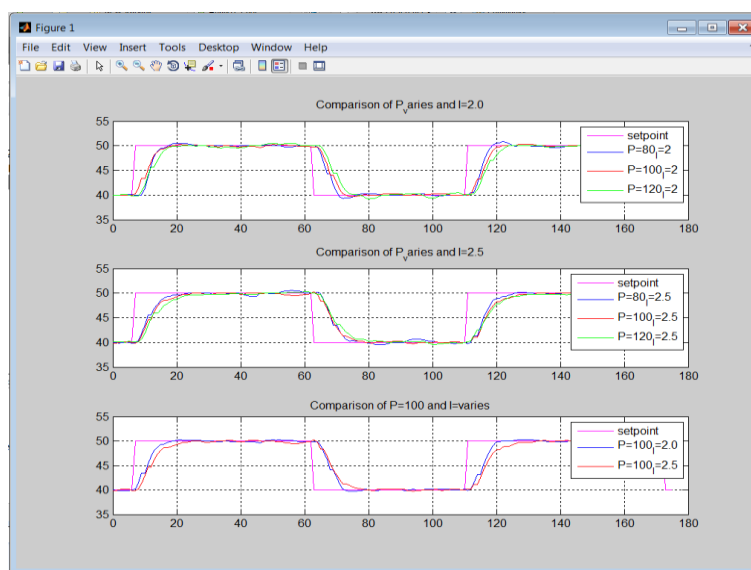


Figure 10. Output response of setpoint tracking analysis.

5.2. Disturbance rejection performance of flow control system

Some systems require strong capability to resist instability of process response due to high frequency of external disturbances rather than the SP change. This is specifically referred to systems, which suffered from noises or external interferences. A proper tuned control system provides reasonably damped response with minimum overshoot and fast recovery to the set point after imposed with disturbances. This is achievable by tuning PI controller so as to produce consistent response with minimum oscillation.

Figure 11 illustrates that PI controller with $PB = 100$ (%) and $\tau_i = 2.0$ (s) caused more oscillatory response compared to $\tau_i = 2.5$ (s). The larger the τ_i , the better the system performs to resist

disturbances imposed to the process. Therefore, PI controller with $PB = 100$ (%) and $\tau_i = 2.5$ (s) is preferably chosen.

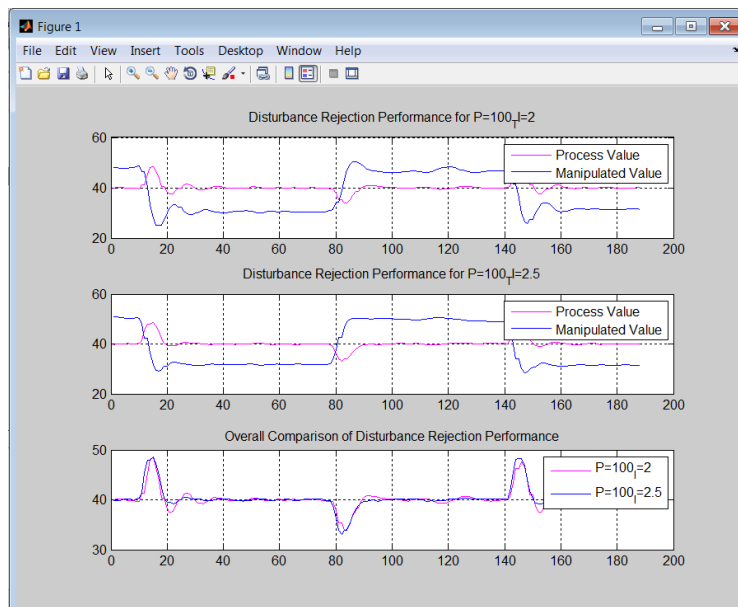


Figure 11. Output response from disturbance rejection performance.

6. Conclusion

This paper discusses the three elements of control actions and improving effectiveness of controllers through combination of these control actions in various forms. A Process Control Simulator had been used as model to analyze process response of various applied control actions and even combination of them. Due to the reaction of physical process is relatively fast to sensor and controller for flow control, PI controller is chosen as control model. With identified *FOPDT* model, correlation tuning parameters of PI controller were determined by using Cohen-Coon tuning method.

The analysis of process response is further extended to setpoint tracking analysis and disturbance rejection performance. The analysis is purposely to justify the best value of K_c and τ_i for optimized system performance with PI controller. In conclusion, $PB = 100$ (%) and $\tau_i = 2.0$ (s) is preferably chosen for changes of *SP* value. Meanwhile, $PB = 100$ (%) and $\tau_i = 2.5$ (s) is preferably selected for rejection to the noises and external inferences imposed to the system.

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