CHAPTER 2

PROCESS DESCRIPTION

2.1 INTRODUCTION

A process having only one input variable used for controlling one output variable is known as SISO process. The problem of designing controller for SISO systems can be handled conveniently. But in several important situations, process may have MIMO making them multivariable nature. However, most of the ideas and techniques presented for SISO systems can be extended to MIMO systems. This chapter discusses two MIMO models, namely Level-Temperature cascaded Process and Level-pH cascaded Process. Both these processes are highly nonlinear and interacting processes.

2.2 GENERAL FORMULATION OF THE MIMO SYSTEM

All process systems consist of three main factors or terms: the manipulated variables, disturbances, and the controlled variables as shown in Figure 2.1. Typical manipulated variables can be valve position, motor speed, damper position, or blade pitch. The controlled variables for various process applications are those conditions such as temperature, level, position, pressure, pH, density, moisture content, weight, and speed that must be maintained at some desired value. For each controlled variable, there is an associated manipulated variable. The control system must adjust the
manipulated variables so that the desired value or “set point” of the controlled variable is maintained despite any disturbances.

Figure 2.1 General elements of a process

Disturbances affect the process and tend to drive the controlled variables away from their desired value or setpoint condition. If the setpoint is changed, the manipulated quantity must also be changed so as to bring the controlled variable to its new desired value.

Thus, a process control system consists of four essential elements: process, measurement, evaluation, and control. A block diagram of these elements is shown in Figure 2.2. The diagram also shows the disturbances that enter into the process. Figure 2.2 shows the input and output of the process and the setpoint used for control.

Figure 2.2 Four elements of a control system
A SISO system has a single manipulating variable to control a single output variable. In SISO system, no interaction exists. The processes encountered in the real world are usually MIMO systems. Systems with more than one input and/or more than one output are called MIMO system. The MIMO system can either be interacting or non-interacting. One output is affected by only one input, then it is called non-interacting system. If more than one output is affected by an input it is called interacting system. System with more than one controlled output and command input are called multivariable or MIMO systems. A multivariable system experiences interactions and responds poorly. The control of interacting system is more complex than the control of non-interacting system. The output of MIMO system can either be linear or non-linear. For example, an automobile driving system is a MIMO system. MIMO system can be decoupled into SISO systems. A decoupled SISO system has no interactions. Therefore, Input/Output (I/O) linearization is proposed before applying a linear controller (Nida Sheibat Othman et al 2011).

Suitable SISO controllers are PID controller, Auto tuning PID controller, Fuzzy Logic controller, and Adaptive controller and Neural Network controller. For MIMO process Model Predictive controller, Adaptive controller and Internal Model controller are suitable (Xiaoping Liu et al 2004). SISO techniques are applicable in Food processing industry, Petrochemical industry, and Cement factory. Similarly MIMO is applicable in Distillation column, Boiler control, Power plant, Continuous Stir Tank Reactor (CSTR).

Multiloop SISO controllers are often used for controlling interacting multivariable processes because of their simplicity in implementation and they are easily understandable to control engineers and require fewer parameters to tune than multivariable controllers. Another
advantage of the multiloop controllers is that loop failure tolerance of the resulting control system can be easily obtained.

Two approaches widely used for the analysis and design of control systems are the transfer function approach and the state variable approach. The transfer function approach is also called the conventional approach or the classical approach and the state variable approach is called the modern approach. The transfer function approach has certain drawbacks. The transfer function approach is generally applicable only to linear time invariant systems and it is generally restricted to single input single output systems. State variable approach is applicable to linear as well as non linear SISO and MIMO systems. State variable approach has number of advantages when compared to other approaches.

Most of the chemical processes are multivariable system. SISO control loops are formed by selecting a measurable output that is most strongly affected by a particular manipulated input (Gopal 2009). This is done because SISO design techniques are easy to understand, and hardware and software are readily available for SISO controllers. Systems that use several SISO controllers on a multivariable process are referred as Multivariable Single Input-Single Output (MVSISO) controllers. The selection of a particular measurable output to pair with a certain manipulated input is known as variable “pairing” and is elaborated in the next chapter.

Consider an open loop stable multivariable system with n-inputs and n-outputs as shown in Figure 2.3. In a Liquid level and temperature process, parameters level couples with liquid flow rate \( u_1 \), and temperature couples with liquid flow rate \( u_1 \) and heater input \( u_2 \). Where \( r_i, i = 1....n \) are the reference inputs; \( u_i, i = 1....n \) are the manipulated variables; \( y_i, i = 1....n \) are the system outputs \( G(s) \) and \( G_c(s) \) are process transfer function matrix and full
dimensional controller matrix respectively with compatible dimensions (Qiang Xiong et al 2007).

\[
G(s) = \begin{bmatrix}
g_{11s} & g_{12s} & \cdots & g_{1ns} \\
g_{21s} & g_{22s} & \cdots & g_{2ns} \\
\vdots & \vdots & \ddots & \vdots \\
g_{n1s} & g_{n2s} & \cdots & g_{nns}
\end{bmatrix}
\text{ and }
\]

\[
G_c(s) = \begin{bmatrix}
g_{c11s} & g_{c12s} & \cdots & g_{c1ns} \\
g_{c21s} & g_{c22s} & \cdots & g_{c2ns} \\
\vdots & \vdots & \ddots & \vdots \\
g_{cn1s} & g_{cn2s} & \cdots & g_{cnns}
\end{bmatrix}
\]

Figure 2.3 Closed loop multivariable control system

Recently, there has been a considerable effort to design decoupling algorithms so that the closed-loop response is exactly linear in a global sense. Input/output linearization involves finding nonlinear state feedback laws so that the input/output behavior of the closed-loop system is exactly linear. In the case of SISO systems, the problem is completely solved and explicit formulas for the input/output linearizing state feedback laws are available (Kravaris and Chung 1987). Such a state feedback law can be applied to a nonlinear process, and the resulting control structure is called the Globally
Linearizing Control (GLC) structure (Kravaris and Chung 1987). This methodology is extended to MIMO systems.

A non-linear system with the identical number of inputs and outputs can be represented as

\[
\dot{x} = f(x) + \sum_{j=1}^{m} g_j(x)u_j
\]

\[y = h(x)\]

The following conditions are sufficient for a system in the form represented by Equation (2.3) to be input/output linearizable: (In Joong Ha and Elmer Gilbert 1986)

i. Each output \( y \), possesses a relative order \( r_i \).

ii. System characteristic matrix is nonsingular for all values of \( x \).

These concepts are used to derive necessary and sufficient conditions for existence of a state feedback that linearizes a MIMO nonlinear system in an input/output sense and also to provide explicit formulas for the control law. In a case where all outputs possess relative orders but the characteristic matrix is singular, it may be possible to modify the system by applying an invertible linear matrix differential operator to the system outputs, so that the modified system possesses a nonsingular characteristic matrix. Then, an input/output linearizing state feedback can be used for the modified system to generate an input/output linearizing state feedback for the original system (Ali Nejati et al 2012).

A state feedback is applied to a MIMO nonlinear process and then the problem of controlling the outputs to setpoint reduces to a linear multivariable control problem. The latter can be solved by using the linear
multivariable control theory. This motivates the control structure of Figure 2.4, which is the Multi Input-Multi Output Globally Linearizing Control (MIMO GLC) structure.

![Figure 2.4 Schematic diagram of the globally linearizing control](image)

This work reports the application of the decoupling and linearization control methods to two MIMO chemical control processes namely, Level-Temperature cascaded process and Level-pH cascaded process. The system considered has two input variables and two output variables. Both these processes are highly nonlinear and interacting. The first process considered is the Level-Temperature cascaded process. It has two inputs viz., liquid flow rate, $u_1$ and heat input $u_2$ produced by the electric heating coil. The two outputs are liquid level $y_1$ and temperature $y_2$. Due to the flow rate, $u_1$ liquid level increases. This will automatically affect the temperature of the liquid in the reactor also. So an interaction exists between liquid level and liquid temperature.

### 2.3 DESCRIPTION OF THE LEVEL-TEMPERATURE CASCADED PROCESS

In process industries, the control of level, temperature, pressure, and flow are important in many process applications. In this work, the interacting non-linear stable MIMO systems (i.e. Level-Temperature process and Level-pH process) are discussed. The control of level and temperature of
liquid in tanks and acid and base flow in tanks are the basic problem in the process industries. A schematic diagram of the Level-Temperature cascaded process model is shown in Figure 2.5. The target is to control the level and temperature of the tank at the desired level. The tank is heated electrically by the coil heater. The aim of the controller is to keep the liquid level and the temperature as variables to be controlled within the set limits (Kazuhiko et al 1991). The liquid is water, and the level is measured by the differential pressure level transmitter. The temperature is measured by the thermocouple installed in the tank. In general, the liquid level and the temperature are controlled by adjusting the feed flow rate and the current to the heater respectively. It is clear that an interaction exists in this process. If the feed flow-rate is changed then the temperature as well as the liquid level changes. Liquid level ‘\(x_1\)’ depends on flow rate ‘\(u_1\)’ and liquid temperature ‘\(x_2\)’ depends on flow rate ‘\(u_1\)’ and heater input ‘\(u_2\)’.

**Figure 2.5** Schematic diagram of the Level-Temperature cascaded process (a) Differential pressure level transmitter (b) Thermocouple (c) Control valve (d) Heater controller and (e) Heater
Based on the assumptions that the tank is adiabatic, the tank content is perfectly stirred and the dynamics of the actuator can be negligible, the system is stable. The process model for a stable system based on mass and energy balance is given by

\[ \dot{x}_1 = -\left( \frac{k}{S} \right) x_1^2 + \frac{1}{S} u_1 \]  
(2.4)

\[ \dot{x}_2 = \left( \frac{T_0 - x_2}{S x_1} \right) u_1 + \left( \frac{1}{S \rho \zeta S x_1} \right) u_2 \]  
(2.5)

and the output equations are given by

\[ y_1 = x_1 \]  
(2.6)

\[ y_2 = x_2 \]  
(2.7)

where \( x_1 \) and \( x_2 \) are the liquid level and liquid temperature respectively. \( u_1 \) and \( u_2 \) are the feed flow rate to the tank and the heat flow rate from the heater respectively. The feed flow rate and heat flow rate are constrained as \( 0 \leq u_1 \leq 22 \text{cm}^3\text{s}^{-1} \) and \( 0 \leq u_2 \leq 2700 \text{Js}^{-1} \). \( k = \text{Constant Coefficient} = 1.8 \), \( S = \text{Cross sectional area of tank, 191 cm}^2 \), \( x_1 = \text{Liquid level in cm} \), \( x_2 = \text{Liquid temperature, } ^\circ\text{C} \), \( T_0 = \text{Temperature of the feed 18°C} \), \( \rho = \text{Specific heat, 4.2 J}^\text{K}^{-1} \), \( \zeta = \text{density of the liquid} \).

### 2.4 DESCRIPTION OF THE LEVEL-pH CASCADED PROCESS

The main objective of pH process is to control the effluent pH value by manipulating the flow rate of acid and base. Control of pH is important in the chemical industry. However, pH processes are difficult to control due to their nonlinear dynamics with uncertainties (Yoon et al 2002). Control of pH is vital in the chemical industry especially in waste water
treatment. In a chemical process involving the mixing of streams (acid, base, salts), the pH is a measure of the hydrogen ion concentration, that determines the acidity / alkaline of a solution.

A neutralization reaction process of a strong acid (HCL) at a concentration CAO and a strong base (NaOH) at a concentration CBO is shown in Figure 2.6. The two inputs are acid flow rate $u_1$ and base flow rate $u_2$ and the two outputs are liquid level in the tank, $y_1$ and pH value of the liquid, $y_2$. As the acid or base flow rate varies, it automatically affects the pH value also. This process is more non-linear than the Level-Temperature cascaded process and an interaction also exists between the parameters. The aim of this control process is to keep the liquid level and the pH at the desired values. It is known that this control problem is very difficult when the setpoint is near the point of neutrality, even if the control system is a SISO system. The reactor used is the same vessel as that of the level and temperature process and a similar measuring and control system is used. The liquids flowing are an acid and a base. The liquid level and pH are controlled by adjusting the feed flow rates of acid and base. Liquid level and pH depends on flow rate of acid and base $u_1$ and $u_2$ respectively.

The process model under the appropriate assumptions is given by (Nakamoto and Watanabe 1991)

$$ x_1 = \left(-\frac{k}{S}\right)x_1^{1/2} + \frac{1}{S}(u_1 + u_2) $$

$$(2.8)$$

$$ x_2 = \left[\frac{-1}{Sx_{1} \log_{10}(a)}\right] \left[b \cdot \text{CAO}U_1 + (b + \text{CBO})U_2 \right] $$

$$(2.9)$$

where $b = -10^{x_2 - 14} + 10^{-x_2}$,
\[ a = 10^{x_2^{14}} + 10^{-x_2} \]

Output equation is given by

\[ y_1 = x_1 \quad (2.10) \]
\[ y_2 = x_2 \quad (2.11) \]

The process model under the appropriate assumptions is given by

![Figure 2.6 Schematic diagram for the Level-pH cascaded process](image)

(a) Difference pressure level transmitter (b) pH sensor
(c,d) Control valves (e) pH meter

Here, \( x_1 \) and \( x_2 \) are the liquid level and the values of pH respectively. \( u_1 \) and \( u_2 \) are feed flow rate of strong acid and strong base respectively. The values ‘S’ and ‘k’ are cross sectional area of the tank 191cm\(^2\) and constant coefficient 1.8cm\(^{5/2}\)s\(^{-1}\) respectively. The feed concentrations are \( \text{CAO} = \text{CBO} = 0.03\text{mol cm}^3 \). The feed rates are constrained as \( 0 \leq u_1, u_2 \leq 22\text{cm}^3\text{ s}^{-1} \).
2.5 SUMMARY

In this chapter, the liquid Level-Temperature cascaded process and liquid Level-pH cascaded process are described in detail. The mathematical models are explained and process parameters are mentioned. The general description of SISO process and their applications and MIMO process are also explained. The next chapter deals with the implementation of decoupling algorithms for the nonlinear interacting MIMO system and the simulation results are analyzed after implementing algorithms.