Inverted decoupling MIMO internal model control using Mp tuning

Z Azizah¹, J P Sutikno*, R Handogo¹, R A Hikmadiyar¹

¹Chemical Engineering Department, Institut Teknologi Sepuluh Nopember, Kampus ITS Sukolilo, Surabaya 60111, Indonesia

*juwari@chem-eng.its.ac.id

Abstract. Chemical industry requires a very high-security level and thus requires better process control. Each operating unit needs different operating conditions depending on where one unit with another unit often interact with each other. A very strong interaction process requires multivariable controller. Illustrative examples such as wood & berry and desisobutanizer dual condenser columns are given to show the performance of the proposed control scheme where both processes have time delay and interaction between variables. In this study, not only select the pairing but also add the strategy of inverted decoupling to reduce interactions between process variables. The controller used is MIMO IMC with maximum peak (Mp) stability criteria tuning method. Inverted decoupling MIMO IMC is able to obtain better performance than decoupling MIMO IMC and MIMO IMC without decoupling.

1. Introduction
Many processes in the industry are multivariable that cause the interaction that occurs between a process variable is very strong. The detuning method [1] and relay auto-tuning method [2, 3] represent the development of methods to overcome the problem of interaction. Both methods are easy to implement, but unfortunately, the performance given is not good if the interaction that occurs in a process is very strong [4]. Decoupling is a control that is capable to overcome interaction problems. The role of decoupling is to decompose a multivariable process into a series of single loop subsystems that do not affect each other [5]. There are several types of decoupling are the ideal [6], simplified [7], and inverted decoupling [8, 9]. Luyben [6] comparing ideal decoupling and simplified decoupling used to control binary distillation column. Ideal decoupling provides unstable results in high purity columns, whereas simplified decoupling provides effective, stable, and no interaction between loops. But in practice, ideal decoupling is rarely used because it has complicated decoupling elements. The simplified decoupling has a simple decoupler but it has complicated decoupled process. Chen proposed an inverted decoupling scheme for stable linear multivariable process and provides good results and easily realized [10]. The decoupling structure of MIMO system can be seen in figure 1 below:
by assuming \( D_{11}=D_{22}=1 \) to form simplified decoupling [8] in the following matrix form:

\[
T = \begin{bmatrix}
T_{11} & 0 \\
0 & T_{22}
\end{bmatrix}
\]  
\( \quad (1) \)

\[
G_p = \begin{bmatrix}
G_{p11} & G_{p12} \\
G_{p21} & G_{p22}
\end{bmatrix}
\]  
\( \quad (2) \)

\[
D = \begin{bmatrix}
1 & D_{12} \\
D_{21} & 1
\end{bmatrix}
\]  
\( \quad (3) \)

\[
C = \begin{bmatrix}
C_{11} & 0 \\
0 & C_{22}
\end{bmatrix}
\]  
\( \quad (4) \)

So the decoupled process \( T \) becomes:

\[
T = G_p D
\]  
\( \quad (5) \)

\[
T = \begin{bmatrix}
G_{p11} & \frac{G_{p12}G_{p21}}{G_{p22}} & 0 \\
0 & G_{p22} & G_{p22}-\frac{G_{p12}G_{p21}}{G_{p11}}
\end{bmatrix}
\]  
\( \quad (6) \)

The result of \( T \) is complex, thus causing the controller design to decoupled process becomes difficult. Shinskey [11] proposed a method of inverted decoupling structure in figure 1 with assume \( T_{11}=G_{p11} \) and \( T_{22}=G_{p22} \) then decoupler \( D \) becomes:

\[
D = G_p^{-1} T
\]  
\( \quad (7) \)

\[
D = \frac{1}{G_{p11}G_{p22}-G_{p12}G_{p21}} \begin{bmatrix}
G_{p22} & -G_{p12} \\
-G_{p21} & G_{p11}
\end{bmatrix} \begin{bmatrix}
G_{p11} & 0 \\
0 & G_{p22}
\end{bmatrix}
\]  
\( \quad (8) \)

From equation (8), the input process \( u \) to output controller \( c \) becomes:
\[
\begin{bmatrix}
  u_1 \\
  u_2 
\end{bmatrix} = \begin{bmatrix}
  \frac{G_{p11}G_{p22} - G_{p12}G_{p21}}{G_{p11}G_{p22} - G_{p12}G_{p21}} & \frac{G_{p12}G_{p22} - G_{p11}G_{p21}}{G_{p11}G_{p22} - G_{p12}G_{p21}} \\
  \frac{-G_{p21}G_{p11}}{G_{p11}G_{p22} - G_{p12}G_{p21}} & \frac{G_{p12}}{G_{p11}G_{p22} - G_{p12}G_{p21}}
\end{bmatrix} \begin{bmatrix}
  c_1 \\
  c_2 
\end{bmatrix}
\]  

(9)

Transforming equation (9) becomes [10]:

\[
\begin{bmatrix}
  u_1 \\
  u_2 
\end{bmatrix} = \begin{bmatrix}
  1 & 0 \\
  0 & 1
\end{bmatrix} \begin{bmatrix}
  c_1 \\
  c_2 
\end{bmatrix} + \begin{bmatrix}
  0 & -G_{p12} / G_{p21} \\
  -G_{p21} / G_{p22} & 0
\end{bmatrix} \begin{bmatrix}
  u_1 \\
  u_2 
\end{bmatrix}
\]  

(10)

Based on equation (10), the inverted decoupling scheme is illustrated as shown in figure 2 with a modified decoupling structure of simplified decoupling.

**Figure 2.** Inverted Decoupling Scheme.

Chen [10] uses this inverted decoupling structure, but still uses the PID controller which have several disadvantages, including the presence of new disturbance known after output measurement, so that new control actions can be carried out after the disturbance has affected the process. This is certainly a significant problem especially for processes with long time delay.

In this study, structure of inverted decoupling is added to the MIMO Internal Model Control (IMC) scheme. The controller used is IMC because in addition to interaction, the time delay is also a problem encountered in multivariable processes and become the restriction in the process of operating in the industry [12]. IMC is a powerful controller to overcome time delay [13, 14]. Many industries are using IMC which is one type of model-based control [15]. The basic philosophy of IMC states that good control can be achieved if the control system contains representative processes that will be controlled either explicitly or implicitly. In the industry in general, there is an inaccuracy between the model and the process. Models can not necessarily represent the process as a whole because the process is often affected by unidentified disturbances. A situation where there is an inaccuracy between the model and the process that is actually called the uncertainty process. The causes are variations of the actual parameters affecting plant operations, non-linear processes, experimental identification of processes, the variation of transfer functions, and mathematical models developed [16]. It became the basis for
the development of a perfect control strategy. General Internal Model Control strategy scheme is shown in figure 3 [17].

IMC controller algorithm [18] formulated as follows:

$$ G_{c1} = \frac{rs + 1}{k \lambda s + 1} $$  \hspace{1cm} (11)

The $\lambda$ parameter is calculated using the Maximum Peak stability criterion (Mp) defined as the maximum magnitude of the closed-loop frequency response. Mp is one of the principles of stability analysis, which gives an indication of the stability system. Magnitudes are usually expressed in decibels (dB) which make it easy to display in graphs with the following formula:

$$ |T(j\omega)|_{db} = 20 \log_{10} |T(j\omega)|_{absValue} $$  \hspace{1cm} (12)

Then find for maximum peak value with the formula:

$$ Mp_{db} = \max |T(j\omega)|_{db} $$  \hspace{1cm} (13)

$$ Mp_{absValue} = 10^{\frac{Mp_{db}}{20}} $$  \hspace{1cm} (14)

The large Mp value indicates the large maximum overshoot of the step response [19]. In general, the value of Mp on an acceptance control system should be in the range 1 - 1.5 [20]. Small Mp values indicate slow control effects, whereas a large Mp value indicates a large maximum overshoot and can cause an unstable response, so the optimal Mp value is 1.05. The value of Mp will be obtained by a maximum overshoot of 10% [15]. Juwari [18] developed a tuning method using a maximum peak to obtain parameters on IMC. The method is tested in several first order to higher order processes where the process contains parametric uncertainty and gives good control results. But still limited only to SISO system. Dinny [21] use IMC controller with tuning Mp which is applied to the MIMO system. The results obtained show that the use of Mp is better than conventional PID. Mp tuning is also used on the PID controller type of filter set point and feedback proposed by Dayah [22]. However in a fairly strong interaction, IMC controller with Mp tuning is not fully able to overcome interaction. The result of IAE is still large, so it requires additional controller that can reduce interaction. In this paper, a new approach is made by adding inverted decoupling to the MIMO IMC structure as shown in figure 4.

![Figure 3. Internal Model Control scheme.](image-url)
Inverted decoupling reduces the interaction between process variables and IMC can overcome the time delay problem. So they are combined to form an advanced control strategy to overcome interaction and time delay. The tuning method used is maximum peak stability criteria.

2. Experimental Section

2.1 Case Studies
In this paper, there are two MIMO $2 \times 2$ systems that will be studied. The first example is the transfer function by Wood & Berry column [23] and the second example uses Deisobutanizer Dual Condenser Column proposed by Luyben [24], then MIMO $2 \times 2$ system is taken from this column.

Example 1. Wood & Berry Column:

\[
G(s) = \begin{bmatrix}
12.8e^{-s} & -18.9e^{-3s} \\
16.7s + 1 & 21s + 1 \\
6.6e^{-7s} & -19.4e^{-3s} \\
10.9s + 1 & 14.4s + 1
\end{bmatrix}
\] (15)

Example 2. Deisobutanizer Dual Condenser Column:

\[
G(s) = \begin{bmatrix}
0.038e^{-3s} & 0.749e^{-16.823s} \\
9.063s + 1 & 27.086s + 1 \\
-0.058e^{-10.776s} & -1.804e^{-9.497s} \\
134.764s + 1 & 81.626s + 1
\end{bmatrix}
\] (16)

2.2 Research Procedures
The research method consists of four main steps: The first step is to determine the best configuration for each $2 \times 2$ control system using the RGA method. The best pairing recommendation will minimize interaction between loops with the following formula:

\[
G(s) = \begin{bmatrix}
12.8e^{-s} & -18.9e^{-3s} \\
16.7s + 1 & 21s + 1 \\
6.6e^{-7s} & -19.4e^{-3s} \\
10.9s + 1 & 14.4s + 1
\end{bmatrix}
\] (15)
\[ \lambda = KO\left[K^{-1}\right]^T \]  \hspace{1cm} (17)

Where \( \lambda \) is the matrix with the elements of \( \lambda_{ij} \) and the operator O denotes the product of two matrices (element by element multiplication) \([25,26]\). The second step is to determine the decoupling based on the transfer of diagonal functions on each matrix. The equation for calculating decoupling:

\[ D_{12} = - \frac{G_{p12}}{G_{p11}} \]  \hspace{1cm} (18)

\[ D_{21} = - \frac{G_{p21}}{G_{p22}} \]  \hspace{1cm} (19)

The third step is determining the worst case of each diagonal transfer function. Worst case is obtained from the lower and upper limits of the model uncertainty. The value deviation of the parameter is calculated at \( \pm 20\% \). From the difference between the process model and the plant will be searched for the most difficult parameter to control and make the complementary sensitivity function of the combination of these values. The most difficult case to control is that gives the highest \( \max|T(j\omega)| \). According to Juwari \([18]\), the most difficult cases to control are the parameters with the largest \( k \), the largest \( \theta \), and the smallest \( \tau \). The fourth step is to determine the parameter of the controller by using the Mp criteria as follows: (i) set initial value \( \lambda \) equal to \( \theta \) of the process model divided by 20; (ii) because the system is MIMO, when determining \( \lambda \) parameter on each controller, first the other controller is designed as a SISO system to simplify iteration. The equation to calculate \( |T(j\omega)| \) as SISO:

\[ Y_{sp1} = \frac{G_{c1}G_{p11}}{1+G_{c1}(G_{p11}-G_{pm11})} \]  \hspace{1cm} (20)

\[ Y_{sp2} = \frac{G_{c2}G_{p22}}{1+G_{c2}(G_{p22}-G_{pm22})} \]  \hspace{1cm} (21)

The equation to calculate \( |T(j\omega)| \) as MIMO:

\[ Y_{sp1} = \frac{G_{c1}G_{p11} + G_{c1}G_{c2}(G_{p11}G_{p22} - G_{p12}G_{p21})}{(1+G_{c1}G_{p11})(1+G_{c2}G_{p22}) - G_{c1}G_{c2}(G_{p11}G_{p22} - G_{p12}G_{p21})} \]  \hspace{1cm} (22)

\[ Y_{sp2} = \frac{G_{c2}G_{p22} + G_{c1}G_{c2}(G_{p11}G_{p22} - G_{p12}G_{p21})}{(1+G_{c1}G_{p11})(1+G_{c2}G_{p22}) - G_{c1}G_{c2}(G_{p11}G_{p22} - G_{p12}G_{p21})} \]  \hspace{1cm} (23)

### 3. Result and discussion

#### 3.1 Interaction analysis

After performing interaction analysis for both columns, the results in table 1 are recommended pairing by the RGA method. The configuration for both columns is 1-1 / 2-2. The best pairing configuration will minimize the interaction between variables.
Table 1. The result of interaction analysis using RGA method.

| Case                        | RGA         | Pairing |
|-----------------------------|-------------|---------|
| Wood & Berry                | 2,0094 -1,0094 | 1-1/2-2 |
|                             | -1,0094 2,0094 |         |
| Deisobutanizer Dual Condenser | 2.6845 -1.6845 | 1-1/2-2 |
|                             | -1.6845 2.6845 |         |

3.2 Decoupling

The decoupling equation in each column is calculated using equation (18) and equation (19). The simplified decoupling and inverted decoupling structures are applied to the Wood & Berry and Deisobutanizer Dual Condenser columns. In both structures, the decoupling equation used is the same, only the structure is different (opposite). The result of decoupling can be seen in table 2 below:

Table 2. Decoupling equation on each column.

| Type of Column       | $D_{12}$                  | $D_{21}$                  |
|----------------------|---------------------------|---------------------------|
| Wood & Berry         | $1.4766 \frac{16.7s + 1}{21s + 1} e^{28s}$ | $0.3402 \frac{14.4s + 1}{10.9s + 1} e^{48s}$ |
| Deisobutanizer Dual  | $-19.6762 \frac{9.063s + 1}{27.086s + 1} e^{-13.823s}$ | $-0.0319 \frac{81.626s + 1}{134.764s + 1} e^{1.279s}$ |
| Condenser            |                           |                           |

3.3 Worst case

The parameters of the process model are calculated as the deviation of ± 20% respectively. The lower and upper limits of each process model parameter form a combination of cases where in each case the $\max |T(j\omega)|$ value is calculated. Table 3 through table 6 are a combination of cases in the Wood & Berry and Deisobutanizer Dual Condenser columns.

Table 3. Combination case on loop 1 Wood & Berry distillation column.

| Case | $k$   | $\tau$ | $\theta$ | $\max |T(j\omega)|$ |
|------|-------|--------|----------|----------------|
| 1    | 10.24 | 13.36  | 0.8      | 1.0000         |
| 2    | 10.24 | 13.36  | 1.2      | 1.0000         |
| 3    | 10.24 | 20.04  | 0.8      | 1.0069         |
| 4    | 10.24 | 20.04  | 1.2      | 1.0112         |
| 5    | 15.36 | 13.36  | 0.8      | 1.0000         |
| 6    | 15.36 | 13.36  | 1.2      | 1.3999         |
| 7    | 15.36 | 20.04  | 0.8      | 1.0081         |
| 8    | 15.36 | 20.04  | 1.2      | 1.0160         |
Table 4. Combination case on loop 2 Wood & Berry distillation column.

| Case | \( k \) | \( \tau \) | \( \theta \) | Max \( |T(j\omega)| \) |
|------|---------|---------|---------|----------------|
| 1    | -15.52  | 11.52   | 2.4     | 1.0000        |
| 2    | -15.52  | 11.52   | 3.6     | 1.0000        |
| 3    | -15.52  | 17.28   | 2.4     | 1.0014        |
| 4    | -15.52  | 17.28   | 3.6     | 1.0122        |
| 5    | -23.28  | 11.52   | 2.4     | 1.0000        |
| 6    | -23.28  | 11.52   | 3.6     | 1.3367        |
| 7    | -23.28  | 17.28   | 2.4     | 1.0099        |
| 8    | -23.28  | 17.28   | 3.6     | 1.0463        |

Table 5. Combination case on loop 1 deisobutanizer dual condenser column.

| Case | \( k \) | \( \tau \) | \( \theta \) | Max \( |T(j\omega)| \) |
|------|---------|---------|---------|----------------|
| 1    | 0.0304  | 7.2504  | 2.4     | 1.0000        |
| 2    | 0.0304  | 7.2504  | 3.6     | 1.0000        |
| 3    | 0.0304  | 10.8757 | 2.4     | 1.0000        |
| 4    | 0.0304  | 10.8757 | 3.6     | 1.0076        |
| 5    | 0.0457  | 7.2504  | 2.4     | 1.0000        |
| 6    | 0.0457  | 7.2504  | 3.6     | 1.2840        |
| 7    | 0.0457  | 10.8757 | 2.4     | 1.0068        |
| 8    | 0.0457  | 10.8757 | 3.6     | 1.0652        |

Table 6. Combination case on loop 2 Deisobutanizer Dual Condenser Column

| Case | \( k \) | \( \tau \) | \( \theta \) | Max \( |T(j\omega)| \) |
|------|---------|---------|---------|----------------|
| 1    | -1.4430 | 65.3011 | 7.5974  | 0.9995        |
| 2    | -1.4430 | 65.3011 | 11.3961 | 0.9995        |
| 3    | -1.4430 | 97.9517 | 7.5974  | 1.0055        |
| 4    | -1.4430 | 97.9517 | 11.3961 | 1.0135        |
| 5    | -2.1645 | 65.3011 | 7.5974  | 0.9997        |
| 6    | -2.1645 | 65.3011 | 11.3961 | 1.3771        |
| 7    | -2.1645 | 97.9517 | 7.5974  | 1.0103        |
| 8    | -2.1645 | 97.9517 | 11.3961 | 1.0287        |

In each table, there are 8 cases with the combination of gain, dead time, and time constant parameters. In the Wood & Berry column, the highest value \( |T(j\omega)| \) in the 6th case with the value of each for loop 1 = 1.3999 and loop 2 = 1.3367. Similarly, in the Deisobutanizer Dual Condenser Column, the 6th case has the largest \( |T(j\omega)| \) with the value of each for loop 1 = 1.284 and loop 2 = 1.3771. The parameters with the highest \( |T(j\omega)| \) are the worst cases for the two columns that can be seen in table 7. The worst cases in each column have the largest gain value, the largest time delay, and the smallest time constant. This is appropriate to that proposed Juwari [18].
3.4 Maximum peak tuning

The Mp tuning method specifies the control parameter with \( \max |T(j\omega)| = 1.05 \). Because with that value, the resulting overshoot is about 10%. If the resulting overshoot is less than 10%, then the response becomes slow, but if more than 10% the response becomes unstable [15]. To find the parameters of \( \lambda \) in each loop, first calculate the \( \lambda \) value by ignoring the interaction and assuming a single loop using equation (20) and equation (21). This is because the calculations of \(|T(j\omega)|\) on the MIMO system contain another \( G_c \) loop. For the iteration to be simpler, the calculated \( \lambda \) value of SISO is used to calculate the \( \lambda \) MIMO (contains the interaction information) using equation (22) and equation (23). The results of the calculation of \( \lambda \) SISO and \( \lambda \) MIMO can be seen in table 8 below.

### Table 7. Worst case on each column.

| Column          | Loop | Model Proses           | Worst case model          |
|-----------------|------|------------------------|---------------------------|
| Wood & Berry    | 1    | 12.8e^-4               | 15.36e^1.2s               |
|                 | 2    | 16.7s +1               | -19.4e^-3s                |
|                 |      |                        | -23.32e^-3.6s             |
| Deisobutanizer  | 1    | 9.063s +1              | 7.25s +1                  |
| Dual Condenser  | 2    | -1.804e^-9.497s        | -2.165e^-11.396s          |
|                 |      | 81.626s +1             | 65.301s +1                |

In figure 5 and figure 6 are the result of maximum peak tuning on the Wood & Berry column respectively, for loop 1 and loop 2. As well as on the Deisobutanizer Dual Condenser column that can be seen in figure 7 and figure 8. The Mp value in figure 5 to figure 8 is calculated using equation (14), where the value of Mp is obtained from the max \(|T(j\omega)|\) value on equation (13).
3.5 Simulation result
In each column, the step change is done on Loop 1 and Loop 2 as well as disturbance given to Loop 1. Process transfer function is the result of the worst case. The \( \lambda \) control parameter is obtained from maximum peak tuning. Furthermore, the decoupling equation is included in the simplified decoupling and inverted decoupling schemes. Results from the Wood & Berry column as shown in figure 9 and figure 10.
Based on the results of the responses that have been obtained, surprisingly IAE of MIMO IMC without decoupling is better results than decoupling IMC. This happens because the process model at IMC scheme uses an unperfect process model because in fact, parameters of model transfer function have differences with the plant because the condition of the equipment that changes, so that parameters process and model process such as gain, time constant, and time delay are not the same. According to Seborg [27], the benefit of decoupling may not be fully realized because use unperfect process model. Decoupling MIMO IMC gives the largest IAE value while inverted decoupling MIMO IMC gives the smallest IAE value. As well as the Deisobutanizer Dual Condenser column with the results in figure 11 and figure 12. MIMO IMC with inverted decoupling gives the smallest IAE value. That is, inverted decoupling combined with MIMO IMC scheme can reduce the interaction between loops compared with the controller without decoupling or with decoupling.
4 Conclusions

The method of inverted decoupling in the IMC scheme with maximum peak tuning has been proposed. A maximum peak value of 1.05 can be applied to find $\lambda$ parameters in MIMO IMC. The inverted decoupling scheme is added to the MIMO IMC scheme which can reduce the interaction between loops. When loop 1 is given a disturbance, the response in loop 2 only change slightly. It mean changes that occur in one variable do not affect each other because inverted decoupling decompose MIMO process which has many loops into single loops that doesn’t interact between loops. The proposed method is used in the Wood & Berry and Deisobutanizer dual condenser columns with the result of being able to give a satisfactory response. The IAE value of inverted decoupling IMC is smallest compared to decoupling IMC and IMC without decoupling.
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Symbols used
- $C$: Controller
- $c$: Output controller
- $D$: Decoupler
- $d$: Disturbance input
- $Gc$: Transfer function of controller
- $Gd$: Transfer function of disturbance
- $Gp$: Transfer function of process
- $Gpm$: Transfer function of model
- $k$: Gain of process
- $Mp_{\text{dB}}$: Maximum peak in decibels
- $Mp_{\text{AbsValue}}$: Maximum peak in absolute value
- $T$: Decoupled process
- $|T(j\omega)|_{\text{AbsValue}}$: Complementary sensitivity function in absolute value
- $|T(j\omega)|_{\text{dB}}$: Complementary sensitivity function in decibels
- $u$: Input process
- $Y$: Measurement
- $Ysp$: Setpoint

Greek symbols
- $\lambda$: Filter time constant
- $\theta$: Time delay
- $\tau$: Time constant of the process
- $\omega$: Frequency

Abbreviations
- IMC: Internal Model Control
- Mp: Maximum peak
- MIMO: Multiple Input Multiple Output
- RGA: Relative Gain Array
SISO  

Single Input Single Output

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