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Double-Loop Multi-Scale Control using Routh-Hurwitz Dimensionless Parameter Tuning for MIMO Processes

Shi Min Lim[1], Jobrun Nandong[1,2*]

[1]Department of Chemical Engineering,
Curtin University Malaysia, CDT 250, Miri 98009, Sarawak, MALAYSIA

[2]Intelligent System, Design and Control (ISDCON),
Curtin University Malaysia, CDT 250, Miri 98009, Sarawak, MALAYSIA

*Corresponding Author

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Abstract: This paper presents a new approach to controlling MIMO processes by using the double-loop multi-scale control scheme in the decentralized control architecture. The decentralized PID control system has been used in process industry despite its several limitations due to process interactions, time-delays and right half plane poles. To overcome the performance limitation due to process interactions, decoupling controllers are often added to the decentralized PID control system. The proposed strategy based on the double-loop multi-scale control scheme has some advantages over the existing control strategies for MIMO processes. An advantage of the proposed scheme over the decentralized PID control with decoupling system is that, the proposed strategy has a fixed number of dimensionless tuning parameters that are easy to tune. For an n×n MIMO process, the proposed scheme requires the tuning of only 3 to 6 dimensionless parameters instead of the 3n original PID parameters.

Keywords: Decentralized control, PID tuning, MIMO processes, decoupling, stability

1. Introduction

PID controllers are still widely used in many industries despite the existence of several advanced control systems. Research in the PID control has taken place for several decades which resulted in a vast number of PID tuning formulas or rules. The methods to derive PID tuning formulas have been extensively reported in the open literature. A large quantity of the PI/PID tuning formulas which have been produced over many years of research can be found in the PI/PID handbook (O'Dwyer, 2009). However, most of these tuning rules were developed for a single-input and single-output (SISO) system. For this reason, it is often not convenient to directly apply such rules in industry given the fact that, most processes in industry are multi-input and multi-output (MIMO) in nature. The major reason why these SISO PID formulas cannot simply be applied to a MIMO process is due to the presence of interactions in the MIMO process. Consequently, direct application of a SISO PID formula in the MIMO process can lead to poor or even unstable closed loop responses.

A few control schemes have been used to control MIMO processes, which include decentralised (multi-loop) control, decentralised plus decoupled control and centralised control (Rajapandiyan & Chidambaram, 2012). The decentralized PID control (or multi-loop PID control) is one of the most widely used scheme in many MIMO systems where the coupling effects (interactions) are relatively weak. The multi-loop PID control strategy has several key advantages, which are relatively simple to apply, failure tolerant structure with robust performance, and rather easy to understand (Vu & Lee, 2010). The major task in a PID controller tuning is to find appropriate values of the controller parameters, not only to stabilize a given process but also to ensure fast and smooth closed-loop responses. There exist several strategies for

*Corresponding author: jobrun.n@curtin.edu.my

the design or tuning of the multi-loop PID control strategy: (a) detuning (Luyben, 1986), (b) sequential loop closing (Mayne, 1973; Hovd & Skogestad, 1994), (c) iterative or trial and-error (Lee, Cho, & Edgar, 1998), (d) simultaneous equation solving (Wang, Lee, & Zhang, 1998), (e) independent methods (Economou & Morari, 1986; Skogestad & Morari, 1989; Hovd & Skogestad, 1993; Vu & Lee, 2010), (f) iterative optimization (Bao, Forbes, & Mclellan, 1999), (g) relay auto-tuning (Astrom & Hagglund, 1988) and (h) dimensionless parameter tuning approach via Routh-Hurwitz criteria (Mohd & Nandong, 2018) and multi-scale control approach (Nandong, 2015) and (Nandong & Zang, 2013).

In view of the recent progress in computational technology, one can observe a rapid trend in using the optimization and programing methods to design decentralized and centralized PID control systems. In particular, the heuristic evolutionary approach such as the firefly, particle swarm optimization, colonial competitive and genetic algorithms have received widespread research attentions. Other groups of methods such as the detuning and sequential loop closing have seemed to reach a matured level, in the sense that very few related papers have been published in the last 10 years. This could be due to the performance limitation factor which means that, only little or no improvement (either in terms of performance or simplicity) that can be achieved through further modification to the methods. Generally, the control of MIMO systems in process industry often faces several difficulties, for examples, due to the computational procedures required in the tuning which involve complicated iterations (Lee, Lee, Lee, & Kim, 2004). Therefore, the development of a simpler and effective control scheme for MIMO systems is still an active research. Recently, a new class of methods has been introduced to address the complicated tuning procedure in decentralized PID control. This new class of methods is better categorized as the dimensionless parameter tuning as it uses a few fixed dimensionless parameters to determine the tuning values of the original PID parameters. The dimensionless parameter tuning has several advantages: (1) allows for simultaneous tuning of all the control-loops, (2) reduces the total number of tuning parameters to only 3 to 6 dimensionless parameters, and (3) allows similar values of dimensionless tuning parameters to be used in different processes.

The present work introduces a new way to alleviate the limiting effect on performance of the process interactions in a decentralized control system, via the double-loop multi-scale control (DL-MSC) scheme introduced in (Seer & Nandong, 2016). In brief, the DL-MSC scheme consists of two (a primary and secondary) controllers and one multi-scale predictor. It has two layers or (loops) -an inner-layer with the secondary controller and outer-layer with the primary controller. In the present work, the DL-MSC scheme is used to replace each PID controller in a given control loop. Thus, each control loop has two controllers rather than a single PID controller (as in the case of conventional decentralized PID scheme). The rationale of using this DL-MSC scheme is that, the secondary controller in the scheme can help reduce the limiting effect of process interactions on control performance. Thus, this scheme provides an alternative approach to the traditional decoupling controllers which reduce the effect of process interactions. It should be pointed out, however, the secondary controller in this DL-MSC scheme is much easier to design (i.e., uses a simple low order controller form) than the traditional decoupling controller. So far, there is no work reported about using the DL-MSC scheme in the decentralized control structure. This paper present a simple method to tune the decentralized DL-MSC (DDL-MSC) scheme. The rest of the paper is organised as follow. Section 2 provides a brief description of EOTF for MIMO Process Model. In Section 3, the fundamental of the double loop multi-scale control scheme is presented. Section 4 shows the application of the DDL-MSC scheme. Conclusions are highlighted in Section 5.

2. Preliminaries

2.1 MIMO Process Model

Consider an $n \times n$ MIMO process given as follows

$$\mathbf{P}(s) = \begin{bmatrix} g_{11}(s) & \cdots & g_{1n}(s) \\ \vdots & \ddots & \vdots \\ g_{n1}(s) & \cdots & g_{nn}(s) \end{bmatrix} \quad (1)$$

The transfer function g_{ij} is represented by the First-Order plus Deadtime (FOPDT) model

$$g_{ij}(s) = \frac{k_{ij}\exp(-\theta_{ij}s)}{\tau_{ij}s+1} \quad (2)$$

where k_{ij}, τ_{ij} and θ_{ij} denote the process gain, time constant and deadtime respectively.

The $n \times n$ MIMO process (1) can be simplified to the purely decentralized form as follows

$$\mathbf{P}(s) = \begin{bmatrix} g_{11}^e(s) & 0 & \dots & 0 \\ 0 & g_{22}^e(s) & \dots & 0 \\ \vdots & \vdots & \dots & \vdots \\ 0 & 0 & \dots & g_{nn}^e(s) \end{bmatrix} \tag{3}$$

Here, g_{ii}^e denotes the so-called effective open-loop transfer function (EOTF) where for a 2×2 MIMO process, it is given by

$$g_{11}^e(s) = g_{11}(s) - \underbrace{\frac{g_{12}(s)g_{21}(s)}{g_{22}(s)}}_{g_{int,1}} \tag{4}$$

$$g_{22}^e(s) = g_{22}(s) - \underbrace{\frac{g_{12}(s)g_{21}(s)}{g_{11}(s)}}_{g_{int,2}} \tag{5}$$

Notice that, the EOTFs (4) and (5) consist of two parts: a main (diagonal) part, i.e., g_{ii} and interactive part $g_{int,}$.

2.2 Double-Loop Multi-Scale Control Scheme

The details about the double-loop multi-scale control scheme can be found in (Seer & Nandong, 2016) and its advanced triple-loop variant in (Seer & Nandong, 2018). Fig. 1 shows the block diagram of a decentralized double-loop control system for a 2x2 MIMO process. In the figure, the blocks G , G_{cpi}, W_i and g_{ij} denote the secondary controller, primary controller, multi-scale predictor and transfer function respectively. The signals Y_i and R_i denote the controlled output and setpoint respectively.

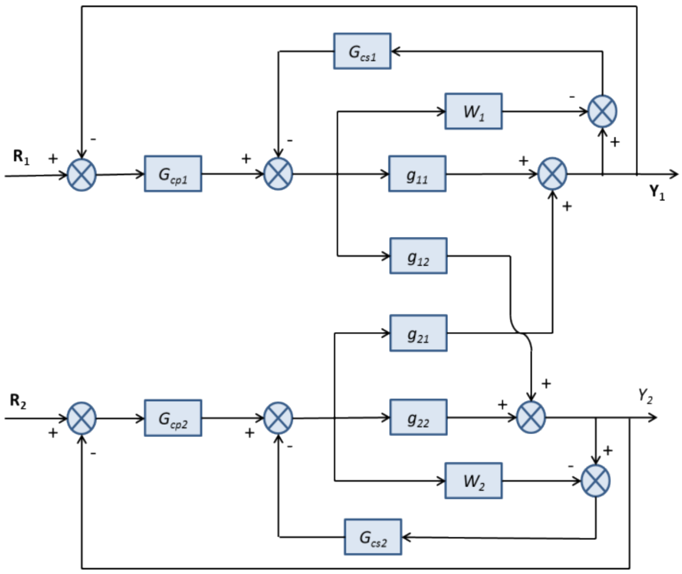

Fig. 1 - Realization block diagram of the decentralized DL-MSC (DDL-MSC) scheme for 2x2 MIMO process.

The basic idea of the double-loop multi-scale control scheme is to first stabilize one part of the system, i.e., the interactive part using a simple controller (e.g., P controller). Then, another controller (e.g., PID) is used to provide an overall performance based on the pre-stabilized system. Please note that, this is the first time that this control technique is applied to the decentralized control system for controlling MIMO processes.

3. Control Design

3.1 Inner Layer Stability Region

If all transfer functions are given in the form of first-order plus deadtime (FOPDT) model, then the interaction transfer function for a 2×2 MIMO system for i-th loop is given as

$$g_{int,i}(s) = \frac{k_{int,}(\tau_j s+1)e^{-\theta_{e,i}s}}{(\tau_{ij}s+1)(\tau_{ji}s+1)} \tag{6}$$

where $k_{int,i} = \frac{k_{ij}k_{ji}}{k_{jj}}$ and $\theta_{e,i} = \theta_{ij} + \theta_{ji} - \theta_{jj}$ for $i, j = 1, 2$.

Consider a P-only controller is used in the inner layer and $\exp(-\theta_{e,i}s) \cong 1 - \theta_{e,i}s$, the closed-loop characteristic equation can be written as follows

$$(\tau_{ij}\tau_{ji} - K_{int,L_i}\tau_{jj}\theta_{e,i})s^2 + [\tau_{ij} + \tau_{ji} + K_{int,L_i}(\tau_{jj} - \theta_{e,i})]s + K_{int,L_i} + 1 = 0 \quad (7)$$

where $K_{int,L_i} = k_{int,c_i}k_{int,i}$ is the loop gain and k_{int,c_i} is the controller gain. By applying the PID stability theorem (Seer & Nandong, 2017a) to the characteristic equation, it can be easily shown that the upper limit of the loop gain is

$$K_{int,L_i} < \overline{K}_{int,L_i} = \frac{\tau_{ij}\tau_{ji}}{\theta_{e,i}\tau_{jj}} \quad (8)$$

and the lower limits are

$$K_{int,L_i} > \underline{K}_{int,L_i a} = -1 \quad (9)$$

$$K_{int,L_i} > \underline{K}_{int,L_i b} = -\left(\frac{\tau_{ij}+\tau_{ji}}{\tau_{jj}-\theta_{e,i}}\right) \quad (10)$$

Please note that, the second lower limit of the loop gain is obtained under the condition that $\tau_{jj} - \theta_{e,} > 0$. On the contrary, if $\tau_{jj} - \theta_{e,} < 0$, then another upper limit will exist; this condition is likely for a delay dominant process. Here, we assume that the first condition holds, i.e., a lag dominant process. The details of procedure to develop stability regions of PID control for second-order and fourth-order systems can be found in (Seer & Nandong, Stabilization and PID tuning algorithms for second-order unstable processes with time-delays, 2017a) (Seer & Nandong, 2017b).

3.2 Tuning Relations for Inner Layer

Based on the upper and lower limits derived in the previous section, we propose two tuning relations: direct and reverse tuning approaches. For the direct tuning approach, it is desired to place the loop gain in between the upper limit and zero, which shall yield the following equation

$$k_{int,c_i} = \frac{r_k}{k_{int,i}}\left(\frac{\tau_{ij}\tau_{ji}}{\theta_{e,i}\tau_{jj}}\right) \quad (11)$$

where the dimensionless tuning parameter r_k must lie in the range of $r_k = (0, 1)$,

For the reverse tuning approach, it is desired to place the loop gain in between maximum lower limit and zero, which shall lead to the following

$$k_{int,c_i} = \frac{r_k}{k_{int,i}}\left[max\left(-1, \underline{K}_{int,L_i b}\right)\right] \quad (12)$$

where the dimensionless tuning parameter r_k gain must lie in the range of $r_k = (0, 1)$

3.3 Tuning Relations for Outer Layer

The Routh-Hurwitz (RH) tuning relations proposed by (Mohd & Nandong, 2018) are adapted in this study. The RH tuning relations for SISO case are given as follows

$$\tau_{D_i} = r_d\left(\frac{\theta_{ii}}{2}\right),\ r_d > 1 \quad (13)$$

$$K_{C_i} = \frac{r_p}{k_{ii}}\left(\frac{\tau_{ii}}{\tau_{D_i}}\right),\ 0 < r_p < 1 \quad (14)$$

$$\tau_{I_i} = r_i\left(\frac{\tau_{ii}}{2}\right),\ r_i > 1 \quad (15)$$

Note that, the RH tuning method uses only three dimensionless parameters: r_p, r_i and r_d to be tuned so to obtain values of the original PID controller parameters for all control-loops involved.

3.4 Inner-Layer Tuning Cases

The controller tuning for the inner loop can be divided into three cases:

i. Case A: all direct tuning

ii. Case B: all reverse tuning

iii. Case C: mixed direct-reverse tuning

When the main effect is in the same direction as the interactive effect, it might be more desirable to use all reverse or mixed reverse-direct tuning approaches. This will help achieve better cooperation between the interacting control loops, thereby improving the overall performance robustness. On the other hand, if the main effect is in the same direction as that of the interactive effect, then it might more desirable to use the direct tuning approach.

3.5 Decentralized PID Tuning Formulas for Primary Controller

Assuming the ideal PID controller form is used for a given i-th control-loop, then the following modified RH formulas can be derived directly from the stability region of PID controller:

$$K_{ci} = (r_P/k_{ii})(\tau_{ii}/\tau_{Di}),\ r_P \in (0,1) \tag{16}$$

$$\tau_{Di} = r_D(\theta_{ii}/2),\ r_D > 1 \tag{17}$$

$$\tau_{Ii} = r_I \tau_{Imin_i}(\tau_{ii}/\theta_{ii})[(\tau_{pa}+\theta_a)/(\tau_{ii}+\theta_{ii})],\ r_I > 1 \tag{18}$$

where τ_{pa} and θ_a represent the average values of time-constants and time-delays respectively. For example, in the 3x3 MIMO process, the average value of time-constant is

$$\tau_{pa} = \sum_{i=1}^{3}(\tau_{ii})/3 \tag{19}$$

In (18), the maximum lower limit on the rest time τ_{Imin_i} is given as

$$\tau_{Imin_i} > max[0.5\theta_i, \tau_{Isc_i}] \tag{20}$$

while the lower limit based on the sufficient stability criterion is

τ (

$$\tau_{Isc_i} = \left(\frac{0.5\theta_{ii}K_{L_i}}{1+K_{L_i}}\right)\left(1+\frac{\tau_{ii}-K_{L_i}\tau_{Di}}{0.5\theta_{ii}+\tau_{ii}+K_{L_i}(\tau_{Di}-0.5\theta_{ii})}\right) \tag{21}$$

where the primary loop gain is $K_{L_i} = K_{ci}k_{ii}$.

The relation (18) also considers the influence of process dynamic characteristic (τ_{ii} /) on the performance of the closed-loop system. Also, the formula (18) takes into account the significant differences in dynamics behaviours of different channels or loops in the given MIMO process. The inclusion of this latter effect represents a modification made to the original Routh-Hurwitz tuning formulas introduced in (Mohd & Nandong, 2018). It should be noted that, the formulas (16) -(18) are used to tune the outer-layer controller of DL-MSC scheme in each control-loop. The inner-layer (secondary) controller is tuned as in the following section.

3.6 Inner-Layer Controller Tuning

For the inner-layer controller, it is preferable to us a simple control law, either P-only controller, or P controller with a lead-lag filter given as follows

$$g_{cs_i}(s) = k_{cs_i}(\tau_{ld_i}s+1)/(\tau_{lg_i}s+1) \tag{22}$$

where k_{cs_i}, τ_{ld_i} and τ_{lg_i} are controller gain, lead time-constant and lag time-constant respectively.

Following the same stability analysis as in the previous cases of P and PID controllers, it can be shown that one of the stability regions for the controller (22) in the inner layer is given by

$$-1 < K_{int,} < [0.5\theta_{ii}(\tau_{ii}+\tau_{lg}) + \tau_{ii}\tau_{lg\ i}]/(0.5\theta_{ii}\tau_{ld_i})(23)$$

where the secondary loop gain is $K_{int,L_i} = k_{int,i}k_{cs_i}$. The following conditions must be satisfied:

$$\tau_{ld_i} > 0.5\theta_{ii} \tag{24}$$

$$\tau_{lg_i} > \tau_{ld_i} - \theta_{ii} - \tau_{ii} \tag{25}$$

Consider two tuning approaches for the inner-layer controller: (a) direct tuning and (b) reverse tuning. Assume that a P controller is used in the inner-layer of DL-MSC scheme, the following tuning relations can be applied to direct and reverse tuning approaches.

Direct tuning approach:

$$k_{cs_i} = \frac{r_k}{k_{int,i}}\left(\frac{\tau_{ii}}{\theta_{ii}}\right), \quad r_k \in (0, 1) \tag{26}$$

Reverse tuning approach:

$$k_{cs_i} = -\left(\frac{r_k}{k_{int,i}}\right), \quad r_k \in (0, 1) \tag{27}$$

When the P controller with lead-lag filter is used, the following relations are adopted.

Direct tuning approach:

$$k_{cs_i} = \frac{r_k}{k_{int,i}}\{[0.5\theta_{ii}(\tau_{ii} + \tau_{lg_i}) + \tau_{ii}\tau_{lg_i}]/(0.5\theta_{ii}\tau_{ld_i})\}, \; r_k \in (0, 1) \tag{28}$$

Reverse tuning approach:

$$k_{cs_i} = -\left(\frac{r_k}{k_{int,i}}\right), \quad r_k \in (0, 1) \tag{29}$$

For either direct or reverse tuning approach, the lead-lag time-constants are tuned as follows.

$$\tau_{ld_i} = r_{ld}(0.5\theta_i), \; r_{ld} > 1 \tag{30}$$

If $\tau_{ld_i} - \theta_{ii} - \tau_{ii} > 0$, then

$$\tau_{lg_i} = r_{lg}(\tau_{ld_i} - \theta_{ii} - \tau_{ii}), \; r_{lg} > 1 \tag{31}$$

Otherwise,

$$\tau_{lg_i} = r_{lg}\tau_{ld_i i}, \; r_{lg} \in (0, 1) \tag{32}$$

Note that , $r_{ld}$and $r_k$are the dimensionless tuning parameters for the inner-layer of the DL-MSC scheme. Given an n×n MIMO process, if the DDL-MSC scheme uses P controllers in the inner-layers and PID controllers in the outer-layers, then there are 4 dimensionless tuning parameters in total. If the P controller augmented with lead-lag filter is used in the inner-layer, then there are 6 dimensionless tuning parameters in total. Note that, for an n×n MIMO process with PID controllers, there are 3n tuning parameters in total. Thus, the DDL-MSC scheme offers simpler way to tuning the control system via the dimensionless RH tuning method.

4. Illustrative Example

Example 1 -2x2 Wood and Berry Column

Consider the well-known Wood and Berry (Wood & Berry, 1973) distillation column system given by

$$\mathbf{P}(s) = \begin{bmatrix} \frac{12.8e^{-s}}{16.7s+1} & \frac{-18.9e^{-3s}}{21s+1} \\ \frac{6.6e^{-7s}}{10.9s+1} & \frac{-19.4e^{-3s}}{14.4s+1} \end{bmatrix} \tag{33}$$

The Relative Gain Array (RGA) corresponding to this system (33) is

$$\mathbf{RGA} = \begin{bmatrix} 2.0094 & -1.0094 \\ -1.0094 & 2.0094 \end{bmatrix} \tag{34}$$

The computation of the EOTFs leads to two transfer functions ad follows

$$g_{11}^{e}(s) = \frac{12.8e^{-s}}{16.7s+1} - \frac{6.43(14.4s+1)e^{-7s}}{(10.9s+1)(21s+1)} \tag{35}$$

$$g_{22}^{e}(s) = \frac{-19.4e^{-3s}}{14.4s+1} + \frac{9.75(16.7s+1)e^{-9s}}{(10.9s+1)(21s+1)} \tag{36}$$

The inner layers for both loops 1 and 2 are tuned using the relations presented in the previous section. Table 1 show the setting values for $r_k$and corresponding values of controller gains under four different tuning cases. A PID controller augmented with lag filter is used in the outer layer for each loop. Thus, the PID controller is expressed in the form of

$$G_c(s) = K_c\left(1 + \frac{1}{\tau_I s} + \tau_D s\right)\left(\frac{1}{\tau_f s+1}\right) \tag{37}$$

The lag filter time constant is approximated as follows

$$\tau_f = \frac{\tau}{\epsilon}, \ \ 100 < \epsilon < 250 \tag{38}$$

The controller setting values used are $r_d = 1.3$, $r_p = 0.45$ and $r_i = 1.2$; $\epsilon = 200$. The resulting controllers are

$$G_{c_1} = 0.9032\left(1 + \frac{1}{10s} + 0.65s\right)\left(\frac{1}{0.08s+1}\right) \tag{39}$$

$$G_{c_2} = -0.1713\left(1 + \frac{1}{8.64s} + 1.95s\right)\left(\frac{1}{0.07s+1}\right) \tag{40}$$

Figures 2(a)-(b) show the comparative performances under different double-loop multi-scale control tuning approaches (reverse or direct). The inner-layer tuning values are shown in Table 1. The value of Integral Absolute Error (IAE) for each case is shown on the figure legend in the bracket. The performance of the control system is also tested under modelling errors: 10% errors in deadtimes and gains of the diagonal transfer functions, and -10% errors in the deadtimes and gains of the off-diagonal transfer functions in (33). The results are shown in Figures 3(a)-(b). It can be shown that the reverse tuning approach (scheme B) gives the best performance in terms of the IAEs (smallest total IAE value). This is expected because for the Wood-Berry column, the main and interactive effects are in the opposite directions; see equations (35) and (36) where main gain and interactive gain have opposite signs.

Table 1: Inner layer controller tuning for all cases (example 1).

Case		Loop 1	Loop 2
A	Tuning	Direct	Direct
	r_k	0.15	0.15
	k_{cs_i}	-0.053	0.0234
B	Tuning	Reverse	Reverse
	r_k	0.15	0.15
	k_{cs_i}	0.0233	-0.0154
C.1	Tuning	Direct	Reverse
	r_k	0.15	0.3
	k_{cs_i}	-0.053	-0.0308
C.2	Tuning	Reverse	Direct
	r_k	0.3	0.15
	k_{cs_i}	0.0467	0.0234

The performance of the double-loop multi-scale control scheme, Case B (DL-MSC-B scheme) is compared against a decentralized PID control scheme, tuned using a two different optimization-based methods: iterative optimization (Euzebio & Barros, 2015), and retuning optimization (Veronesi & Visioli, 2018). These two methods are adopted because they provide the best performance of decentralized PID control for the Wood-Berry column so far. The performances are compared based on sequential 1 unit step changes in setpoints of Y1 and Y2, under nominal condition and perturbed condition. For the perturbed condition, it is assumed that the diagonal deadtimes and gains of process (33) have 15% errors from the nominal values. Meanwhile, the off-diagonal deadtimes and gains have -15% errors. Figures 4(a)-(b) show the nominal responses under these different control systems. All of the control systems show very comparable performances in terms of the total IAE values. Figures 5(a)-(b) show the control performances under the perturbed conditions (15% modeling error). This time, it is obvious that the DL-MSC-B outperforms the decentralized PID control system tuned via the above mentioned optimization methods. Please note that, no tuning optimization is applied to the DL-MSC-B scheme. In other words, the performance robustness of the DL-MSC-B scheme can be further improved by optimisation. However, it is worth mentioning that even without tuning optimization, the DL-MSC-B scheme can still deliver a superior performance to that of the conventional decentralized PID control system, with rigorous tuning optimization. In summary, the advantage of the DL-MSC scheme lies in its simplicity in term of the tuning approach - there is no need for a tedious optimization or trial and error approach to produce a good control performance.

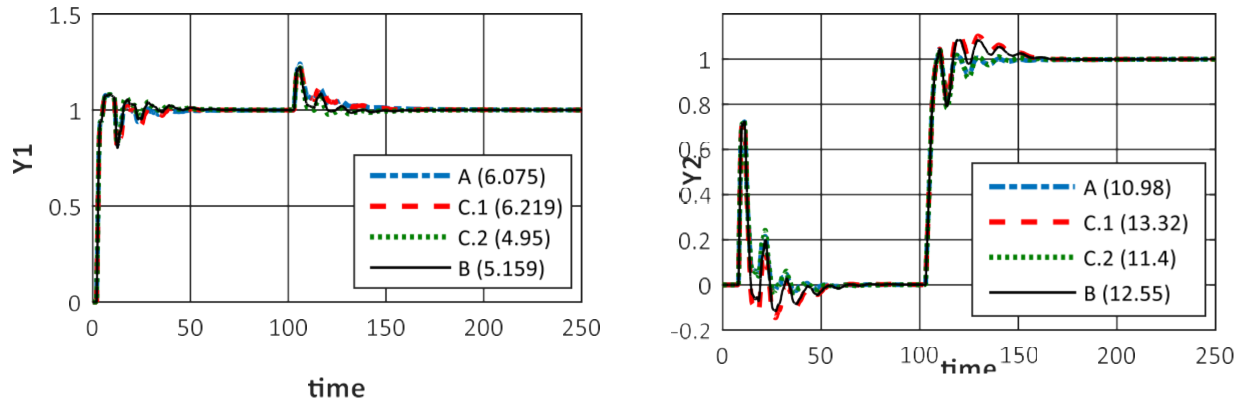

Fig. 2 - Closed loop responses at nominal condition under different tuning cases: (a) Loop 1, (b) Loop of example 1

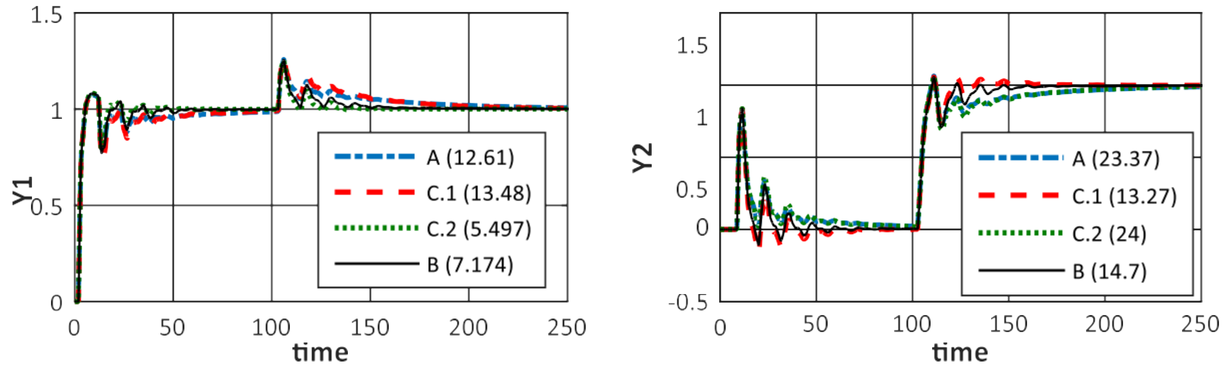

Fig. 3 - Closed loop responses at perturbed condition (10% errors) under different tuning cases: (a) Loop 1 (b) Loop 2 of example 1

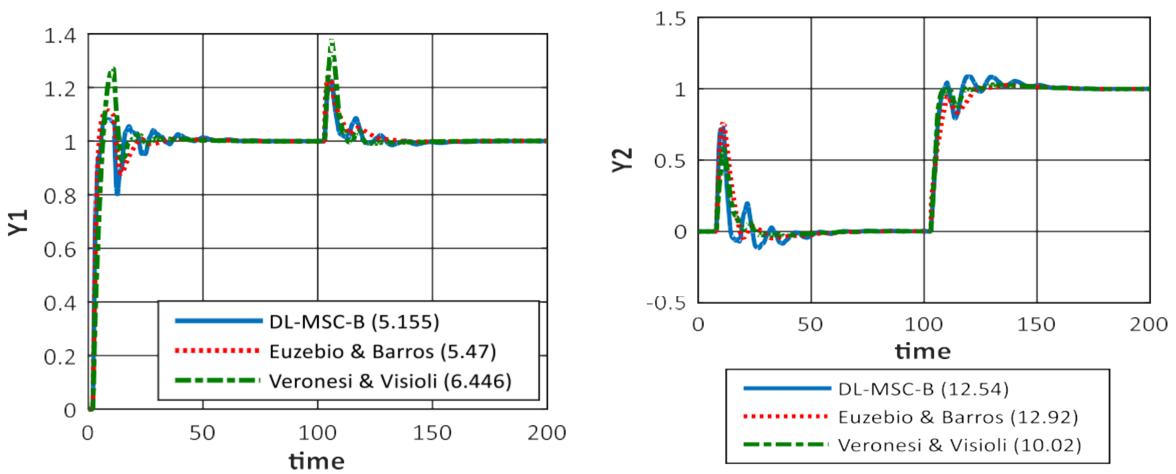

Fig. 4 - Closed-loop response at nominal condition under different control schemes: (a) Loop 1 and (b) Loop 2 of example 1

Example 2 -3x3 Tyreus Distillation

The second example, consider the 3x3 Tyreus distillation process:

The Tyreus process has been adopted in a number of case studies, examples are (Lin, Jeng, & Huang, 2009; Shiu & Hwang, 1998; Mohd & Nandong, 2018). Also, the process was used to compare the performance of inter-communicative multi-scale control scheme with that of some PID plus decoupling control systems (Nandong & Zang, 2014).

Before proceeding with the secondary controller design in the DDL-MSC strategy, it is necessary to first reduce the interactive terms, to the FOPDT form. The associated FOPDT models for all three loops are given as follows:

$$g_{int,1} = 0.188 \exp(-3.64s) / (361.6s + 1) \tag{41}$$

$$g_{int,2} = -3.5 \exp(-7.4s) / (144.2s + 1) \tag{42}$$

$$g_{int,3} = -133 \exp(-20.5s) / (70s + 1) \tag{43}$$

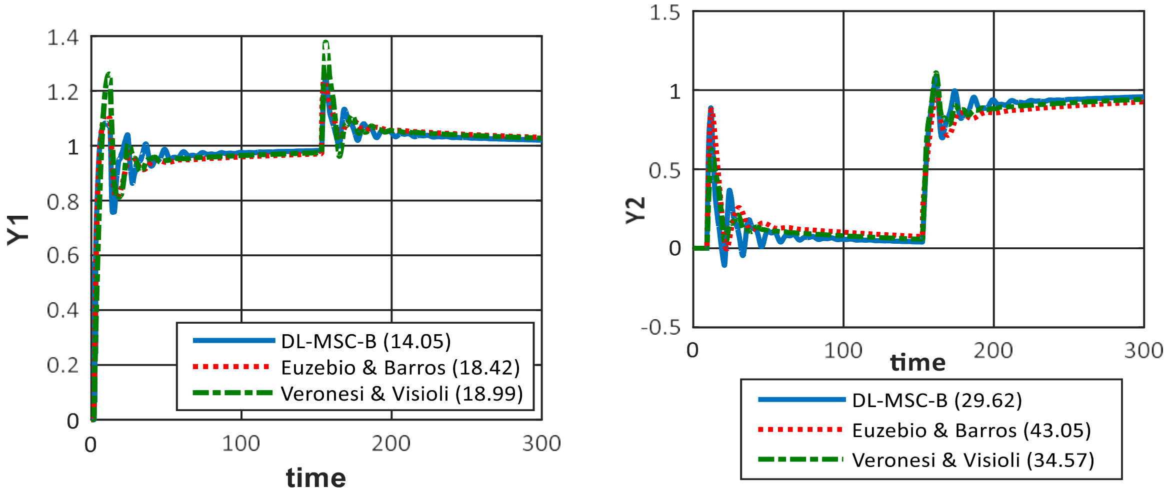

Fig. 5 - Closed loop responses at perturbed condition (15% errors) under different control schemes: (a) Loop and (b) Loop 2 of example 1.

Note that g_{22} is a second-order time delay system. To be able to use the proposed RH tuning method, g_{22} need to be reduced to the FOPDT form, which leads to an approximated transfer function

$$g_{22} = 0.33 \exp(-s) / (4.53s + 1) \tag{44}$$

Table 2 shows the tuning values of the decentralized DL-MSC (DDL-MSC) scheme, and the conventional decentralized single-loop (DSL-RH) tuned using the modified Routh-Hurwitz formulas given in this work. The tuning values of the decentralized PID controllers based on sequential loop closing are given in (Shiu & Hwang, 1998). The control performance is evaluated on the basis of sequential 1 unit step changes in the setpoints of Y_1, Y_2 and Y_3. The mean integral absolute value (MIAE) is calculated for the three different control strategies. Note that, the MIAE is calculated as follows

$$MIAE = \sum_{i=1}^{n} IAE_i / n \tag{45}$$

where n denotes the number of control loop and IAE_i the integral absolute error corresponding to the i-th control loop. Fig. 2 shows the three different control performances in terms of their closed-loop responses (for Y_3 only) and MIAE values (in the legend). For the closed-loop performance comparison, only the responses of controlled variable Y_3 are presented for the illustration. From Fig. 2, it shows that the performance of the standard decentralized PID control via RH tuning (DSL-RH) is better than that based on the sequential loop tuning method (Shiu & Hwang). This is also confirmed by the MIAE values (se figure legend). The DSL-RH gives smaller value than that of Shiu & Hwang decentralized PID system; i.e., the latter shows about 52% performance improvement over the former in term of the MIAE. Meanwhile, the DDL-MSC scheme shows even better performance (in term of MIAE) than the DSL-RH scheme; i.e., the DDL-MSC shows about 17% improvement over the DSL-RH scheme. Therefore, the incorporation of the simple secondary controllers in the DDL-MSC scheme can further improve the decentralized control performance overall. This improvement is due to the ability of the secondary controllers to reduce the coupling effects in the control system. Thus, the DDL-MSC scheme can be viewed as an alternative to the decentralized PID system augmented with decoupling controllers. But it should be noted that, the DDL-MSC scheme is easier to design than the decoupling decentralized PID control system.

Table 2: Controller tuning parameter values (example 2)

Strategy	$K_c^{\$}$	$\tau_I^{\$}$	$\tau_D^{\$}$	$K_c^{\#}$	$\tau_{ld}^{\#}$	$\tau_{lg}^{\#}$
DSL-RH	34.4, 10.8, 0.53	26, 16.7, 19.2	0.39, 0.385, 0.875	-	-	-
DDL-MSC	34.4, 10.8, 0.53	26, 16.7, 19.2	0.39, 0.385, 0.875	-0.53, 0.0039, -0.018	36, 90, 7	0.1, 0.1, 10

$Primary controller parameters for the DDL-MSC system.
#Secondary controller parameters for the DDL-MSC system.

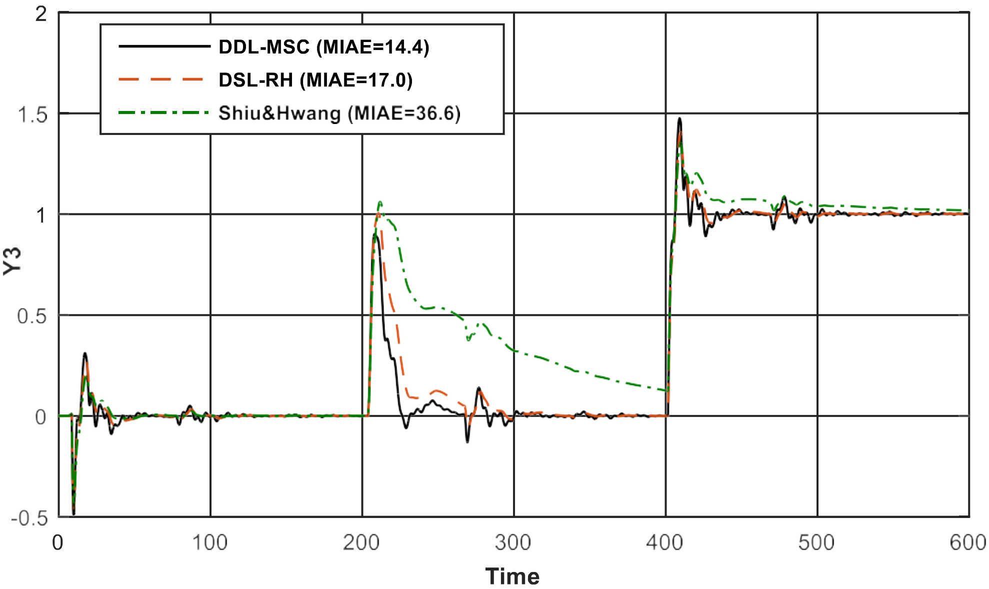

Fig. 6 - Closed loop responses and MIAE values under different control schemes of example 2.

5 Conclusion

The proposed DDL-MSC has been shown to be able to provide improved performance over the conventional decentralized PID control system. Moreover, the DDL-MSC scheme has been shown to be able to mitigate the effects of process interactions, i.e., via the inner-layer (secondary) controllers. It is worth to highlight that, the modified Routh-Hurwitz tuning formulas can give better tuning values than the sequential loop closing method. Additionally, the RH tuning method is very easy to apply compared to other PID running methods for the decentralized PID systems. In future works, the DDL-MSC system will be applied to other types of MIMO processes, e.g., unstable and integrating MIMO processes. The combination of the DDL-MSC scheme with a decoupling technique is also a potential future research direction.

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