Design of Adaptive Internal Control Model on Binary Distillation Column

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Abstract. The binary distillation column is one of the most important operating units in chemical engineering. Wood & Berry binary distillation columns separate feed streams (F, XF) into top products (D, XD) and bottom products (B, XB). The control design in the binary distillation column has several constraints caused by non-linearity of the process, multivariable interactions, and presence of a disturbance. Based on that constraints, it needs a modern control method that can make the system response to track the set point change and reduce or eliminate the disturbances, so the product composition output as desired. Adaptive Internal Model Control 2 Degree of Freedom (AIMC 2 DoF) method is one of the modern control methods that are capable of controlling multivariable plants and reduce or eliminate existing disturbances. Based on all the tests performed, the AIMC 2 DoF controller using Skogestad filter parameter tuning method has the smallest IAE value compared to the other methods.

1. Introduction
Distillation is one of the most important operating units in chemical engineering. A simple binary distillation column separates a mixed feed stream into two parts, the top product and the bottom product. The control design in the binary distillation column has several constraints caused by non-linearity of the process, multivariable interactions, and the presence of disturbance. Based on that constraints, it needs a modern control method that can make the system response to track the set point change and reduce or eliminate existing disturbance, so the product composition output as desired. Adaptive Internal Model Control 2 Degree of Freedom (AIMC 2 DoF) method is one of a kind of modern control method capable of controlling multivariable plants and reduce or eliminate existing disturbances. The AIMC 2 DoF method in this paper is a traditional modified MRAC method based on the IMC 2 DoF structure.

The AIMC 2 DoF method in this paper is a traditional modified MRAC method based on the IMC 2 DoF structure. AIMC 2 DoF controller is chosen because by combining adaptive controllers such as MRAC and robust controllers such as IMC 2 DoF can improve the transient response of most systems¹. The tuning methods of the IMC control filter parameters that are compared are Chien & Fruehauf, RC.Panda, and Skogestad². This controller is applied Wood & Berry binary distillation columns multivariable system. Comparative analysis of AIMC 2 DoF system performance with three empirical methods of tuning IMC controller filter parameters based on IAE values.
2. Binary Distillation Column
The binary distillation column separates a mixed feed stream into two parts, the top product or distillate ($X_D$) and the bottom product ($X_B$). The purpose of this separation is to obtain the purity of the final product. A simple binary distillation column generally consists of several trays with identical size, condenser, reflux drum, reflux, top product or distillate ($X_D$), reboiler, and bottom product ($X_B$). The schematic diagram of the binary distillation column is shown in Figure 1.

![Figure 1. Diagram of the binary distillation column](image)

The operation on the binary distillation column can be explained as follows. The feed stream goes into the feed tray and then heated on the reboiler to produce vapour. The liquid that is released from the reboiler and non-volatile is called the bottom product ($X_B$). Vapour moves up toward the top of the column, then condensed by condenser. The condensation results are stored on the reflux drum. Some of this liquid is put back to the top of the distillation column, that is called reflux. Some of the other liquid is released, that is called the top product or distillate ($X_D$). The controlled output variables are top product ($X_D$) and bottom product ($X_B$), the disturbance variable is the feed flow rate change ($F$), and the manipulated input variables are the reflux flow rate ($R$) and the steam flow rate ($S$). The distillation column used is a model of Wood & Berry methanol-water separation binary distillation column. The transfer function of this column is represented by equation (2).

\[
\begin{bmatrix}
X_D(S) \\
X_B(S)
\end{bmatrix} =
\begin{bmatrix}
12.8e^{-1.8s} & -18.9e^{-3.8s} \\
16.7s + 1 & 21s + 1 \\
6.6e^{-7s} & -19.4e^{-3.8s} \\
10.9s + 1 & 14.4s + 1
\end{bmatrix}
\begin{bmatrix}
R(S) \\
S(S)
\end{bmatrix}
+ \begin{bmatrix}
3.8e^{-0.1s} \\
14.9s + 1 \\
14.9e^{-3.4s} \\
13.2s + 1
\end{bmatrix} F(S)
\]

(1)

A transfer function of binary distillation column is a combination of a first-order system with time delay is called the First-Order Plus Dead Time (FOPDT) model. The mathematical model of the FOPDT process response can be represented in the form of the transfer function ($G(s)$) by the Laplace transform shown in the equation (2).

\[ G(s) = \frac{Y(s)}{U(s)} = \frac{K}{\tau s + 1} e^{-\theta s} \]

(2)

K is the gain of the process, $\theta$ is the dead time of the process, and $\tau$ is the time constant of the process.

3. Adaptive IMC 2 DoF
AIMC 2 DoF controller is the development of IMC 2 DoF controller by adding online parameter estimates. The AIMC 2 DoF controller in this paper used a traditional MRAC controller that is
modified based on IMC 2 DoF control structure. The structure of AIMC 2 DoF is the development from AIMC 1 DoF structure used by Qing Wei Jia and Shinobu Yoshida. The AIMC 2 DoF structure is shown in Figure 2.

Based on Figure 2, AIMC 2 DoF structure consists of set point tracking controller transfer function \( G_{cst} \), disturbance rejections controller transfer function \( G_{cdr} \), process transfer function \( G_p \), process model transfer function \( G_{pm} \), disturbance transfer function \( G_d \), MRAC controller \( G_{cm} \), adaptation mechanism, controlled output set point variable \( y_{sp} \), controlled output variable \( y \), process model output variable \( y_m \) controlled output that affected only by manipulated input variable \( y_u \), controlled output that affected only by disturbance \( y_d \), controller output variable \( u \), estimated effect of disturbance variable \( de \), compensation gain variable \( K_a \), manipulated input variable / MRAC controller output \( u_{up} \), set point tracking controller output variable \( u_{Gcst} \), and disturbance rejections controller and disturbance rejections controller output variable \( u_{Gcdr} \).

The distillation column used is a model of Wood & Berry methanol-water separation binary distillation column. Control method used in this system is AIMC 2 DoF. The transfer function of this column is represented by equation (1). The equation of the process transfer function \( G_p \) in FOPDT model from can be written by equation (3).

\[
\begin{bmatrix}
X_{du}(s) \\
X_{nu}(s)
\end{bmatrix} = \begin{bmatrix} G_{p11} & G_{p12} \\
G_{p21} & G_{p22}
\end{bmatrix} \begin{bmatrix} R(s) \\
S(s)
\end{bmatrix}

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

The equation of the disturbance transfer function \( G_d \) in FOPDT model form can be written by equation (4)

\[
\begin{bmatrix}
X_{du}(s) \\
X_{nu}(s)
\end{bmatrix} = \begin{bmatrix} G_{d11}(s) \\
G_{d21}(s)
\end{bmatrix} F(s) = \begin{bmatrix}
3.8e^{-8.1s} \\
14.9s + 1 \\
4.9e^{-3.4s} \\
13.2s + 1
\end{bmatrix} F(S)
\]

The equation of the process model transfer function \( G_{pm} \) in FOPDT model form in AIMC 2 DoF system can be written by equation (5)

\[
\begin{bmatrix}
y_{m1}(s) \\
y_{m2}(s)
\end{bmatrix} = \text{diag.} \begin{bmatrix} G_{p11}(s) & G_{p12}(s) \end{bmatrix} \begin{bmatrix} u1(s) \\
u2(s)
\end{bmatrix}
\]
The process model transfer function \( G_{pm11} \) and \( G_{pm22} \) can be divided into two parts, the invertible part \( (G_{pm}^-) \) and non-invertible part \( (G_{pm}^+) \), which can be written by equation (8) and equation (9).

\[
G_{pm11} = \frac{12.8e^{-1.8} \cdot 1 - \frac{s}{\tau_1}}{16.7s + 1}; \theta_1 = 1, \tau_1 = 16.7
\]  

(6)

\[
G_{pm11} = \frac{-19.4e^{-1.8} \cdot 1 - \frac{3s}{\tau_1}}{14.4s + 1}; \theta_2 = 3, \tau_1 = 14.4
\]

(7)

IMC filter parameter tuning method \( \tau_c \) in the set point tracking controller \( (G_{cst}) \) and the disturbance rejections controller \( (G_{cdr}) \) can be shown by Table 1.

| IMC Filter Parameter Tuning Method | Selection of \( \tau_c \) |
|-----------------------------------|--------------------------|
| Chien & Fruehauf                  | \( \tau > \tau_c > \Theta \) |
| RC. Panda                         | \( \tau_c = \max (0.2\tau, 1.7\Theta) \) |
| Skogestad                         | \( \tau_c = \Theta \) |

Based on the value of dead time \( (\theta_1, \theta_2) \) and time constant \( (\tau_1, \tau_2) \) in process model transfer function \( (G_{pm}) \), the selection of \( \tau_c \) in Table 1, and empirical tests in the system, the filter parameter tuning \( \tau_c \) value in the set point tracking controller \( (G_{cst}) \) and the disturbance rejections controller \( G_{cdr} \) can be shown by Table 2.

| IMC Filter Parameter Tuning Method | Tuning Value |
|-----------------------------------|--------------|
| Chien & Fruehauf                  | \( \tau_1 = 3.7, \tau_2 = 5.4 \) |
| RC. Panda                         | \( \tau_1 = 3.34, \tau_2 = 5.1 \) |
| Skogestad                         | \( \tau_1 = 1, \tau_2 = 3 \) |

The set point tracking controller transfer function \( (G_{cst}) \) in AIMC 2 DoF can be designed using equations (10) and (11).

\[
\begin{bmatrix}
 u_{Gcst1}(s) \\
 u_{Gcst2}(s)
\end{bmatrix} =
\begin{bmatrix}
 G_{cst1}(s) & 0 \\
 0 & G_{cst2}(s)
\end{bmatrix}
\begin{bmatrix}
 y_{sp1}(s) \\
 y_{sp2}(s)
\end{bmatrix}
\]  

(10)

\[
\begin{bmatrix}
 G_{cst1}(s) \\
 G_{cst2}(s)
\end{bmatrix} =
\begin{bmatrix}
 \text{inv. } G_{pm11}^{-1}(s), f_i(s) \\
 \text{inv. } G_{pm22}^{-1}(s), f_i(s)
\end{bmatrix}
\]

(11)

Where
The set point tracking controller transfer function \( G_{\text{cst}} \) can be designed using equation (14).

\[
\begin{bmatrix}
G_{\text{cst}1}(s) \\
G_{\text{cst}2}(s)
\end{bmatrix} = \begin{bmatrix}
16.7s + 1 \\
12.8(\tau_{c1} s + 1) \\
14.4s + 1 \\
-19.4(\tau_{c2} s + 1)
\end{bmatrix}
\]

(14)

Substituting the value of filter parameter tuning \((\tau_{c1}, \tau_{c2})\) in Table 2 into equation (14), so the set point tracking controller transfer function \((G_{\text{cst1}}, G_{\text{cst2}})\) can be shown by Table 3.

Table 3. Set point tracking \((G_{\text{cst1}})\) controller transfer function \((G_{\text{cdr}})\) based on filter parameter tuning value \((\tau_c)\)

| Method         | \( G_{\text{cst1}} \)       | \( G_{\text{cst2}} \)       |
|----------------|-------------------------------|-------------------------------|
| Chien & Fruehauf | \(47.36s + 12.8\)            | \(-104.76s - 19.4\)          |
| RC. Panda       | \(16.7s + 1\)                | \(14.4s + 1\)                |
| Skogestad      | \(42.752s + 12.8\)           | \(-98.94s - 19.4\)           |

The disturbance rejections controller transfer function \((G_{\text{cdr}})\) in AIMC 2 DoF can be designed using Equation (15).

\[
\begin{bmatrix}
u_{G_{\text{cdr}1}}(s) \\
u_{G_{\text{cdr}2}}(s)
\end{bmatrix} = \begin{bmatrix}
G_{\text{cdr}1}(s) & 0 \\
0 & G_{\text{cdr}2}(s)
\end{bmatrix}\begin{bmatrix}de_1(s)
\end{bmatrix}
\]

\[
\begin{bmatrix}
G_{\text{cdr}1}(s) \\
G_{\text{cdr}2}(s)
\end{bmatrix} = \begin{bmatrix}
\frac{\alpha_{c1} s + 1}{\tau_{c1} s + 1} \\
\frac{\alpha_{c2} s + 1}{\tau_{c2} s + 1}
\end{bmatrix}
\]

where

\[
\alpha_1 = \frac{(1 - \frac{\tau_{c1}}{\tau_1})^2 - e^{\frac{\theta_1}{\tau_1}}}{e^{\frac{\theta_1}{\tau_1}}}. \tau_1
\]

\[
\alpha_2 = \frac{(1 - \frac{\tau_{c2}}{\tau_2})^2 - e^{\frac{\theta_2}{\tau_2}}}{e^{\frac{\theta_2}{\tau_2}}}. \tau_2
\]

Substituting the value of filter parameter tuning \((\tau_{c1}, \tau_{c2})\) in Table 2, the set point tracking controller transfer function \((G_{\text{cst1}}, G_{\text{cst2}})\) in Table 3, and also the value of dead time \((\theta_1, \theta_2)\) and time constant \((\tau_1, \tau_2)\) in process model transfer function \((G_{\text{pm}})\), so the disturbance rejections controller transfer function \((G_{\text{cdr1}}, G_{\text{cdr2}})\) can be shown by Table 4.
Table 4. Disturbance rejections controller transfer function ($G_{cdr}$) based on filter parameter tuning value ($\tau_c$).

| Method           | Disturbance Rejections Controller Transfer Function |
|------------------|--------------------------------------------------|
|                  | $G_{cdr1}$                                      | $G_{cdr2}$                                      |
| Chien & Fruehauf | $119.713s^2 + 23.86$                            | $141.593s^2 + 24.233$                          |
| RC. Panda        | $175.232s^2 + 94.72s$                            | $-565.704s^2 - 209.52$                         |
| Skogestad        | $110.775 s^2 + 23.33$                            | $137.136s^2 + 23.923$                          |

The equation on adaptation mechanism using adaptation law in AIMC 2 DoF can be written by equation (18).

\[
K_a(s) = -\frac{1}{\gamma_1} u_1(s) u_{Gcdr1}(s) \\
K_a(s) = -\frac{1}{\gamma_2} u_2(s) u_{Gcdr2}(s)
\]  

The value of adaptation gain ($\gamma$) is obtained by performing empirical tests on the system. The value of adaptation gain ($\gamma$) based on empirical tests result is shown by Table 5.

Table 5. Adaptation gain value ($\gamma$) on each filter parameter tuning method

| IMC Filter Parameter Tuning Method | Tuning Value |
|-----------------------------------|--------------|
| Chien & Fruehauf                  | 100 99       |
| RC. Panda                         | 100 100      |
| Skogestad                         | 30 30        |

The equation on the MRAC ($G_{cm}$) controller in AIMC 2 DoF can be written by equation (19).

\[
u_{1up}(s) = K_a(s) u_1(s) \\
u_{2up}(s) = K_a(s) u_2(s)
\]  

4. Experimental result

The tests are done with perfect model without disturbance assumption and perfect model with disturbance assumption. Perfect model without disturbance assumption tests are done by change the set point value of top product composition ($X_D$) and bottom product composition ($X_B$). Perfect model with disturbance assumption tests are done by change step input on disturbance variable ($F$).

In increasing the top product composition ($X_D$) set point $X_D + 0.006$ without changing the bottom product composition ($X_B$) set point test, the top product composition ($X_D$) response is shown in Figure 3 while the bottom product composition ($X_B$) response is shown in Figure 4.
Based on the system response graphs in Figure 3 and Figure 4, it can be seen as AIMC 2 DoF controller capable of tracking set point changes on the top product composition (X_D) and able to maintain the bottom product composition (X_B) set point. The smallest IAE value in this test are 0.04826 for the top product composition (X_D) response and 0.1152 for the bottom product composition (X_B) response using Skogestad filter parameter tuning method.

The test using step input is done by increasing the disturbance variable F + 0.004 and increasing for the top product composition (X_D) and the bottom product composition (X_B) set point each of +0.006. In this test, the top product composition (X_D) response is shown in Figure 5 while the bottom product composition (X_B) response is shown in Figure 6. Based on the system response graphs in Figure 5 and Figure 6, it can be seen that the AIMC 2 DoF controller reduces or eliminates the feed flow rate (F) change disturbance and returns the top product composition (X_D) response and while the bottom product composition (X_B) at the given set point. The smallest IAE value in this test are 0.1246 for the top product composition (X_D) response and 0.12863 for the bottom product composition (X_B) response using Skogestad filter parameter tuning method.

Figure 4. Bottom product composition (X_B) response to the increase of X_D+0.006.

Figure 5. Top product composition (X_D) response to the increase of disturbance F+0.004.

Figure 6. Bottom product composition (X_B) response to the increase of disturbance F+0.004.
5. Conclusion

Based on the tests that have been done, it can be concluded that AIMC 2 DoF controller that used in Wood & Berry methanol-water separation binary distillation column is able to control the system to track the set point value of the product composition given and damp or eliminate the incoming disturbance. Based on all the tests done, Skogestad filter parameter tuning method with tuning values of $c_1 = 1$ and $c_2 = 3$ and also adaptation gain values of $\gamma_1 = 30$ and $\gamma_2 = 30$ have the smallest IAE values compared to the other two methods.

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