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Analytical Scheme of Centralized PI Controller for Non-square Processes with Time-delays

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Abstract: Based on the direct synthesis approach, a simple and effective design method of centralized proportional integral (PI) controller for non-square processes is investigated in this paper. With the help of desired closed-loop diagonal transfer function to reduce interaction between individual loops, analytical expressions for PI controller, through the steady and dynamic information of the open-loop transfer function, are derived for the first order plus time delays model which often arises in the chemical production process. Compared with the existing direct synthesis approaches, the proposed controller design method requires no approximation of the pseudo-inverses of process. Example is introduced to show the effectiveness and simplicity of the proposed technique.

Keywords: Non-square processes, Time-delays, PI controller, Centralized control.

1. INTRODUCTION

With the high demand on product quality and energy integration, most modern industrial processes take the forms of multi-input and multi-output (MIMO) (Balaguer & Romero, 2012; Gigi & Tangirala, 2013; Luan, Chen & Liu, 2014). There are two types of MIMO systems on the basis of the number of input and output variables. When the number of inputs is equal to that of outputs, we call this kind of systems as square systems. If the input number is unequal to the output number, the systems are called as non-square systems. A simple way of controlling the non-square systems is to find ways to transform them to square systems by adding or removing appropriate inputs or outputs (Luo, Liu, Cai, Jia, Jia & Song, 2012; Quan, Jin & Wang, 2011; Ren, Luo, Liu & Xu, 2012). However, adding variables will increase the control cost, while deleting variables may reduce the control performance because of the missing information. Therefore, superior performance can be achieved by finding ways to tackle the original non-square systems directly (Davison, 1983; Treiber & Hoffrnan, 1980).

In designing the non-square systems, the interactions between different loops are the main obstacle. In order to eliminate the interactions, multi-loop control and centralized control are the most common control strategies in practice. In decentralized control, we can decompose the multivariable processes firstly into multiple single-input and single-output (SISO) loops. Then the controllers are designed directly for SISO processes (Sarma & Chidambaram, 2013; Loh, 1997). Although multi-loop control has less tuning parameters, it is only applicable to the systems with modest interactions.

In some situations that the interactions among channels are strong, it is necessary to design centralized controller to eliminate the interactions. In recent years, many researchers adopted centralized control strategy for non-square systems with time-delays. To deal with the multiple time-delays existing in non-square control systems, reference (Sharma & Chidambaram, 2003) proposed a method of Smith delay compensator to design centralized PI controller for non-square systems using the pseudo inverse of the steady-state gain matrix. To simplify the calculation process of pseudo inverse for non-square systems, reference (Seshagiri & Chidambaram, 2006) proposed a static decoupling PI control technique for non-square systems. Only using the steady-state information of the systems will lead to the limitation of control performance. Hence reference (Chen, He & Xin, 2011) developed a new method to compensate dynamically for shortcomings caused by static decoupling. In order to consider simultaneously the steady and dynamic information of the system and get better control performance, reference (Jing, Guo, etc., 2010) presented the internal model control (IMC) design technique for a class of non-minimum phase non-square systems by calculating the pseudo inverse of the model. However, it is difficult to obtain a reasonable solution for the pseudo inverse of process model because the solution may very complicated. Therefore, (Shen, Sun & Xu, 2014) proposed the equivalent transfer function (ETF) based method to replace the calculation of pseudo inverse of the process model. Nevertheless, the approximation way to obtain ETF inevitably has modeling errors.

Motivated by the aforementioned reasons, this paper presents a novel technique to investigate the PI control design for non-square processes with more inputs than outputs, which often arises in chemical process. By exploring the desired closed-loop diagonal transfer function (DCDTF) to reduce interactions among different loops, the relationship between the steady and dynamic information of open-loop transfer function and the tuning parameters of centralized PI controller are directly derived. Compared with the existing non-square control design methods, the proposed method requires no approximation of the pseudo-inverses of process and the process of calculation is also simple. Simulation studies are used to show the effectiveness and advantages of the proposed design approach.

2. PROBLEM STATEMENT

This article mainly focuses on the centralized controller design for multivariable control processes with more inputs than outputs (Sharma & Chidambaram, 2003). Consider an m -inputs and n -outputs $(m > n)$ open-loop stable and physically proper non-square system with time delays, as shown in Fig. 1,

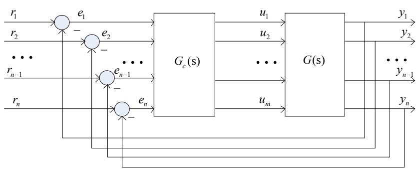

Fig. 1. Closed-loop non-square control system

where r_i, $i=1,2,\cdots n$ are the reference inputs, $e_i, i=1,2,\cdots n$ are the errors between feedback and reference, $u_i, i=1,2,\cdots m$ are the manipulated variables, $y_i, i=1,2,\cdots n$ are the system outputs, $G(s)$ is the $(n\times m)$ process transfer function described as following:

$$G(s)=\begin{bmatrix} g_{11}(s) & g_{12}(s) & \cdots & g_{1m}(s) \\ g_{21}(s) & g_{22}(s) & \cdots & g_{2m}(s) \\ \vdots & \vdots & \ddots & \vdots \\ g_{n1}(s) & g_{n2}(s) & \cdots & g_{nm}(s) \end{bmatrix}$$

where the transfer function from jth input to ith output is $g_{ij}(s)=g_0 e^{-\theta_{ij}s}$ ($g_{0ij}(s)=\dfrac{k_{ij}}{\tau_{ij}s+1}$), g_{0ij} is the strictly proper and stable transfer functions, and θ_{ij} is the corresponding time delay of process transmission. And $G_c(s)$ is a $m\times n$ centralized PI controller, which is represented as

$$G_c(s)=\begin{bmatrix} g_{c,11}(s) & g_{c,12}(s) & \cdots & g_{c,1n}(s) \\ g_{c,21}(s) & g_{c,22}(s) & \cdots & g_{c,2n}(s) \\ \vdots & \vdots & \ddots & \vdots \\ g_{c,m1}(s) & g_{c,m2}(s) & \cdots & g_{c,mn}(s) \end{bmatrix}$$

From Fig. 1, the closed-loop transfer function matrix between outputs and set-points can be determined as:

$$H(s)=(\mathrm{I}+G(s)G_c(s))^{-1}G(s)G_c(s) \quad (1)$$

According to equation (1), a centralized controller is derived as follows:

$$G_c(s)=G^{-1}(s)(H^{-1}(s)-I)^{-1} \quad (2)$$

Whereas the exact inverse for non-square systems does not exist, hence Moore-Penrose pseudo inverse is proposed (Jin, Hao & Wang, 2013). For matrix A , the Moore-Penrose pseudo inverse of A can be expressed as $A^*=A^H(AA^H)^{-1}$, where A^H is the Hermitian matrix of A .

Using the Moore-Penrose pseudo inverse, equation (2) should be transformed into the following form:

$$G_c(s)=G(s)^H(G(s)G(s)^H)^{-1}(H^{-1}(s)-I)^{-1} \quad (3)$$

where the $G^H(s)$ is the Hermitian matrix of $G(s)$. Assuming that the system is completely decoupled, the desired ideal closed-loop transfer function is as follows:

$$H(s)=\begin{bmatrix} h_{11}(s) & 0 & \cdots & 0 \\ 0 & h_{22}(s) & \vdots & 0 \\ \vdots & 0 & \ddots & \vdots \\ 0 & 0 & \cdots & h_{nn}(s) \end{bmatrix} \quad (4)$$

where h_{ii} $i=1,2,\cdots n$ are a diagonal element of $H(s)$ corresponding to the DCDTF of each loop. Then the $(H^{-1}(s)-I)^{-1}$ can be expressed as

$$\left(H^{-1}(s)-I\right)^{-1}=\begin{bmatrix} \dfrac{h_{11}}{1-h_{11}} & 0 & 0 \\ 0 & \ddots & \vdots \\ 0 & \cdots & \dfrac{h_{nn}}{1-h_{nn}} \end{bmatrix} \quad (5)$$

In multivariable systems, the required ideal structure of matrix $H(s)$ is in diagonal form, which reveals the system is perfectly decoupling and that each output can track its reference independently. This paper aims to establish the relations between PI controller tuning parameters and steady and dynamic characteristics of open-loop system without calculating $G^*(s)$ directly. Next section will present the design algorithm to obtain the tuning relations for the PI controller.

3. CONTROLLER DESIGN

3.1 Design of Controller Parameters

In this section, formulae for the calculation of PI controller tuning parameters are derived.

In term of internal model control (IMC) theory, the DCDTF is expressed in the form of (Jin, Guo, Liu & Song, 2010)

$$h_{ii}=\frac{e^{-d_i s}}{(\lambda_i s+1)^{m_i}}\prod_{k=1}^{q_i}\left(\frac{z_k-s}{z_k^*+s}\right)^{R_i}, i=1,2,\cdots n \quad (6)$$

where d_i is the maximum predictive value presented in the ith column of $G^*(s)$, z_k is the non-minimum phase poles,

z_k^* is the conjugate complex of z_k, R_i is the number of the same pole in the ith column, q_i represent how many different poles exist in the ith column of $G^*(s)$, λ_i is adjustable parameter that provides the tradeoff between performance and robustness, and m_i is the relative order of the numerator and denominator in $g_{ij}(s)$.

Substituting equation (5) into equation (3) yields

$$g_{c,ji}(s) = G^H(s)\frac{adj(G(s)G^H(s))}{\left|G(s)G^H(s)\right|}\frac{h_{ii}(s)}{1-h_{ii}(s)} \tag{7}$$

Setting

$$G(s)G^H(s) = A(s) \tag{8}$$

So $A(s)$ become a $n \times n$ square matrix and the equation (7) is expressed in the form of

$$g_{c,ji}(s) = G^H(s)\frac{adj(A(s))}{\left|A(s)\right|}\frac{h_{ii}(s)}{1-h_{ii}(s)} \tag{9}$$

where $adj(A)$ is the ith row and jth column element of the adjugate matrix of $A(s)$, $|A|$ is the determinate of $A(s)$.

The standard PI controller is given by

$$g_{c,ji}(s) = k_{C,ji} + \frac{k_{I,ji}}{s} \tag{10}$$

According to equation (9) and equation (10), it can be obtained that

$$k_{C,ji} + \frac{k_{I,ji}}{s} = G^H(s)\frac{adj(A(s)_{ji})}{\left|A(s)\right|}\frac{h_{ii}(s)}{1-h_{ii}(s)} \tag{11}$$

Multiplying both sides of (11) by s, we have

$$sk_{C,ji} + k_{I,\mathrm{ji}} = G^H(s)\frac{adj\left(A(s)_{ji}\right)}{\left|A(s)\right|}\frac{sh_{ii}(s)}{1-h_{ii}(s)} \tag{12}$$

Taking the derivative of both sides of equation (11), it yields

$$k_{C,\mathrm{ji}} = (G^H\frac{adjA}{|A|}\frac{sh_{ii}}{1-h_{ii}})' = -\frac{G^H}{|A|^2}\sum_{p=1}^{m}(\sum_{q=1}^{m}(adjA_{jq})\mathrm{a}'_{qp})adjA_{pi}\frac{sh_{ii}}{1-h_{ii}} + G^H\frac{adjA}{|A|}\left(\frac{sh_{ii}}{1-h_{ii}}\right)' + (G^H)'\frac{adjA}{|A|}\frac{sh_{ii}}{1-h_{ii}} \tag{13}$$

where a'_{qp} is the first derivative of a_{qp}.

Letting $s=0$ and solving equation (12) and equation (13), the controller parameters can be directly calculated as

$$k_{I,ji} = G^H\Big|_{s=0}\frac{adjK_{ji}}{|K|}\frac{sh_{ii}}{1-h_{ii}}\Bigg|_{s=0} \tag{14}$$

$$k_{C,ji} = (G^H)'\Big|_{s=0}\frac{adjK}{|K|}\frac{sh_{ii}}{1-h_{ii}}\Bigg|_{s=0} - G^H\Big|_{s=0}\frac{1}{|K|^2}\sum_{p=1}^{m}(\sum_{q=1}^{m}(adjK_{jq})\mathrm{a}'_{qp})adjK_{pi}\frac{sh_{ii}}{1-h_{ii}}\Bigg|_{s=0} + G^H\Big|_{s=0}\frac{adjK}{|K|}\left(\frac{sh_{ii}}{1-h_{ii}}\right)'\Bigg|_{s=0} \tag{15}$$

where

$$|K| = \begin{vmatrix} k_{11} & \cdots & k_{1m} \\ \vdots & \ddots & \vdots \\ k_{m1} & \cdots & k_{mm} \end{vmatrix}$$

$adjK_{ji}$, $adjK_{jq}$ and $adjK_{pi}$ are simplified as a single formula using subscripts x and y, which are defined as

$$adjK_{xy} = (-1)^{x+y}\begin{vmatrix} k_{1,1} & \cdots & k_{1,x-1} & k_{1,x+1} & \cdots & k_{1,m} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ k_{y-1,1} & \cdots & k_{y-1,x-1} & k_{y-1,x+1} & \cdots & k_{y-1,m} \\ k_{y+1,1} & \cdots & k_{y+1,x-1} & k_{y+1,x+1} & \cdots & k_{y+1,m} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ k_{m,1} & \cdots & k_{m,x-1} & k_{m,x+1} & \cdots & k_{m,m} \end{vmatrix}$$

where k_{xy} is the steady gain of open loop transfer function of A.

Remark: From equations (14)-(15), it can be seen that tuning relations for PI controller parameters are directly derived according to the desired closed-loop output response. Different from the existing direct synthesis method, the proposed design method need not use equivalent transfer function to approximate $G^*(s)$ so that better performance can be achieved through more accurate controller tuning relations. What's more, there is no need to compute the inverse of the process model. The straightforward design procedure makes it easier to compute and understand by engineers and applicable to practical applications.

3.2 Performance and robustness of control system

To analyze the performance of control system, the integral square error (ISE)criteria (Lin, Jang & Shieh, 1999) is used as follows. We can choose two outputs system as an example and a unit step change in r_1, the ISE value corresponding to y_1 is $ISE_{y_1-r_1} = \int_0^\infty (1-y_1(t))^2 dt$. From the interactive response, the ISE value is $ISE_{y_2-r_1} = \int_0^\infty (0-\mathrm{y}_2(t))^2 dt$. In the same way, as for the unit step change in r_2, the corresponding ISE values are presented as $ISE_{y_2-r_2} = \int_0^\infty (1-\mathrm{y}_2(t))^2 dt$ and the ISE value for y_1 is $ISE_{y_1-r_2} = \int_0^\infty (0-\mathrm{y}_1(t))^2 dt$. Therefore, the sum of ISE values are expressed as:

$$ISE = ISE_{y_1-r_1} + ISE_{y_2-r_1} + ISE_{y_1-r_2} + ISE_{y_2-r_2}$$

There is an inverse relationship between the ISE and the performance of the system, the performance is better when the ISE is smaller.

Finally, to investigate the robust stability of the resulting control system, a well-known way (Vu & Lee, 2010) is used. The output multiplication uncertainty can be used to examine the robust stability of the controlled system, since it is often less restrictive than input uncertainty in term of control performance (Vu & Lee, 2010). For a system with an output uncertainty as $\Delta G_o(s) = G(s)[I + \Delta_o(s)]$, where $\Delta_o(s)$ represents the multiplicative output uncertainties. The closed-loop system is stable if

$$\gamma < 1/\bar{\sigma}\left[(I + G(jw)G_c(jw))^{-1} G(jw)G_c(jw)\right]$$

where γ represents the degree of robust stability, $\bar{\sigma}$ is maximum singular value. It should be noted that a control system with a larger γ means more robust stability. For a fair comparison, γ Should be the same as or large than that of the other methods in the simulation.

4. SIMULATION STUDIES

To verify the effectiveness and superior of the proposed method, the following shell(2×3) control problem in chemical process (Liu, Chen, Yu & Tan, 2014) is considered. The transfer function matrix is expressed as:

$$G(s) = \begin{bmatrix} \dfrac{4.05e^{-81s}}{50s+1} & \dfrac{1.77e^{-84s}}{60s+1} & \dfrac{5.88e^{-81s}}{50s+1} \\ \dfrac{5.39e^{-54s}}{50s+1} & \dfrac{5.72e^{-42s}}{60s+1} & \dfrac{6.9e^{-45s}}{40s+1} \end{bmatrix}$$

According to equation (5), the DCDTF matrix is expressed

$$H(s) = \begin{bmatrix} h_{11}(s) & 0 \\ 0 & h_{22}(s) \end{bmatrix} = \begin{bmatrix} \dfrac{e^{-81s}}{\lambda_1 s+1} & 0 \\ 0 & \dfrac{e^{-42s}}{\lambda_2 s+1} \end{bmatrix}$$

where λ_i, $i = 1,2$ are the adjustable parameters that provide the tradeoff between performance and robustness in tuning the controller parameters, which is adjusted to obtain the same value of γ or lager than that of others. The results developed by References (Chen, He & Xin, 2011; Shen, Sun & Xu, 2014) are employed here for comparison and the values of λ_i , $i = 1,2$ can be calculated by obtaining the same valve of γ . According to equation (14) and equation (15), the controller parameters are obtained and listed in Table 1.

Table 1. Controller parameters

Method	Loop	$k_{C,ij}$	$k_{I,ij}$	$k_{C,ij}$	$k_{I,ij}$	λ_1	λ_2	γ
		$j = 1$	$j = 1$	$j = 2$	$j = 2$			
Proposed	$i = 1$	0.06992	0.00046	-0.08000	-0.00005	90	20	0.9
	$i = 2$	-0.16744	-0.00196	0.35147	0.00443			
	$i = 3$	0.06337	0.00127	-0.03332	-0.00130			
Chen	$i = 1$	0.03910	0.00058	-0.00190	-0.00002	134.5	134.5	0.9
	$i = 2$	-0.16607	-0.00246	0.16377	0.00201			
	$i = 3$	0.10711	0.00159	-0.04798	-0.00059			
Shen	$i = 1$	0.04938	0.00047	-0.06992	-0.00004	0.060	0.0125	0.9
	$i = 2$	-0.21862	-0.00202	0.21276	0.00344			
	$i = 3$	0.09712	0.00130	-0.02183	-0.00101			

Using these controller settings, the response and interactive response of the non-square system is shown by adding a unit step change in r_1 and r_2 in Fig. 2. From Fig. 2, it can be seen that the proposed method shows better response and less interaction. Sum of ISE values corresponding to the response of y_1 and y_2 for a step change in r_1 and r_2 are demonstrated in Table 2. From the Table 2, the proposed method shows lower ISE values.

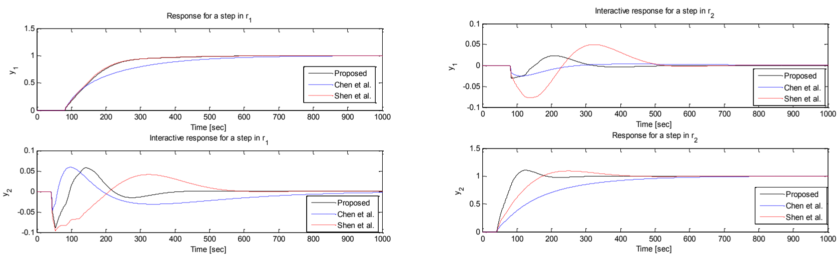

Fig. 2. Response and interactive response in step change in r_1 and r_2

Table 2. ISE values for example

Method	Step input in	ISE values for output y_1	ISE values for output y_2	Sum of ISE values
Proposed	r_1	128.56	0.36	128.92
	r_2	0.07	56.45	56.52
Chen	r_1	139.64	0.50	140.14
	r_2	0.05	105.71	105.76
Shen	r_1	125.64	0.86	126.5
	r_2	0.78	72.18	72.96

To further investigate the robustness in comparison to different methods, perturbation uncertainties of 30% are inserted in the time constants and time delays respectively. From Fig. 3 to Fig. 4, they show the servo response and corresponding interactive response respectively. Sum of ISE values corresponding to the response for perturbation are given in Table 3. As seen from Table 3, the smallest ISE values verify that the proposed controller has a good robust performance.

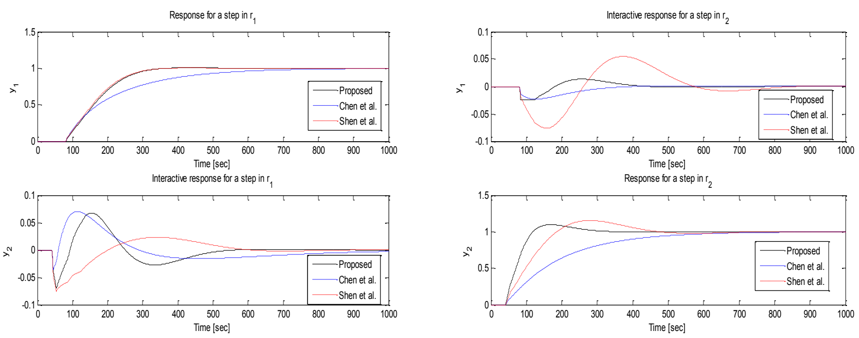

Fig. 4. Response and interactive response of a step change in r_1 and r_2 for +30% time constants perturbation

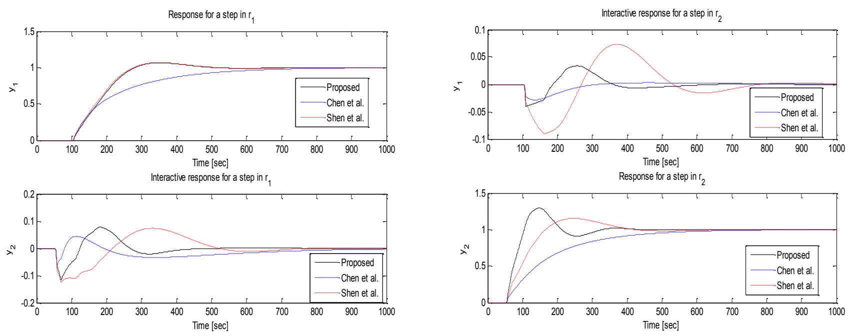

Fig. 5. Response and interactive response of a step change in r_1 and r_2 for +30% time delays perturbation

Table 3 ISE values for the perturbation of +30%

Method	Step input in	ISE values for output y_1	ISE values for output y_2	Sum of ISE values
Perturbation of +30% in each time constant				
Proposed	r_1	135.89	0.51	136.40
	r_2	0.05	61.28	61.33
Chen	r_1	149..45	0.54	149.99
	r_2	0.06	119.88	119.96
Shen	r_1	132.71	0.39	133.10

	r_2	0.97	81.74	82.71
Perturbation of +30% in each time delay				
Proposed	r_1	151.06	0.75	151.81
	r_2	0.16	72.75	72.91
Chen	r_1	163.43	0.45	163.88
	r_2	0.07	117.72	117.79
Shen	r_1	148.03	1.90	149.93
	r_2	1.37	83.77	85.14

From Figs. 3-5 and Table 3, we can see that the proposed technique has better robustness than the compared methods.

5. CONCLUSION

A simple effective method to design centralized PI controller for non-square system with multiple time-delays is investigated in this paper. By applying the IMC theory, we can get the desired closed-loop transfer function. Analytical expressions for PI controller, through the steady and dynamic information of the open-loop transfer function, are derived directly. Simulation examples for typical industrial processes demonstrate that the proposed controller design has relatively good control performance and robust performance.

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