3rd International Conference on
Robotics Automation and Non-Destructive Evaluation,
Chennai, India, 23 April 2022.
https://doi.org/10.13180/RANE.2022.23.04.13

SIMULATION STUDIES OF INVERTED DECOUPLING CONTROL ALGORITHM ON A NON-SQUARE PILOT PLANT DISTILLATION COLUMN

R. JANANI and EADALA SARATH YADAV

Department of Electronics and Instrumentation Engineering, Sri Chandrasekharendra Saraswathi Viswa Mahavidyalaya, Enathur, Kanchipuram, Tamilnadu 631502, India

Senior Engineer, Modeling and Simulation, EEV Department, Robert Bosch Engineering and Business Solution, Bangalore, Karnataka, India

E-mail: janani.rajaraman@kanchiuniv.ac.in, sarath.eadala@gmail.com

I. THIRUNAVUKKARASU

Department of Instrumentation and Control Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka 576104, India

E-mail: it.arasu@manipal.edu

The inverted decoupling-based controllers for a time delay multivariable non-square systems is a challenging task. In this case study, a controller is designed on the basis of the inverted decoupling structure for a highly interactive lab scale batch distillation process. The centralized inverted decoupling controller is divided into two sub sections, one on the forward path and the other in the feedback path. The main objective is to achieve a decoupled dynamic behavior characteristic of each loop. The square distillation column model in literature generally uses the heater current and reflux as the two manipulated variables, in the modified lab scale distillation column, the authors have considered the third manipulated variable for the restriction of coolant flow rate to the condenser. The mathematical model used in the simulation study is process with three inputs and two outputs is considered for parameter estimation and simulation studies followed by the validation of control algorithms on a lab scale distillation unit to show the effectiveness of the proposed control algorithm.

1. Introduction

In most of the petrochemical industries, due to the presence of several process parameter measurements and its control the real processes are MIMO (Multiple Input and Multiple Output). A system is said to be a square system, when the system has same quantity of input, outputs. On the other hand, when the quantity of inputs and outputs are different the system non-square. Because of the structural characteristics, the existing conventional control algorithms cannot be used for the such system. In conventional method, the pseudo-inverse of the steady state gain matrix of the process, the two-mode controller is designed. The determination of inverse matrix and adjoin matrix leads to the complexity in obtaining the decoupling elements in ideal and simplified decoupling methods.

Section 2 provides a brief summary on system overview and experimental setup, the design of inverted decoupler, Section 3 explains the design of inverted decoupler and the expression for centralized two-mode controller. Section 4 shows the obtained results of the designed controller based on inverted decoupling for the lab scale batch distillation column.

2. Experimental Setup

Distillation a process of separation based on the boiling points and volatility of two or more components, widely used in petrochemical industries. The combination of isopropyl alcohol and water fed in to the pilot plant binary distillation column is considered here in this work. The schematic of the non-square pilot plant is shown in Fig.1(a). The actual pilot plant of non-square system available at advanced process control lab, MIT, Manipal is shown in Fig.1(b)

The model setup is equipped with temperature transmitter fixed near the bubble cap trays, feed section, reboiler and drum for reflux, and a condenser. The condenser gathers the condensate and is stored in the reflux tank. The temperature near the top tray and bottom tray in the column are recorded by the transmitters (4-20mA) and RTDs. The linearized model of the lab scale distillation column in MIT, Manipal is already modelled as a square system [7, 8]. The mathematical model is identified by LV configuration. The reflux flow rate and re-boiler power supply are the manipulated variables and the temperature across top tray and bottom tray T_1 and T_5 respectively are the controlled variables.

For the lab scale non-square distillation column system in order to obtain the linear transfer function model open loop experimentation is carried out. The change in the tray temperature is recorded when there is a step change in reflux flow rate and reboiler heater power. Initially the reflux flow rate and the heater power supply was kept as $[L_q, H_r] = (10, 50)$ to reach the steady state temperature with top tray (T1) and bottom tray (T5). Further most of the process industries rely on empirical modeling, where the model is identified upon the collection analysis of experimental data. For the conversion of square system to non-square system, the third manipulated variable is considered as the coolant flowrate to the condenser, which will operate based on the top tray temperature. This configuration will avoid the continuous flow of water in the condenser even if the top tray temperature is less than the desired. Coolant water flow is circulated to convert the vapor produced to distillate in general. If the top tray temperature or the pressure in the column is not developed, the coolant water circulation can be reduced or stopped in this modified configuration, which results with significant water saving.

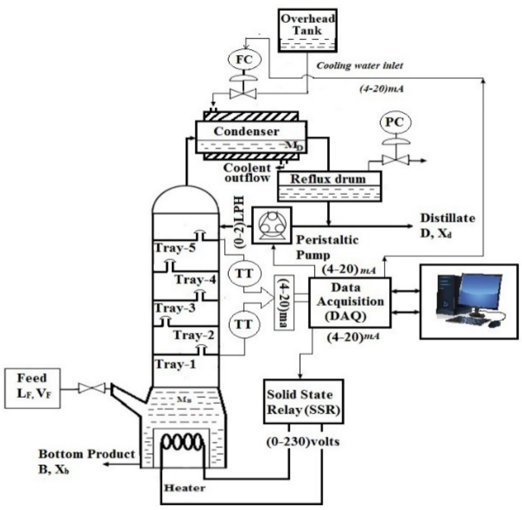


Figure 1(a). Schematic diagram of a Non-Square Pilot Plant Distillation Column.

. Figure 1(b). Non-Square Pilot Plant Distillation Column. Setup with control valve for condenser as third manipulated variable, available in Advanced Process Control Lab, MIT, Manipal

3. Controller Methodology

In this section the concept of inverted decoupling-based two mode controller for a non-square process is illustrated. The mathematical expression for such a system with time delay is shown in eq.1. For any high-dimensional MIMO process the decoupler elements will be high and it requires model reduction. The non-square process with time delay is G(s) in the form of (n*m) with m inputs and n outputs is,

$$G(s) = \begin{bmatrix} g_{11} & g_{12} & g_{1m} \\ g_{21} & g_{22} & g_{2m} \\ \cdots & \cdots & \cdots \\ g_{n1} & g_{n2} & g_{nm} \end{bmatrix} \tag{1}$$

where g_{ij} is represented as $g_{ii} = k_{ii}e^{-\theta_{ii}s}/(\tau_{ii}s + 1)$ is the transfer function The centralized inverted decouple control structure is shown in Fig.2 [3]. This type of control scheme is composed of two blocks $G_d(s)$ in the forward path connecting error signal and process, the other is in the feedback path connecting error signal and process input $G_0(s)$.

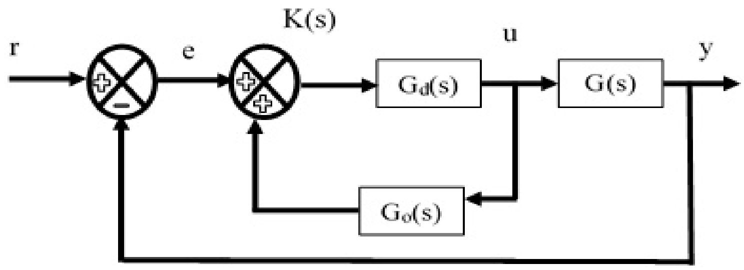


Figure 2. Structure of Inverted Decoupling

$L(s)$ the loop function is

$$N(s) = G(s)G_c(s);\ L(s) = \frac{N(S)}{I + N(S)} \tag{2}$$

$$L(s) = \begin{bmatrix} l_1(s) & 0 & 0 \\ 0 & l_2(s) & 0 \\ 0 & 0 & l_n(s) \end{bmatrix}_{nxn} \tag{3}$$

The centralized controller $G_c(s)$ is

$$G_c(s) = \frac{G_d(s)}{[I - G_0(s)G_d(s)]} \tag{4}$$

$$G_c(s) = \begin{bmatrix} g_{c11} & g_{c12} & g_{c1m} \\ g_{c21} & g_{c22} & g_{c2m} \\ \cdots & \cdots & \cdots \\ g_{cn1} & g_{cn2} & g_{cnm} \end{bmatrix}_{nxm} \tag{5}$$

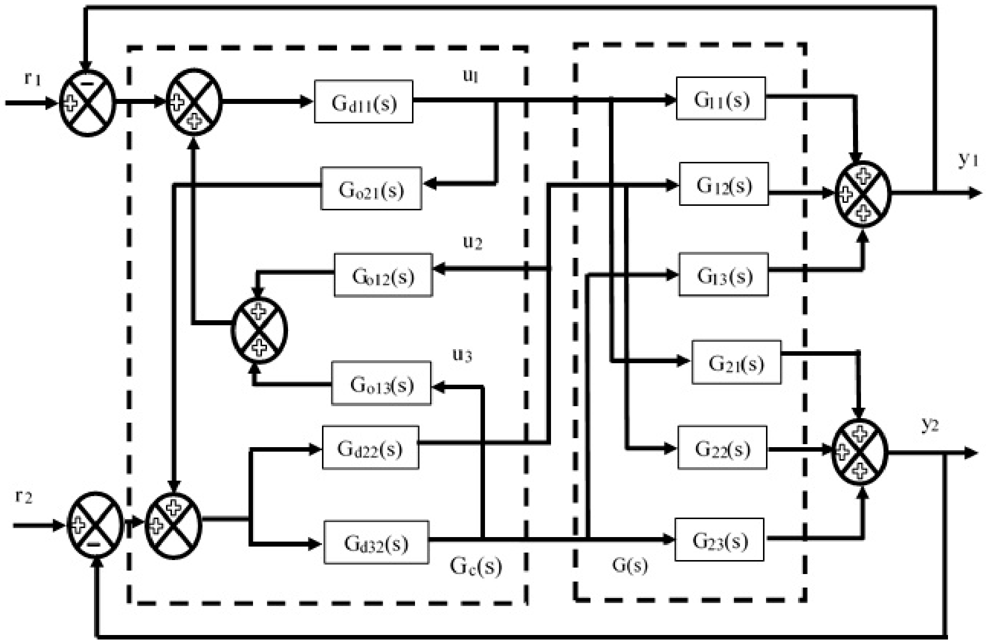


Figure 3. Structure of Centralized Inverted Decoupling for 2*3 process

Using (4) in (2)

$$G_d(s)[I - G_o(s)G_d(s) + G(s)G_d(s)]^{-1} = L(s)/G(s) \tag{6}$$

The centralized controller elements$G_o(s)$, $G_d(s)$ are determined as follows. Let consider $G_d(s)$ be an *(m*n)* matrix and $G_o(s)$ be an *(n*m)* matrix [4].

$$G_d(s) = \left[G_{d1}{}^T(s), G_{d2}{}^T(s)\right]^T \tag{7}$$

$$G_d(s) = \begin{bmatrix} g_{d1} & 0 & 0 \\ 0 & g_{d2} & 0 \\ \vdots & \vdots & \vdots \\ g_{dm1} & g_{dm2} & g_{dnm} \end{bmatrix} \tag{8}$$

$$G_o(s) = \begin{bmatrix} g_{011} & g_{012} & g_{01m} \\ g_{021} & g_{022} & g_{02m} \\ \vdots & \vdots & \vdots \\ g_{0n1} & g_{0n2} & g_{0nm} \end{bmatrix} \tag{9}$$

On substituting (9) (8) (5) (4) in (2)

$$G_d(s) = \begin{bmatrix} \frac{l_1(s)}{(1 - l_1(s))g_{11}(s)} & 0 & 0 \\ 0 & \frac{l_2(s)}{(1 - l_2(s))g_{22}(s)} & 0 \\ 0 & 0 & \frac{l_n(s)}{(1 - l_n(s))g_{nn}(s)} \end{bmatrix} \tag{8}$$

$$G_o(s) = \begin{bmatrix} 0 & -\frac{(1-l_1(s))g_{12}(s)}{l_1(s)} & -\frac{(1-l_1(s))g_{1m}(s)}{l_1(s)} \\ -\frac{(1-l_2(s))g_{21}(s)}{l_2(s)} & 0 & -\frac{(1-l_2(s))g_{2m}(s)}{l_2(s)} \\ -\frac{(1-l_n(s))g_{n1}(s)}{l_n(s)} & -\frac{(1-l_n(s))g_{n2}(s)}{l_n(s)} & 0 \end{bmatrix} \quad (9)$$

The controller elements which are complex in $G_d(s)$ and $G_o(s)$are avoided by the above equations [5] and which also avoids the Moore-Penrose pseudo-inverse method.

4. Simulation Results

The analytical method of determing the inverted decoupled based PI controller is designed for the standard three inputs and two outputs non-square process is given below

$$G(s) = \begin{bmatrix} \frac{4.05}{50s+1}e^{-81s} & \frac{1.77}{60s+1}e^{-84s} & \frac{5.88}{50s+1}e^{-81s} \\ \frac{5.39}{50s+1}e^{-54s} & \frac{5.72}{60s+1}e^{-42s} & \frac{6.9}{40s+1}e^{-45s} \end{bmatrix} \quad (10)$$

The standard form of closed loop transfer function is given as

$$l_i(s) = \frac{k_i}{\lambda_i s + 1}e^{-\theta_i s+1} \quad (11)$$

The closed loop specification is chosen in such that these parameters satisfy the condition of centralized controller is taken as $\lambda_1 = 30, \lambda_1 = 40$ and $\theta l_2 = 81, \theta l_2 = 42$. The elements of the centralized controller are

$$G_d(s) = \begin{bmatrix} \frac{\frac{(50s+1)}{4.05(30s+1)}}{(1-\frac{1}{30s+1}e^{-81s})} & 0 \\ 0 & \frac{\frac{(60s+1)}{(40s+1)}}{(5.72-\frac{5.72}{40s+1}e^{-42s})} \\ 1 & 0 \end{bmatrix} \quad (12)$$

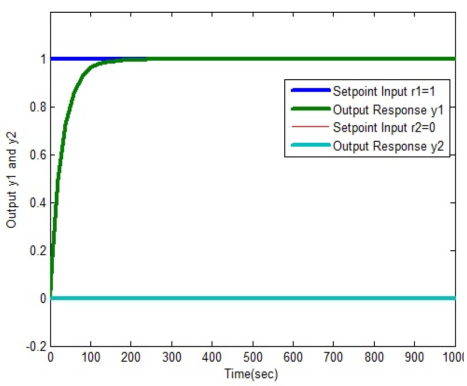
$$G_0(s) = \begin{bmatrix} 0 & g_{012} & g_{013} \\ g_{021} & 0 & g_{023} \end{bmatrix} \quad (13)$$

The elements of the $G_0(s)$ are,

$$g_{012}(s) = \frac{1.77}{60s+1}e^{-84s} - \frac{1.77(30s+1)}{60s+1}e^{-3s}$$
$$g_{013}(s) = \frac{5.88}{50s+1}e^{-81s} - \frac{5.88(30s+1)}{50s+1}$$
$$g_{021}(s) = \frac{5.39}{50s+1}e^{-54s} - \frac{5.39(40s+1)}{50s+1}e^{-12s}$$

$$g_{023}(s) = \frac{6.9}{40s+1}e^{-45s} - 6.9e^{-3s}$$

The feedback control response of the process for step input with inverted decoupled based centralized controller is shown in Fig.4 and the controller behavior is shown in Fig.5



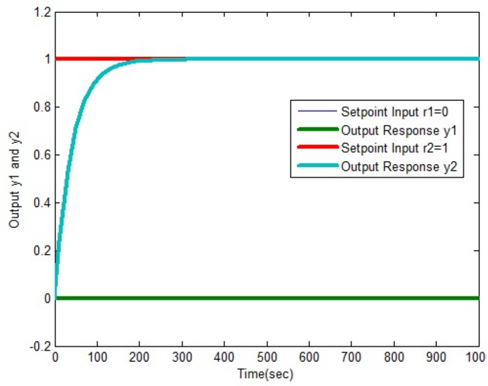
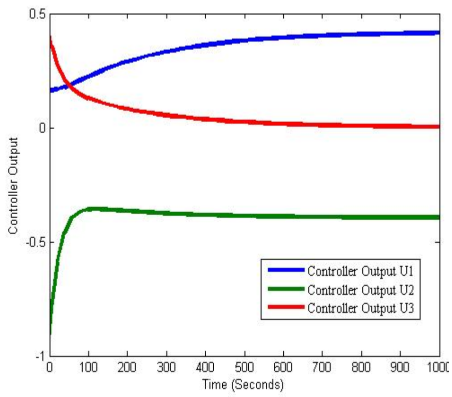


Figure 4(a). Feedback control response with unit step input r1=1 and r2=0
Figure 4(b). Feedback control response with unit step input r2=1 and r1=1



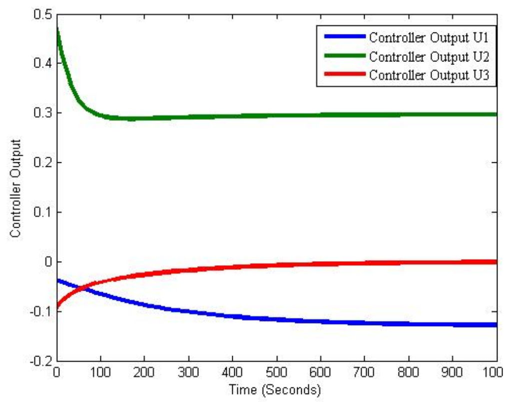


Figure 5(a). Controller response when input r1=1 and r2=0
Figure 5(b). Controller response when input r1=0 and r2=1

Table.1. Performance Indices

Time Domain Characteristics	Y_{11}	Y_{21}	Y_{12}	Y_{22}	Main Action	Interaction	Overall
IAE	30	0.000034	0.000095	39.98	69.98	0.000129	69.9801
ISE	15	0.00048	0.000145	20	35	0.000625	35.0006
ITAE	899.6	0.000302	0.000516	1592	2491	0.000818	2491.60
ITSE	225	0.0000113	0.000523	400	625	0.0005343	625.0005

5. Conclusion

Centralized controller based on inverted decoupling is simulated and the closed loop response is obtained. In order to reduce the complex structure of the centralized inverted decoupler diagonal pre-compensator is introduced. The servo response and performance characteristics table shows the effectiveness of the method.

References

1. Garrido, Juan, Francisco Vázquez, and Fernando Morilla. "Centralized inverted decoupling control" *Industrial & Engineering Chemistry Research*, 7854-7866 (2013).
2. Luan, Xiaoli, et al. "Compensator design based on inverted decoupling for non-square processes." *IET Control Theory & Applications*, 996-1005 (2017).
3. Yunhui, Luo, et al. "Control configuration selection based on RNGA for non-square multivariable processes." *Proceedings of the 31st Chinese Control Conference*. IEEE, (2012).
4. Ganesh, P., and M. Chidambaram. "Multivariable controller tuning for non-square systems by genetic algorithm." *Proceedings of International Conference on Intelligent Sensing and Information Processing,* IEEE, (2005).
5. Vu, Truong Nguyen Luan, and Moonyong Lee. "An extended method of simplified decoupling for multivariable processes with multiple time delays." *Journal of chemical engineering of Japan*, 279-293 (2013).
6. Rajkumar, K., S. Narayanan, and N. Sivakumaran. "Design of centralized controller based on inverted decoupling structure for non-square systems with time delay." *Trends in Industrial Measurement and Automation (TIMA)*. IEEE, (2017).
7. Eadala Sarath Yadav, Thirunavukkarasu Indiran, S. Shanmuga Priya, and Giuseppe Fedele, "Parameter Estimation and an Extended Predictive-Based Tuning Method for a Lab-Scale Distillation Column", *ACS Omega,* 21230–21241. (2019)
8. Eadala Sarath Yadav, Thirunavukkarasu Indiran, S. Shanmuga Priya, "Optimal Energy Consumption of Distillation Process and its Purity Analysis Using UV Spectroscopy" *ACS Omega*, Vol.6, Issue 2, 1697-1708 (2019)