

CHAPTER 3: THEORETICAL BACKGROUND

3.1 INTRODUCTION

As mentioned in Chapter 1 and 2, PCLAB deals with exercises that deal with steady state and dynamic analysis of the process. The analysis is essential part of the controller design. In this chapter, the reader will be introduced to some of the terms that will be encountered in most of the exercises to be performed.

The modeling of industrial processes usually starts with a balance on a conserved quantity mass or energy. Mass and energy balances are very important for the engineer to describe the process mathematically. This balance can be written as:

$$\begin{array}{l} \text{Total flow rate of} \\ \text{(mass/energy) into} \\ \text{the system} \end{array} - \begin{array}{l} \text{Total flow rate of} \\ \text{(mass/energy) out of the} \\ \text{system} \end{array} = \begin{array}{l} \text{Accumulation rate of} \\ \text{(mass/energy) within} \\ \text{system} \end{array} \quad (3.1)$$

As we can imagine, in writing these balances and all other auxiliary equations, we must make use of almost every area of process engineering, such as thermodynamics, heat transfer, fluid flow, mass transfer, reaction engineering, etc. This makes the modeling of industrial processes most interesting and challenging. After characterizing the system by the model, it is then necessary to analyze the behavior of the system in terms of its variables that affect the controlled parameter, or the effect of disturbances that surface to affect the controlled parameter with time. When these variables are known, steps are then taken to keep them in check through the development of control algorithms.

Applying (3.1) usually results in nonlinear ODE equations which can be linearized and converted into transfer function in the form of:

$$\text{First Order with Dead Time (FODT):} \quad y(s) = \frac{ke^{-\theta s}}{\tau s + 1} u(s) \quad (3.2)$$

Second Order with Dead Time (SODT):
$$y(s) = \frac{ke^{-\theta s}}{\tau^2 s^2 + 2\zeta\tau s + 1} u(s) \quad (3.3)$$

3.2 STEADY STATE ANALYSIS

From (3.1), we conclude that the analysis of a process control system requires an understanding of the overall system behavior and the reflection of this behavior in the properties of the system elements. These properties are highlighted during steady state conditions where, the accumulation term in the above equation goes to zero. The state variables do not change with time and the input is then directly related to the output. This leads to the definition of the steady state gain as:

$$K = \text{Change in output} / \text{Change in input} \quad (3.4)$$

This relation is useful to determine the effect of manipulated and load variables on the controlled variable of a process. Thus the relation characterizes the effect that a change in an input variable has on an output variable. Implicit in this characterization is the fact that changes in the controlled variable can be calculated by summing up the changes in all the manipulated and load variables multiplied by a constant gain coefficient. This superposition applies only to linear systems. Steady state models are frequently used to determine set points for controllers whose measured variables are dynamic multiple-input computed variables. They are used to adjust the set points of unit operations performance variable..

3.2.1 Steady State Disturbance Sensitivity Analysis

Steady state disturbance analysis is a tool developed by (Yi and Luyben, [17]) to study the controllability and further the control structure of a given process. It is more suitable for nonlinear processes where the effect of process disturbance on the plant steady state operating condition is investigated.

Steady State disturbance sensitivity analysis can be carried out in two modes:

- ▶ Open loop
- ▶ Closed loop

In the open loop mode, steady state disturbance analysis illustrates how much a chosen process output changes at steady state for various different values of *a given disturbance* when all the manipulated variables are fixed at their corresponding steady state values. In this case, the severity and nonlinearity of the disturbance impact on a certain process output can be investigated. Moreover, one can compare the effect of the designated disturbance on several process outputs and find out which one is the most influenced.

In the closed loop mode, the steady state disturbance sensitivity analysis (*ssdsa*) demonstrates how much a specific input or a group of inputs should change to keep *a controlled output* or group of controlled outputs at its set point at steady state for various values of *a given disturbance* while the other inputs are fixed. Given certain constraints on the inputs, one can select the most appropriate input to regulate a specific output under the influence of a particular disturbance.

The steady state disturbance analysis (SSDA) is obtained by solving the static version of the process model for different values of *a pre-specified disturbance* with *a set of particular outputs* and all the inputs, except those used as manipulated variables, are fixed. The numerical solution is carried out using *fsolve* m-function of MATLAB. Further discussion and analysis of this tool will be discussed in a later chapter.

3.3 DYNAMIC ANALYSIS

The word dynamic conveys the idea of a time variation which can result from a number of unspecified or unknown influences; the word variable simply relates the capacity to vary from these influences. In process control we are interested in those dynamic variables which require regulation in some industrial application. Typical examples are: temperature, pressure, flow rate, level, force, light intensity, and humidity. Dynamic analysis can be performed in open-loop model and closed-loop mode.

3.2.1 Open-loop Dynamic Analysis

In open-loop dynamic analysis no control algorithm is involved. Therefore the dynamic response of a process variable to forced input variation can be studied.

Dynamic response is a measure of the systems reaction, as a function of time, in correcting transient inputs, or adjusting to a new set point. In this case, the dynamic analysis is useful to understand the dynamic behavior of a process and to characterize the process dynamic parameters such as time constant, damping factor, period of oscillation and dead time.

When a FODT process is subject to a step change in its input variable, it responds as shown in Fig. 3.1. The output reaction can be recorded and plotted to infer the system parameter. The figure shows how estimate the gain, time constant and dead time directly from the transient response. This procedure is known as reaction curve method.

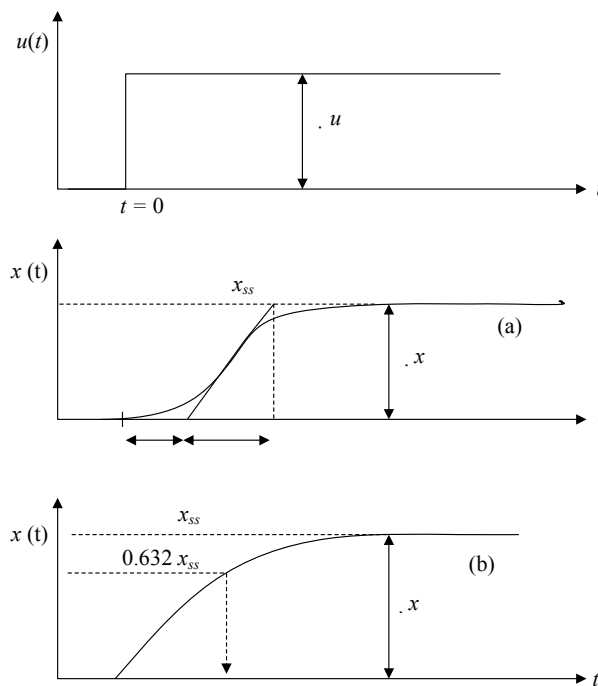


Fig. 3.1: Output response for a step change for first order system, (a) with time delay, (b) without time delay

Accordingly, the time constant is estimated directly from the response curve while the static gain is simply:

$$k = \frac{\Delta x}{\Delta u} \tag{3.5}$$

Similarly, when the input variable is stepped, the output of an under-damped second order system responds as shown in Fig. 3.2. From the recorded data, it is easy to identify the system parameters as follows:

Static gain: $k = \frac{x_{ss}}{\Delta u}$

Damping ratio: solve $\frac{A}{B} = \exp\left(\frac{-2\pi\zeta}{\psi}\right)$ for ζ .

Natural period of oscillation: $\tau = \frac{T\psi}{2\pi}$

Where $\psi = \sqrt{1-\zeta^2}$

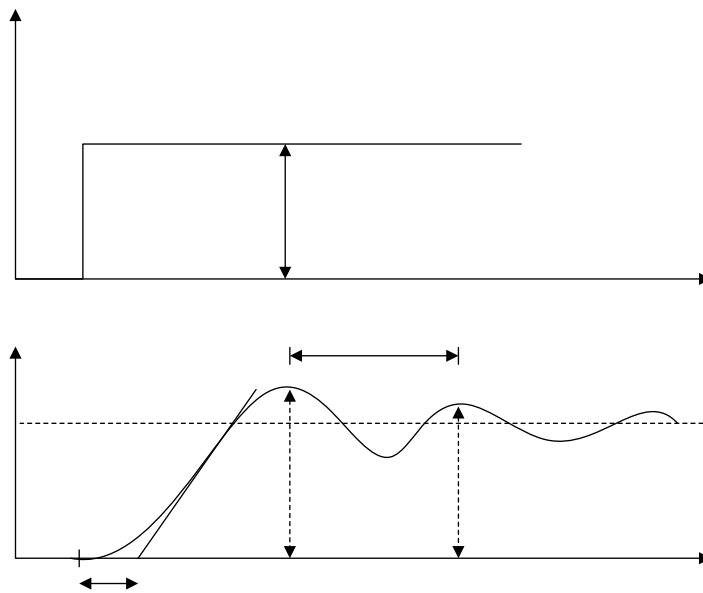


Fig. 3.2: Output response to a step change for second order system

3.2.2 Closed-loop Dynamic Analysis

The evaluation of system performance simply reflects the ability of a process control loop to regulate some dynamic variable in the process. Such regulation is specified through two criteria. The first criterion is the system error of the system in maintaining the controlled dynamic variable at the specific value defined by the set

point C_{SP} . The second criterion is the dynamic response of the system to any disturbance of the process or change of the process control loop set point.

The system error is a measure of the inherent error between the system set point value and the actual value of the dynamic variable maintained by the system. The desired value of the dynamic variable in the process is referred to as the set point.

Generally, a set point C_{SP} is expressed with some allowable deviation $\pm \Delta C$ about the nominal value. Thus, when control has been achieved the actual value of the dynamic variable may be in the range from $(C_{SP} - \Delta C)$ to $(C_{SP} + \Delta C)$. Of course the wider the allowable deviation the easier the control is to achieve. Note that this deviation can never be less than the inherent system error.

Feedback control loop

The regulation of a specific dynamic variable is usually carried out in feed back fashion as shown in fig. 3.3.

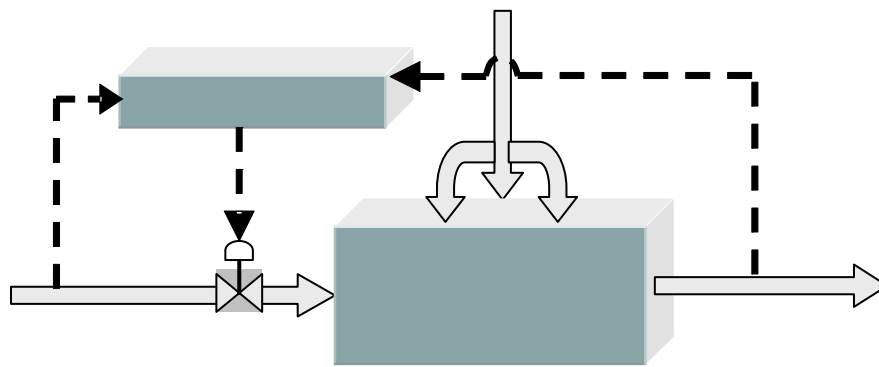


Fig. 3.3 Typical Feedback control configuration

The feedback controller is the component of the feedback loop that issues control commands to the process (via the final control element) based on e , the deviation of the process measurement from its desired set point value. The way the controller calculates the type of command signal to be issued for any given value of e is what differentiates one controller from another. To consider all dynamic elements of a feedback controller, the following block diagram is usually used:

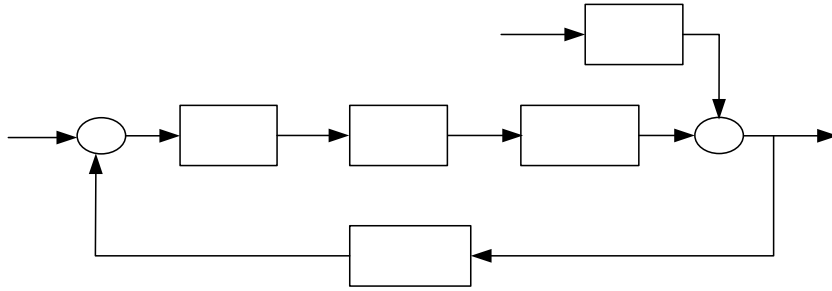


Fig. 3.4 Typical Block diagram for Feedback Control

According to fig. 3.4, the following are defined:

$G_c(s)$ = controller transfer function.

$G_v(s)$ = final control element (valve transfer function).

$G_p(s)$ = process transfer function.

$G_d(s)$ = disturbance transfer function.

$G_m(s)$ = measurement device transfer function.

$C(s)$ = controller signal.

$y_m(s)$ = measured output.

$y_{sp}(s)$ = set point.

$e(s)$ = error .

PID controller

The operating equation for PID controller is:

$$C(t) = K_c \left[e(t) + \frac{1}{\tau_I} \int_0^t e(t) dt + \tau_D \frac{de}{dt} \right] + C_s \quad (3.6)$$

Taking Laplace transform of the above equation we get:

$$C(s) = K_c \left(1 + \frac{1}{\tau_I s} + \tau_D s \right) e(s) \quad (3.7)$$

The transfer function for PID controller is:

$$G_c(s) = K_c \left(1 + \frac{1}{\tau_I s} + \tau_D s \right) \quad (3.8)$$

The parameter K_c is called proportional; gain, τ_D is called the derivative time constant and τ_I is the integral time constant.

Feed-forward system

The objective of the feed-forward control is to keep the values of the controlled output as its defined values. It is configured such that predictive action is taken on the controlled variable, thus it does not wait until the effect of a disturbance is already felt in the system but acts appropriately in anticipation of the disturbance. Fig. 3.5 depicts a typical feed forward control element [16].

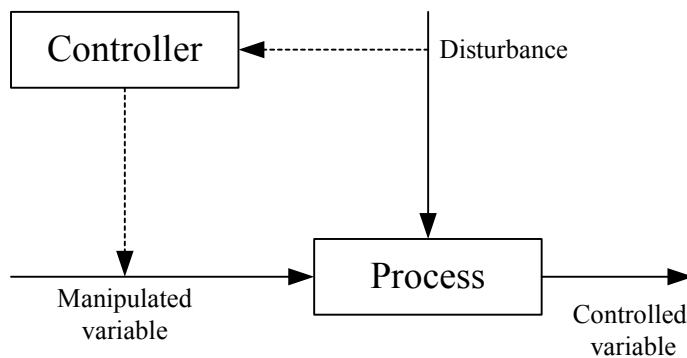


Fig. 3.5 Feed-forward Control configuration

In this control, the direct measurement of a disturbance is used to adjust the values of the manipulated variable to achieve a desired output value. The controller is the active element that receives the information from the measured parameter and takes appropriate action to adjust the values of the manipulated variable.

Consider the open-loop systems to be in the form of:

$$y(s) = G_p(s)u(s) + G_d(s)d(s) \quad (3.9)$$

Let y^{sp} be the desired set point for the controlled variable:

$$y^{sp}(s) = G_p(s)u(s) + G_d(s)d(s) \quad (3.10)$$

The feed forward controller is therefore:

$$u(s) = \left[\frac{1}{G_d} y^{sp} - d(s) \right] \frac{G_d(s)}{G_p(s)} \equiv [G_{sp} y^{sp} - d(s)] G_c \quad (3.11)$$

And the block diagram with FFC looks:

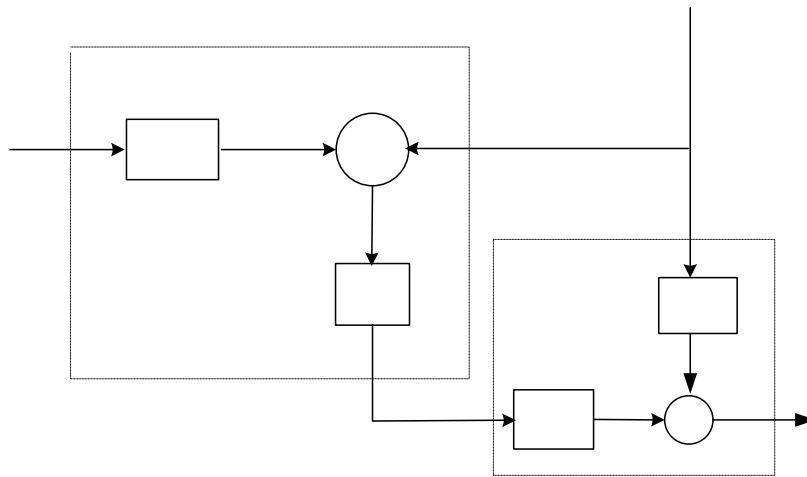


Fig. 3.6: FFC block diagram

Therefore,

$$G_{sp} = \frac{1}{G_d} = \frac{\tau_d s + 1}{k_d} \quad (3.12)$$

$$G_c = \frac{G_d}{G_p} = \frac{k_d \tau_p s + 1}{k_p \tau_d s + 1} \quad (3.13)$$

y_{sp}

G_{sp}

+

Cascade Control

A cascade or multi-loop control is a way of minimizing a disturbance that enters a slow process. It has two sets of controllers, a primary and a secondary. Instead of

adjusting the final control element such as a valve, the output of a primary controller is the set point of a secondary control loop. Thus cascade control uses the output of the primary controller to manipulate the set-point of the secondary controller as if it were the final control element. The block diagram for a cascade controller is shown in Fig. 3.7[16].

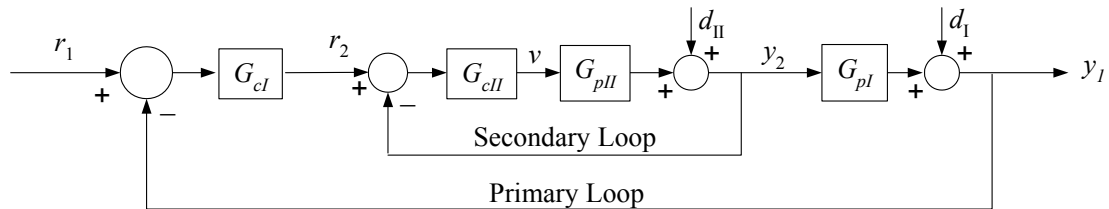


Fig. 3.7 Cascade control configuration

The reasons for using this type of control are as follows:

- Allow faster secondary controller to handle disturbances in the secondary loop.
- Allow secondary controller to handle non-linear valve and other final control element problems.
- Allow operator to directly control secondary loop during certain modes of operation (such as startup).

Requirements:

Secondary loop process dynamics must be at least four times as fast as primary loop process dynamics.

- Secondary loop must have influence over the primary loop.
- Secondary loop must be measured and controllable.

Cascade control can be used when there are several measurement signals and one control variable. It is particularly useful when there are significant dynamics, e.g. long dead times or long time constants between the control variable and the process variable.