Minimizing loop interaction in Multi Input Multi Output (MIMO) system using partial decoupler approach

M S Sulaiman and Z Ahmad

School of Chemical Engineering, Engineering Campus, Universiti Sains Malaysia, 14300, Nibong Tebal, Penang, Malaysia

*E-mail: chzahmad@usm.my

Abstract. This research focus on controlling Multiple Input Multiple Output (MIMO) process for Reflux (L) – Boil up rate (V) configurations. There are a total of 3 phases in the simulation process. In phase 1, transfer functions and best fit curves are obtained for LV. The best fits are 88.28 % (CV1) and 93.07 % (CV2). The controller for LV configurations was developed. In phase 2, the controllers were tuned and analyze based on the set point tracking and disturbance rejection. In phase 3, partial decouplers were developed and analyzed for a static plus dynamic approach. It is observed that the partial decoupler provides better performance as compared to conventional full decoupler. The performance was proven based on the outcomes from the simulations and calculations. As a conclusion, the partial decoupler is able to minimize the loops interaction and obtain the best set point tracking and disturbance rejection.

1. Introduction
The function of the distillation is to separate feed (F) into multiple products depending on the requirement of each industry. Distillation columns are categorized into 2 types which are batch column and continuous column. Continuous columns are classified into 2 types, binary column (feed contains only 2 components) and multi-component column (feed contains more than 2 components) [1]. The key concept in the distillation column is to maintain the product streams compositions. This is done by identification, classification (manipulated variables and disturbances) and control of all the parameters that contribute to the change in product composition [2]. Thus, a control system is implemented to accomplish the target. From a control perspective, in a binary distillation column, reflux flow (L), boil up flows (V), distillate (D) and bottom (B) can all be used as control inputs to control the logarithmic purities of top product (X_B), bottom product (X_D) and the levels in the condenser and reboiler [3]. Depending on which control inputs are used to control which outputs, different control configurations for the binary distillation column can be defined. In this study, one control configurations are used which is Liquid-Vapor (LV) control configuration [4]. In LV configuration, reflux rate (L) is used to control the composition of the top product and boil-up rate (V) is used to control the composition of the bottom product.

These research study the interactions of loops particularly between the composition of top and bottom products. These interactions occur because changes in a manipulated variable cause the changes in multiple loops. In other words, the loops are interconnected by a variable. Normally the controlling parameter is selected in pairs and for that, a multiple input multiple output (MIMO) system is required. MIMO system contains multiple loops which, in most cases, interact with one another. These interactions result in the destabilization of a system. A control system is required in order to stabilize
and minimizes the loop interactions. Therefore, partial decoupler is introduced in this study to further reduce or minimize the effect of the loop interactions.

2. Methodology

2.1. Modelling
The case study is taken from Skogestad and Postlethwaite [6]. It’s a binary mixture with constant pressure, constant relative volatility, and equilibrium on all stages, total condenser, constant molar flows, no vapor holdup and linearized liquid dynamics. However, the main effects important for dynamics and control is there for multi loops control study and in this paper on LV configuration were considered. The column has 40 theoretical stages and separates a binary mixture with relative volatility of 1.5 into products of around 99 % purity [7]. In order to get the model of the system for control and decoupler design, step test analyses were implemented and it runs in the Matlab™ Simulink environment as shown in figure 2.

![A Binary Distillation Column][1]

![A Step Test Block Diagram configuration.][2]
System Identification toolbox is selected for transfer function model identification. In the toolbox, the best-fit percentage is displayed for the model prediction for both CV1 and CV2. In this study, the best-fit percentage for either CV1 or CV2 or both is set to higher than 80 %, if the best-fit percentage is lower than 80 %, the step test is repeated with the change of inputs to improve the model prediction.

2.2. Tuning of Controller: Direct synthesis (DS) method

The gain ($K_P$), time constant ($\tau_P$) and time delay ($\theta$) values obtained from the transfer function model from section 3.1 are used to tune the controllers. The equation to calculate $K_C$, $\tau_i$ and $\tau_d$ for direct synthesis method are stated in the table 1.

| Controller | $K_C$ | $\tau_i$ | $\tau_d$ |
|------------|-------|----------|----------|
| PI         | $\tau_P / K_P (\lambda + \theta)$ | $\tau_P$ | -        |
|            | $\tau_P / K_P (\lambda + \theta)$ | $\tau_P$ | -        |
| PID        | $K_P (\lambda + \theta) + 0.5\theta$ | $\tau_P$ | $\tau_P (2\tau_P + \theta)$ |

2.3. Decoupler

After the controller is tuned, the controlled variables are observed with respect to performance indicator for further improvement by implementing decoupler. For a static decoupler, the value of the gain for the decoupler is obtained through the gain of the process model and for dynamics decoupler, the dynamics part is added to the block as part of the decoupler. The block diagram for static decoupler is shown in Figure 3.

![Figure 3. Control System with Static Decoupler.](image)

Furthermore, the full type of decoupler is also compared with the partial top and bottom type decoupler. This is to provide a better insight into the functionality of each decoupler directly to the respective loops. Thus a total of 3 types of decouplers are implemented and compared which are conventional decoupler, partial top decoupler and static partial bottom decouplers. Figure 4 and 5 represent the partial top and bottom decoupler respectively.
3. Results and discussions

3.1. Modelling: Step test
Based on the step test result through identification toolbox in Matlab™, after multiple steps testing, the best fit curve for both the top and bottom process (CV1 and CV2) was obtained as shown in Figure 6 and 7 respectively. In those figures, the best fit of 88.28 % and 93.07 %, and the model error within the range of 0.02 to -0.01 and 0.0005 to -0.0007 for CV1 and CV2 were obtained respectively and it is within the valid range [7]. Thus the transfer functions determine from the steps test function were accepted to be used for the tuning of the controller and also for the decoupler design.
3.2. Direct Synthesis (DS) Tuning Method
The set point change with the step time started at 700 seconds with the initial value of the set point of 0.98 and the final value of 0.99 for CV1. In CV2 the set point change from 0.02 to 0.03 at the step time of 350 seconds was implemented respectively. The transfer functions for the distillation column based on the step test result shows in Figure 6 and 7 are shown below:

\[
\begin{bmatrix}
\text{CV1} \\
\text{CV2}
\end{bmatrix} =
\begin{bmatrix}
0.3254e^{6s} \\
0.0052e^{-14s}
\end{bmatrix}
\begin{bmatrix}
0.0202e^{22s} \\
-0.0039e^{-14s}
\end{bmatrix}
\begin{bmatrix}
6s+1 \\
26s+1
\end{bmatrix}
\begin{bmatrix}
\text{MV1} \\
\text{MV2}
\end{bmatrix}
\begin{bmatrix}
6s+1 \\
5.37s+1
\end{bmatrix}
\]

The initial DS tuning parameter are shown in table 2 with the $\lambda$ of 0.5 from the time constant

| Controller | $K_c$ | $\tau_i$ |
|------------|------|--------|
| PI (CV1)   | 3.0-10.0 | 6     |
| PI (CV2)   | -83-(-100) | 5.37 |

The controller performances based on DS tuning method for set point tracking are shown in Figure 8 where the initial values of $K_c$ is based on DS method however the final $K_c$ values can be adjusted to get a good set point tracking for each loops. It clearly shows that the control variables were able to follow the set point tracking for both CVs, however due to the loop interaction, the spike was observed when the set point change for both CVs at step time of 350 seconds for loop 1 and 700 seconds respectively for loop 2. It confirms that the loops interaction has significantly occurred in the system. The data analyses for both responses were shown in table 3. Therefore, based on this observation, full conventional and partial decoupler was proposed in this study in the aims of to significantly reduce or minimize the loop interaction in both loops.
### Table 3. Set point tracking controller performance

| Controller | Rise time/fall time (s) | Overshoot (%) | Settling time (s) |
|------------|-------------------------|---------------|------------------|
| CV1        | 50                      | <1            | 100              |
| CV2        | <1                      | <1            | 70               |

![Graph of controller performance](image1)

![Graph of controller performance](image2)

**Figure 8.** Response curve for top and bottom composition after DS tuning.

#### 3.3. Decoupler

Conventional decoupler is the most common and simple decoupler used to eliminate loop interaction and disturbance. Figure 9 and Figure 10 show the performance of conventional decoupler for CV1 and CV2 as well as after adding the full and partial decoupler to the system. The decoupler values were calculated for both the static and dynamic parts. It shows that a loops interaction occurred due to the magnitude of CV1 and CV2 spike when a new set point was introduced. Set point changed was introduced for CV is at time 700 second from 0.98 to 0.99 while the CV2 set point change was set in time 350 second from an original set point 0.02 to new set point 0.03.

Ideally, when CV1 changed, CV2 should remain at the current set point but due to the loop interaction, the spike was observed in CV2 and vice versa at step time of 350 seconds and 700 seconds respectively. However, even though the decoupler were put in place to eliminate the loop interaction, significant reduction of loop interaction was observed as compared to without decoupler as shown in those figures. It clearly shows that the performances of the controllers were improved by introducing the partial decoupler for both top and bottom respectively. The spikes for both CVs were significantly reduced when full and partial decoupler was added to the control loops. The performances of the CV2 were more less the same as in CV1. This result was supported by the controller performance analysis as shown in table 4. Based on this result, the priority of the loop can be determined and based on that the setting or the design of the decoupler can be made based on that information without compromising the performance of the other loops. In addition to that, it is good to carry out the relative gain analysis (RGA)
and sensitivity analysis to determine and reconfirm the priority of each loop for implementation of top and bottom decoupler.

**Figure 9.** Responses curves for all controllers for CV1.

**Figure 10.** Responses curves for all controllers for CV1.
Table 4. Overall controller’s performances analysis

| Criteria                  | PI Controller CV1 | CV2 | PI controller with partial DC CV1 (Top) | CV2 (Bottom) |
|---------------------------|-------------------|-----|----------------------------------------|--------------|
| Rise time (SP)            | 50 s              | < 1 s | **< 50 s**                              | < 1 s        |
| Settling time (SP)        | 100 s             | 70 second | **< 100 s**                             | **< 70 s**   |
| Settling time (Interaction)| 70 s              | 60 second | **< 70 s**                              | **< 60 s**   |
| Overshoot (Interaction)  | < 1 %             | < 1 % | < 1 %                                  | < 1 %        |
| Overshoot (Interaction)  | 3 %               | 1 %   | **< 3 %**                               | **< 1 %**    |

4. Conclusions
Implementation of partial decoupler effectively reduces the interactions between control loops. Analysis and simulation results indicated that partial decoupler decoupling control systems with dynamics decoupler are able to reduce the interaction and the same time control the composition at the bottom and the top of the binary distillation column. Ideal static conventional decoupling control yields a less robust performance as compare to partial dynamic decoupling control for the proposed process studied. The performance was proven based on the outcomes from the simulations and calculations. As a conclusion, the partial dynamics decoupler is able to minimize the loops interaction and also able to achieve the best set point tracking for the binary distillation column.

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