PID multivariable tuning system using BLT method for distillation column

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Abstract. Most of the process industries are handling Multi-Input-Multi-Output (MIMO) system by using the classical Proportional-Integral-Derivative (PID) controller although there are wide researches in advanced control techniques. However, finding a good value for the controller parameters might be very challenging and best tuning approach need to be considered to obtain a better performance. In this paper, biggest-log modulus (BLT) tuning method is adopted to tune decentralized PID controller based on 2x2 MIMO system and the effectiveness of the tuning method is observed. A comparative study on the settling time, overshoot and integral absolute error (IAE) are evaluated when a step change in u1, u2 and disturbance is introduced to the system. The simulation result demonstrates that BLT method has a better performance for a disturbance change response compared to set point change response.

1. Introduction
Over last few decades, there are numerous research on advance control strategy involving model predictive control (MPC), linear quadratic control etc, yet Proportional Integral Derivative (PID) controller still extensively used in industry over the advance control strategy. PID is preferable over other controller scheme because of simplicity yet resulting most efficient control strategies [1]. This is proven as there are more than 90% of the industrial control loops being operated in the process industries either PI or PID mode [2-4].

However, finding the best tuning parameters for PID controller is still a major problem for the controller due to nonlinearity, time-variability, and time delay of processes [5]. [6] has stated that an improperly tuned PID controllers may resulted in more serious issue which may reduce the profitability and productivity of the plants. Hence, proper tuning is helpful to overcome this problem [7].

Typically, multiple inputs and outputs (MIMO) system is adopted in most of real industrial processes. MIMO system slightly differs compared with single-input single output (SISO) system as it is more complex and require a proper handling to the process interaction in the systems. Interaction process generally encountered when a change in a manipulated variable, affect the corresponding output variable and other output variables. Therefore, proper arrangement of input and output variable may aid in minimizing interaction between control loops [1]. Relative Gain Array (RGA) is one of the quantitative techniques in determining the correct pairing of manipulated and controlled variables.
In literature provided by Katebi [1], multivariable PID tuning method has been categorised into two main groups which involve parametric and non-parametric model. BLT method is classified as one of parametric tuning method. Other than that, there are a few numbers of designing method develop for MIMO method that can be categorised into 5 groups which involve detuning, sequential loop closing, iterative or trial-and-error, simultaneous equation solving and independent methods [8]. Biggest-log-modulus (BLT) proposed by Luyben is one of the most famous method grouped in detuning category yet become preferable method compared to others due to its simplicity and practicality.

In this paper, the simplest form of MIMO system known as two-input two-output (TITO) system is adopted by implementing two PID controllers in PI mode. The previous paper discussed on tuning a multivariable process using BLT method focusing on servo task [9] and a systematic data-based method to tune PID controller based on the disturbance rejection [10]. The outcome of the paper exhibits that the controller tuned using proposed method demonstrated a better performance based on disturbance rejection. Thus, in this study, a TITO system is emphasized on the composition control of distillate and bottom products in a distillation column. Proper tuning using BLT method on which serve as an extension of classical Ziegler-Nichols (Z-N) method is handled on the TITO system and the response for servo (set point) and regulatory (disturbance) performance are observed accordingly.

2. Multivariable System
Multivariable system is a system which involves multiple inputs and multiple outputs (i.e. shown in figure 1). Multivariable control involves the goal of maintaining several control variables at independent set points. A multivariable system will be more challenging to control if there is existence of cross couplings.

Transfer function matrix, \( G_p(s) \) is given by equation 1 and each of the element of the transfer matrix \( G_{ij}(s) \) is represented in a first order plus dead time (FOPDT) model, shown in equation 2.

\[
G_p(s) = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \\
G_{ij}(s) = \frac{K_{pij}e^{-\theta_{ij}}}{(\tau_{ij}s + 1)} \quad ; i = 1,2 \quad j = 1,2
\]

In this study, decentralized controller is designed. The equation 3 indicates the design of PID controller in decentralized form.

\[
G_c(s) = \begin{bmatrix} G_{c11}(s) & 0 \\ 0 & G_{c22}(s) \end{bmatrix}
\]

PID controller mode is defined in \( G_{c,ij}(s) \). Thus, in this study, the parallel form of PID controller is assume and the mode of PID controller is set as in PI mode. Therefore, the elements of the controller is defined as equation 4.

\[
G_c(s) = K_c \left( 1 + \frac{1}{\tau_I s} \right)
\]
3. PID tuning strategy

In this study, two PID controllers will be implemented to the distillation column model which is then properly tuned using BLT method and conventional Internal Model Control (IMC) method. In most multivariable control, the system is treated as a series of single-loop and further designs involving other methodologies is proceeded. One common approach is to detune controller parameters derived using SISO design approach.

3.1. Ziegler-Nichols Method

Ziegler and Nichols have described two techniques for tuning the parameter of P-, PI- and PID mode controllers. The open-loop method indicates in figure 2 has been chosen and calculated using the formula listed below (equation 5 to equation 9).

\[ Y(\theta + \tau) = 0.632(\Delta) \]  
(5)

\[ Y(\theta + \tau/3) = 0.283(\Delta) \]  
(6)

\[ t_{28\%} = \theta + \frac{\tau}{3} \]  
(7)

\[ \tau = 1.5(t_{63\%} - t_{28\%}) \]  
(8)

\[ \theta = t_{63\%} - \tau \]  
(9)

3.2. Biggest-Log Modulus (BLT) Method

BLT method is an extension of the classical Ziegler and Nichols method for multivariable case. Luyben (1986) has proposed this method and stated that there are 2N tuning parameters to be selected if PI
controllers are considered which involves gains and reset times. The gains and reset times should be specified correctly or it will result in unstable system. Steps for BLT method are shows as follows;

**3.2.1. Determine the controller settings.** The controller settings are set by using Ziegler-Nichols open loop method for each individual loop using classical SISO as explained in subsection above. The corresponding tuning parameters is tabulated in table 1.

**Table 1. PID tuning parameters for process reaction curve (method II)**

| Controller | Gain $K_p$ | Integral time $\tau_i$ | Derivative Time $\tau_D$ |
|------------|------------|-------------------------|-------------------------|
| P          | $K\theta$  | $0.9\tau$               | $\theta$                |
| PI         | $K\theta$  | $1.2\tau$               | $0.3\theta$             |
| PID        | $K\theta$  | $0.5\tau$               | $0.5\theta$             |

**3.2.2. A detuning factor $F$ is assumed** using equation 10 and equation 11. The F values usually greater than 1 and within the range of 1.5 to 4.

\[ K_{CI} = \frac{K_{ZNI}}{F} \quad (10) \]

\[ \tau_{ui} = \tau_{ZNI} \times F \quad (11) \]

The $F$ factor is considered as a detuning factor which would be applied to all loops. The larger the value of $F$ indicate the more stable of the system. (*For this simulation $F=1.35$ is chosen*)

**3.2.3. Multivariable Nyquist plot of the scalar fraction is determined** as follows in equation 12 to equation 14:

\[ W_{(i\omega)} = 1 + Det \left[ I + G_m(i\omega)B_{(i\omega)} \right] \quad (12) \]

\[ G_m(s) = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \quad (13) \]

\[ B(s) = \begin{bmatrix} K_c1(\tau_{t,1}s + 1) & 0 \\ \tau_{t,1}s & \frac{K_c2(\tau_{t,2}s + 1)}{\tau_{t,2}s} \end{bmatrix} \quad (14) \]

**3.2.4. Evaluate $L_{cm}^{max}$ value.** The value is estimated using equation 15

\[ L_{cm}^{max} = \max_{\omega} \left\{ 20 \log_{10} \left| \frac{W}{1 + W} \right| \right\} \quad (15) \]

**3.2.5. Repeat step 3.2.4 if the value of $L_{cm}^{max} \neq 2N$, whereby N is indicating the order of the system.** In this study, TITO system is considered. Thus, iteration of F should be stopped as the value of $L_{cm}^{max} = 4db$ is obtained.

**4. Simulation Results**

The distillation column simulation was adapted from [12] to demonstrate the effectiveness and merits of the presented method on MIMO system. Equation 16 expressed the transfer function of the plant.
\[
\begin{bmatrix}
    x_D(s) \\
    x_B(s)
\end{bmatrix} =
\begin{bmatrix}
    0.0747e^{-3s} & -0.0667e^{-2s} \\
    12s + 1 & 15s + 1 \\
    0.1173e^{-2.2s} & -0.1253e^{-2.2s} \\
    11.7s + 1 & 10.2s + 1 \\
\end{bmatrix}
\begin{bmatrix}
    F_R(s) \\
    F_V(s)
\end{bmatrix} +
\begin{bmatrix}
    0.70e^{-5s} \\
    14.4s + 1 \\
    1.3e^{-3s} \\
    12s + 1
\end{bmatrix} x_F(s)
\]

(16)

A few steps changes are introduced to the simulation; (a) a set point change of \( x_D \) (U1), (b) a set point change of \( x_B \) (U2), and (c) a step change of disturbance. The performance of controller tuned using BLT method is compared with Internal Model Control (IMC) and will further discussed in the following section.

The corresponding PI controller parameters for both methods are listed in table 2. The simulation is completely free from steady state error for both tuning method.

| Table 2. PI controller parameters. |
|-----------------------------------|
| Method  | \( K_{p,1} \) | \( K_{i,1} \) | \( K_{p,2} \) | \( K_{i,2} \) |
|---------|---------------|--------------|---------------|--------------|
| BLT     | 35.789        | 2.659        | -27.207       | -3.034       |
| IMC     | 26.774        | 2.231        | -20.351       | -1.995       |

4.1. A step change of first input, \( U1 \) (set point of \( x_D \)) at time, \( t=50s \)

Both figures 3 (a) and (b) illustrate the servo responses for a step change given in U1 and the corresponding control actions (y1 and y2). Table 3 listed the performance analysis of both y1 and y2.

Aggressive oscillation and a higher peak response are observed when the system is tuned by BLT method for both top composition tracking (\( y_1 \)) and bottom composition tracking (\( y_2 \)). Nevertheless, the response is still under control as the percentage overshoot is still within 0% for \( y_1 \) response. Meanwhile, the conventional IMC method demonstrate a minimum oscillation but, it will produce sluggish response for both output accordingly. BLT detuned method is believable to improve the stability of the response but then it will yield a bit sluggish response as the value of \( K_c \) is reduced by the tuning factor, \( F \). BLT method take the shortest time to return its desired steady state value and having the minimum IAE value for both \( y_1 \) and \( y_2 \) responses. The responses tabulated in Table 3 clearly indicates that BLT method have the best result for both \( y_1 \) and \( y_2 \) response in term of lowest IAE value and shorter settling time when a step change in \( u_1 \) is introduced.

**Figure 3 (a).** Response of first output, \( y_1 \) as a step change in first input, \( u_1 \) is set.

**Figure 4 (b).** Response of second output, \( y_2 \) as a step change in first input, \( u_1 \) is set.
4.2. A step change of second input, U2 (set point of \( x_B \)) at time, \( t=50s \)
The response of a step change upon U2 is shown in figure 4 (a) and 4 (b) and table 4 tabulates the parameters on the performance of y1 and y2 on BLT and IMC based on decentralized PI controller. BLT method is observed to have a greater number of oscillations compared to the conventional IMC-PI method and resulted in a significant overshoot for the bottom composition tracking (y2). IMC method seems to be able to surpass the BLT method in reducing the instability of the responses and having less number of oscillation. Nevertheless, IMC method shows the slowest response to return to its desired steady state value for both y1 and y2 response compared to the BLT method. Among the listed methods, BLT method shows the best performance as it having a smaller IAE value and shortest settling time for both y1 and y2 response respectively.

| Method | \( y_1 \) | \( y_2 \) |
|--------|--------|--------|
|        | Maximum peak | Overshoot (%) | Settling Time (s) | IAE | Maximum peak | Overshoot (%) | Settling Time (s) | IAE |
| BLT    | 0.9980 | 0 | 441.14 | 30.53 | 1.1259 | 398.09 | 25.07 |
| IMC    | 0.9958 | 0 | 498.42 | 36.19 | 0.9481 | 520.55 | 37.87 |

4.3. A step change on disturbance input, at \( t=50s \)
Figure 5(a) and 5(b) demonstrate the response of y1 and y2 accordingly when a step change in disturbance is set to the system using two different methods. Performance analysis on both tuning method is tabulated in table 5.

The performance analysis for both tuning method as tabulated in table 5. BLT method shows a significant oscillation for both y1 and y2 response, but correspondingly the IMC method shows less oscillation. From the performance analysis table (Table 5), a faster response towards the new desired steady state value shows by BLT method after a step change at disturbance is introduced to the system.
An insignificant peak is shown by $y_1$ and $y_2$ response respectively. In regulator problem, BLT has a much the lowest settling time and IAE values compared to the servo problem (when a step input of $U_1$ and $U_2$ are introduced to the system) for both $y_1$ and $y_2$ response. These clearly verify that BLT method is one of the most suitable tuning approach for a PID controller mainly in handling with a disturbance change system.

**Figure 7 (a).** Response of first output, $y_1$ as a step change in disturbance is set.

**Figure 8 (b).** Response of second output, $y_2$ as a step change in disturbance is set.

|       | $y_1$ |       | $y_2$ |
|-------|-------|-------|-------|
|       | Maximum peak | Settling Time (s) | IAE  | Maximum peak | Settling Time (s) | IAE  |
| BLT   | 0.0758 | 320.84 | 1.055 | 0.3002 | 130.50 | 3.215 |
| IMC   | 0.0962 | 362.36 | 1.657 | 0.3320 | 179.60 | 4.878 |

5. **Conclusion**

The application of multiloop control structure in various industrial and chemical contexts is widely implemented due to the simplicity and economic consideration for operation. In this paper, the response of First-order plus Time-delay (FOPTD) process is compared by using BLT method and conventional IMC tuning method that operates using PI controller mode. In this paper, BLT method is being adopted to the MIMO system to obtain the best performance of controller parameter of having a minimum IAE value. Although BLT demonstrate a greater number of oscillations in the simulation results, but BLT has a good performance on the regulator problem compared to servo problem. This is because BLT has the fastest time to remain to its desired steady state value for both top composition tracking ($y_1$) and bottom composition tracking ($y_2$) and the relatively minimum IAE value.

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