Identification Process, Design and Implementation Decoupling Controller for Binary Distillation Column Control

SUTANTO HADISUPADMO[1)], RJ.WIDODO[2)], HARIJONO A TJOKRONEGORO[1)], TATANG HERNAS SOERAWIJAYA[3)]

[1)]Engineering Physics Department of ITB [2)] Electrical Engineering Department of ITB

[3)]Chemical Engineering Department of ITB

Jl. Ganesa 10 Bandung, INDONESIA-40132

Abstract: Identification process of the distillation column is the first step for design and implementation decoupling controller for binary distillation column control. For high purity products, the dynamics of the column become highly nonlinear and coupled and the response are sensitive to external disturbances. Distillation column control systems are use to purity the mixture of methanol and water which shows strong interaction, nonlinear dynamics and a large number of possible control structures. In this paper, we consider a decoupling controller to eliminate the strong interactions. The decoupler cancels the effect of the distillate composition to the change of the bottom composition and the effect of the bottom composition by the distillate composition. Simulation result good response for distillate control and bottom product control for decouple control systems with feed composition change from 0.6 to 0.35.

Keywords: identification, distillation control, multivariable system, interactions, decoupling.

1. Introduction

Identification process distillation column is the first step for design and implementation decoupling controller for binary distillation column. Multivariable high purity distillation columns present a number of challenging problems for both system identification and control due to their nonlinear and ill-condition nature. These two characteristics cause these distillation columns to be difficult to identify and control (Luyben, 1987). Decoupling of input and output variables is one of the central control design problems that has attracted considerable attention since the early 70s, in which, the decoupling problems has solved for the case of non uncertain system by means of static measurement matrix is usually uncertain due to the measurement device error[1]. This is difficult problem and has not yet been solved. The objective of this paper is to identify the process and design the decoupling controller that minimizes the control loop interaction between input-output variables of column distillation process.

2. Identification Process Distillation Column

For MIMO identification of high purity distillation columns, it appears that closed loop experiments are preferable to open loop ones due to the directionality aspect of multivariable distillation columns. For multivariable open loop experiments, the usual practice is to apply mutually independent pseudo-random binary signals (PRBSs) to all the manipulated variables (MVs) of the plant. The ill-conditioned nature or directionality of a high purity distillation column means that the two MVs in open loop experiments are highly correlated[8].

We define the systems by Auto Regressive Moving Average (ARMAX) model:

$$A(z^{-1})y_k = z^{-d}B(z^{-1})u_k + C(z^{-1})w_k \qquad (1)$$

Where d is delay time, w_k is white noise and A,B,C are:

$$A(z^{-1}) = 1 + a_1 z^{-1} + \dots + a_{nA} z^{-nA}$$

$$B(z^{-1}) = 1 + b_1 z^{-1} + \dots + b_{nA} z^{-nB}$$

$$C(z^{-1}) = 1 + c_1 z^{-1} + \dots + c_{nA} z^{-nC}$$

The input signal is *Pseudo Random Binary Sequences* (PRBS), and the polynomial form is:

$$P(z^{-1}) = 1 + z^{-1} + z^{-2} + z^{-3} + z^{-4} + \dots + z^{-n} \qquad (2)$$

We find the result of identification process gain distillation columns:

$$G_{11}(s) = \frac{0.006169s + 0.01263}{s + 0.09547} \qquad (3)$$

$$G_{12}(s) = \frac{0.0139}{s + 0.4411} e^{-2.5s} \qquad (4)$$

$$G_{21}(s) = \frac{0.00382}{s + 0.2262} e^{-9s} \qquad (5)$$

$$G_{22}(s) = \frac{0.002185}{s + 0.5241} e^{-7s} \qquad (6)$$

These model processes will be utilized for design decoupling controller.

3. Decoupling Controller

The decoupling structure control system developed by Boksenborm and Hood (1949) is shown in Figure 1. The decoupling matrix **D** is of the form [2]:

$$\mathbf{D} = \begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix} \qquad (7)$$

For the 2x2 MIMO process control can be written as:

$$\mathbf{Gu} = \mathbf{y} \qquad (8)$$

$$\mathbf{u} = \mathbf{D}\,[\mathbf{w}\text{-}\mathbf{y}] \qquad (9)$$

Where G_{ij} the transfer function, **u** and **y** denote the input and the output and $\mathbf{w}=[w_1,w_2]^T$ is the setpoint. Substituting (9) into (8) yields

$$\mathbf{G\,D}\,[\mathbf{w}\text{-}\mathbf{y}]=\mathbf{y} \qquad (10)$$

Rearrange this equation leads to the closed loop expression:

$$\mathbf{y} = [\mathbf{I} + \mathbf{G\,D}]^{-1}\,\mathbf{G\,D\,w} \qquad (11)$$

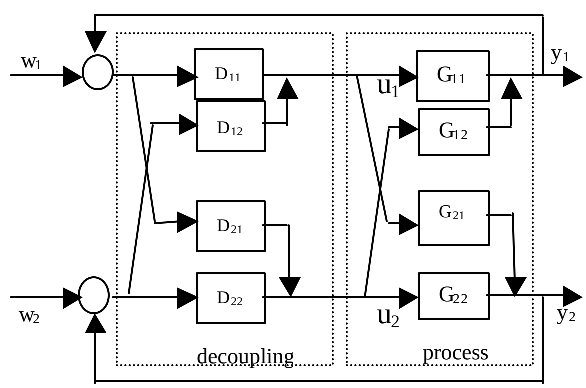

Figure 1. Decoupling control system (Boksenborm and Hood, 1949)

In order to make individual loops of the closed loop system are independent each other, it is required that:

$$\mathbf{X} = [\mathbf{I} + \mathbf{G\,D}]^{-1}\mathbf{G\,D} = \mathrm{diag}[x_1,x_2] \qquad (12)$$

Where **X** must be a diagonal matrix. Since the sum and product of two diagonal matrices are diagonal matrices, and the inverse of diagonal matrix is also diagonal matrix.

The requirement can be ensured if **GD** is a diagonal matrix. From (7) and (8), we have:

$$\mathbf{G\,D} = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix} = \begin{bmatrix} q_1 & 0 \\ 0 & q_2 \end{bmatrix} \quad (13)$$

so

$$\begin{bmatrix} G_{11}D_{11}+G_{12}D_{21} & G_{11}D_{12}+G_{12}D_{22} \\ G_{21}D_{21}+G_{22}D_{21} & G_{21}D_{22}+G_{22}D_{22} \end{bmatrix} = \begin{bmatrix} q_1 & 0 \\ 0 & q_2 \end{bmatrix} \quad (14)$$

Comparing each element of the matrices (14) results in a set of four equations:

$$\begin{aligned} q_1 &= G_{11}D_{11} + G_{12}D_{21} \\ 0 &= G_{11}D_{12} + G_{12}D_{22} \\ 0 &= G_{21}D_{11} + G_{22}D_{21} \\ q_2 &= G_{21}D_{12} + G_{22}D_{22} \end{aligned} \quad (15)$$

If the transfer function elements of **G** are known, and having specified the diagonal element of **D**, then the appropriate off-diagonal elements of **D** to achieve decoupling control are calculated by solving the set of equations in (15). Simplest way is to set **G D** to a diagonal matrix, and this gives the following relationships:

$$D_{12} = \frac{-G_{12}D_{22}}{G_{11}} \quad (16)$$

and

$$D_{21} = \frac{-G_{21}D_{11}}{G_{22}} \quad (17)$$

From equations (3), (4), (5), and (6) we find the elements of decoupler:

$$D_{12}(s) = \frac{-14.422s - 7.558}{2.267s + 1} \quad (18)$$

$$D_{21}(s) = \frac{-1.337s - 0.127}{2.159s^2 + 4.911s + 1} \quad (19)$$

The decoupling elements D_{11} and D_{22} of the decoupling matrix $\mathbf{G_c}$ can then be Proportional-Integral (PI) controller.

4. Dual Composition Control x_B and y_D

The choice of the proper configuration for dual composition control is more challenging than a single composition control, because there are more viable approaches and the analysis of performance is more complex. In this case there are a many of choices for manipulated variables (L, D, L/D, V, B, V/B, B/L, D/V) that can be paired to the four control objectives (i.e. x_B, y_D, reboiler level m_B, and accumulator level m_D) indicating that there are a large number of possible configurations. In this paper it is assumed that the choice for control configuration is L and V. The setpoint for reflux flow controller is set by the overhead composition controller and the setpoint for the flow controller on the reboiler duty is set by the bottom composition controller[5].

The L and V configuration is used since it provides good dynamic response, and in general, the configuration is least sensitive to feed composition disturbances. Moreover it is easy to implement, but it is highly susceptible to coupling. For this reason we design decoupling controller to anticipate this coupling.

In many cases, the control of one of the two products is more important than control of the other. For such cases, when the overhead products are the most important, L is usually used as a manipulated variable. When the bottoms products are most important, V is the proper choice as the manipulated variable. For a low reflux column for which the bottom product is more important, the L and V configuration is preferred.

5. An Example

Consider process distillation column with two inputs and two outputs shown in Fig. 4. The manipulated variables are L reflux flow rate, V boil-up flow rate, and the controlled variables are y_D distillate purity, and x_B bottom purity. The manipulated variables are L reflux flow rate, V boil-up flow rate, and the controlled variables are y_D distillate purity, and x_B bottom purity.

The mathematical model is derived from the fundamental principles as follow:
Overall material balance:
Tray feed, i = N_F

$$\frac{dM_i}{dt} = L_{\{i+1\}} - L_i + V_{\{i-1\}} - V_i + F \quad (20)$$

$$\frac{d(M_i x_i)}{dt} = L_{\{i+1\}}x_{\{i+1\}} + V_{\{i-1\}}y_{\{i-1\}} - L_i x_i - V_i y_i + F z_F \quad (21)$$

Total condenser, i = NT, ($M_{NT} = M_D, L_{NT} = L_T$)

$$\frac{dM_i}{dt} = V_{\{i-1\}} - L_i - D \quad (22)$$

$$\frac{d(M_i x_i)}{dt} = V_{\{i-1\}}y_{\{i-1\}} - L_i x_i - V_i y_i - D x_i \quad (23)$$

Reboiler, i = 1, ($M_i = M_B$, $V_i = V_i = V_B = V$)

$$\frac{dM_i}{dt} = L_{\{i+1\}} - V_i - B \quad (24)$$

$$\frac{d(M_i x_i)}{dt} = L_{\{i+1\}}x_{\{i+1\}} - V_i y_i - V_i y_i - B x_i \quad (25)$$

At steady state condition relation between control variable and manipulated variable are:

$$Äy_D = \left.\frac{äy_D}{äL}\right|_V ÄL + \left.\frac{äy_D}{äV}\right|_L ÄV = K_{11}ÄL + K_{12}ÄV$$
$$Äx_B = \left.\frac{äx_B}{äL}\right|_V ÄL + \left.\frac{äx_B}{äV}\right|_L ÄV = K_{21}ÄL + K_{22}ÄV \quad (26)$$

The K's are steady state gains that can be determined from mathematical models or from experimental test. They describe how, say, L affects y_D when x_B is not controlled. A second gain may be defined that gives a measure of how, say L would affect y_D if x_B were under closed loop control by the relationship:

$$K_{11} = \left.\frac{Äy_D}{ÄL}\right|_{V-\text{constant}(ÄV=0)} \quad (27)$$

and

$$K_{21} = \left.\frac{Äx_B}{ÄL}\right|_{V-\text{constant}(ÄV=0)} \quad (28)$$

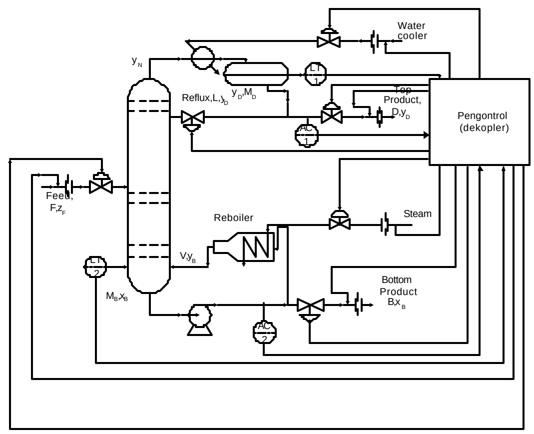

Figure 2. Distillation Column with Decoupling Controller

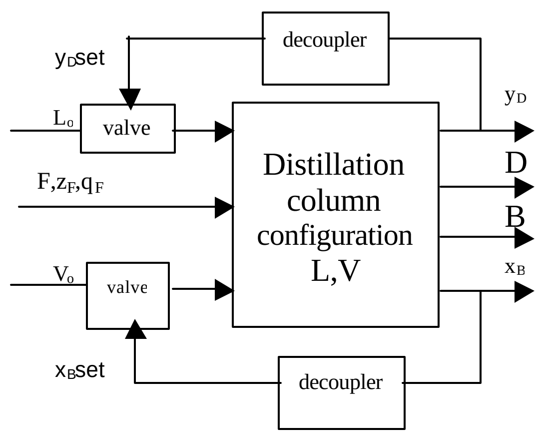

Figure 3. Block diagram distillation column configuration L,V with decoupler

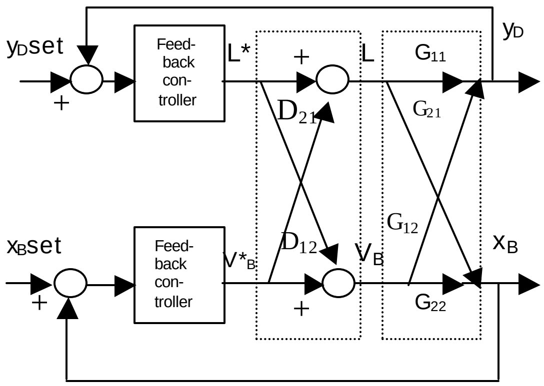

Figure 4. Block diagram control system with decoupler

To simulate the proposed decoupling controller for the distillation column, we use the distillation data [4]:

1. number of tray= 41 (include reboiler and condenser)
2. feed location i = 20
3. relative volatility = alpha = 1.5
4. nominal reboiler holdup = M_O (1) = 0.5 [kmol]
5. nominal holdup condenser= M_O(NT) = 0.5 [kmol]
6. nominal holdup tray = M_O(i) = 0.5*ones (1,NT-2) ; i=2:NT-1
7. nominal feed rate = F_O= 1 [kmol/min]
8. nominal fraction liquid in feed=qF_O = 1.
9. nominal reflux flow = L_O = 2.70629/0.5
10. nominal liquid flow below fed = L_{Ob}= L_O + qF_O*F_O
11. affect flow vapor in liquid flow = lambda = 0
12. nominal vapor flow = V_O = 3.20629/0.5; V_{Ot} = V_O + (1-qF_O)*F_O

Termodynamic data:

a. Boiling point light component =272.65 ^{o}K
b. Boiling point heavy component = 309.25 ^{o}K
c. Heat capacity light component = 96 kJ/kmol ^{o}K
d. Heat capacity heavy component = 121 kJ/mol ^{o}K
e. Hvap for light component = 19575 kJ/kmol
f. Hvap for heavy component = 28350 kJ/kmol
g. Vapor pressure of pure liquid component =1.013e5
h. Vapor pressure of pure heavy liquid component = 1.013e5
i. Universal gas constant = 8.314 kJ/kmol ^{o}K

6. Simulation Result and Conclusions

Simulation result show that the response of the process control with decoupler has smaller offset than the process control without decoupler. And also simulation give the good response for distillate control and bottom product control for decoupler control systems with feed composition change from 0.6 to 0.35.

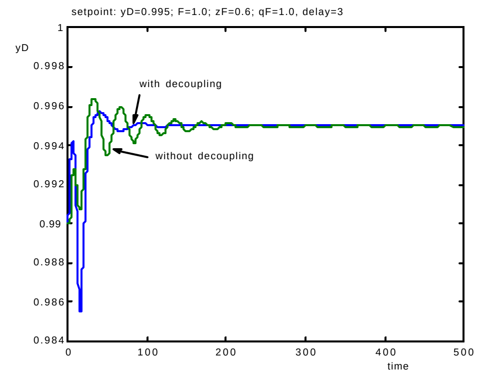

Figure 5. Comparation between control system with decoupler and without decoupler for setpoint y_D=0.995; z_F=0.5; F=1.0; q_F=1; delay time=3.

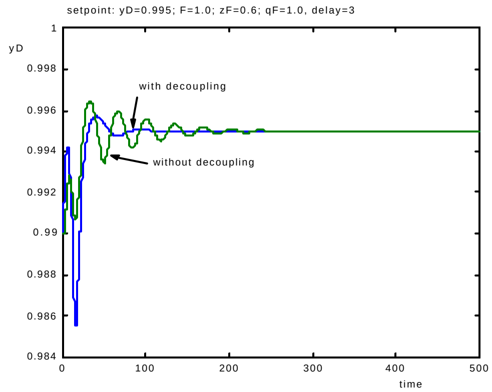

Figure 6. Comparation between control system with decoupler and without decoupler for setpoint y_D=0.995; z_F=0.6; F=0.1; q_F=1; delay=3.

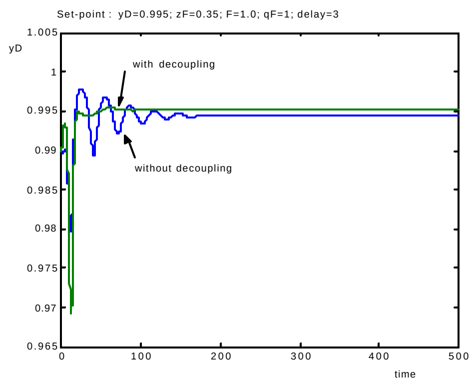

Figure 7. Comparation between control system with decoupler and without decoupler for setpoint y_D=0.995; z_F=0.35; F=1.0; q_F=1; delay=3

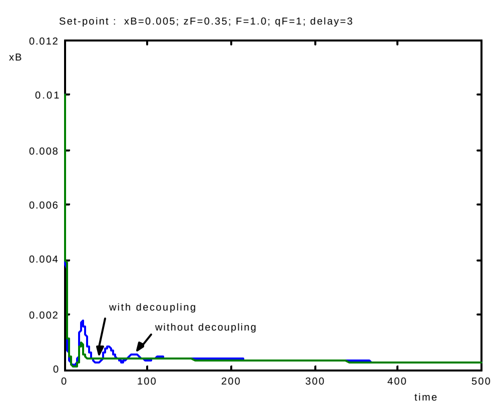

Figure 8. Comparation between control system with decoupler and without decoupler for setpoint x_B=0.005; z_F=0.35; F=1.0; q_F=1; delay=3

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