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Dynamic interaction analysis and pairing evaluation in control configuration design ☆

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ABSTRACT

This paper presents some new dynamic interaction analysis approaches for square or non-square systems and a pairing evaluation method. For square stable systems, an open-loop approach is proposed, which features the tradeoff between the contributions of response time constant and delay time to relative gain. For non-square stable systems, an extension from the proposed open-loop approach for square systems is presented and the corresponding pairing procedure is given. No interaction analysis approach is perfect for all systems, so any recommended pairing needs to be examined. An evaluation method is proposed in closed-loop with optimal controllers for each loop and whether the pairing is appropriate can be evaluated through testing if the equivalent relative gain is within defined scope. The advantages and effectiveness of proposed interaction analysis approaches and pairing evaluation method are highlighted via several examples of industrial processes.

1. Introduction

In industrial processes, multi-input and multi-output (MIMO) systems are difficult to control due to the interactions within loops, while decentralized PID control remains dominant since it is easy for operation and maintenance. With decentralized control strategy, a MIMO system is always decomposed into multiple single-input and single-output (SISO) subsystems for which PID controllers are designed independently. However, the interactions between these subsystems exert profound influence on process control and cannot be ignored. Good control performance may not be achieved with stronger interactions between these subsystems. Therefore, the control configuration design, to determine pairing of manipulated (input) and controlled (output) variables to form multi-SISO-subsystems, is the primary problem for decentralized control system. Interaction analysis is the most extensive means to achieve this goal.

Interaction analysis focuses on measuring the extent of interactions within loops and provides the most reliable variable pairing. The relative gain array (RGA) has been widely used for interaction analysis since its introduction in 1966 by Bristol [1]. RGA shows advantages that it is dependent on process models only and independent of the scaling of inputs and outputs. With the consideration of the stability of decentralized control systems, the Niederlinski index (NI) is used in conjunction with the RGA based pairing rules [2,3]. However, using steady-state gain alone may result in incorrect interaction measures and consequently poor pairing decisions for RGA, since no dynamic information of the process is taken into consideration. To overcome the limitations of RGA method, several dynamic interaction analysis methods have been proposed.

Witcher and McAvoy proposed the relative dynamic array [4] and Gagnepain and Seborg proposed the average relative gain matrix [5] based on the integral of open-loop step response. Meeuse and Huesman proposed the dynamic RGA with closed-loop response based on the best achievable control performance using internal model control [6]. McAvoy *et al.* presented a new approach to define dynamic RGA [7], which assumes the availability of a state space model with proportional output optimal controller designed, and defines the dynamic RGA based on the controller gain matrix. Through defining the effective relative gain array (ERGA), Xiong *et al.* presented a new dynamic loop pairing criterion [8–11]. The elements of ERGA, which include both steady-state gain and bandwidth information of the open-loop transfer functions, can reflect the dynamic loop interactions under finite bandwidth control. He *et al.* proposed the relative normalized gain array (RNGA) as a complement to the RGA-NI loop interaction analysis method [12]. RNGA investigates both the steady-state gain and normalized the integrated error of outputs for interaction measurement and provides a more comprehensive description of loop interactions. Monshizadeh-Naini *et al.* defined the effective relative energy array based on the ERGA [13], each element of which is the product of squared zero frequency gain and bandwidth frequency to reflect the effective energy.

There also exist non-square systems extensively in industrial processes with unequal numbers of inputs and outputs [14,15]. The non-square structure brings new difficulties for control configuration design [16]. Most of the interaction analysis methods above cannot be directly applied in non-square systems. Chang and Yu have extended the RGA to non-square systems with more outputs than inputs [17]. The closed-loop gain is derived with the assumption of perfect

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control in least-square sense of which the control objective is to minimize the sum of square errors of all outputs. Then non-square RGA (NRGA) is derived. The system is first squared down, and then pairing is obtained based on the NRGA criterion. Reeves and Arkun have introduced non-square dynamic block relative gain and relative sensitivities as dynamic interaction measures that depend on the controller tuning, which are consequently applicable to the design of non-square decentralized controllers [18].

These interaction analysis methods including those proposed in this paper have their limitations and may not provide the best pairing result for all processes [19]. It is necessary to evaluate whether the recommended pairing result is suitable; if not, another loop pairing is needed. However, few literatures have reported the research on pairing evaluation.

In this paper, a new open-loop interaction analysis method for open-loop stable square system is introduced and corresponding pairing criterions are derived. More detailed analysis about non-square system and its main pairing problem are taken, and an interaction analysis method is utilized for obtaining proper pairing for non-square multivariable systems. Specific pairing evaluation method is introduced based on closed-loop dynamic relative gain.

2. An Open-loop Interaction Analysis Based on REGA

Using steady-state relative gains of RGA only may result in some incorrect interaction measures and consequently wrong loop pairing decision, since no dynamic information of the process is taken into consideration. A method providing overall evaluation for interactions between control loops is preferred, so a relative energy gain array (REGA) method is proposed here.

Relative gain should include both steady-state and dynamic information of loop interactions. For the interaction analysis method based on REGA, the steady-state information is extracted from the process steady-state gain and the dynamic information is extracted based on step response analysis.

For $n \times n$ system, we have transfer function matrix as below.

$$\begin{bmatrix} y_1(s) \\ y_2(s) \\ \cdots \\ y_n(s) \end{bmatrix} = \begin{bmatrix} g_{11}(s) & g_{21}(s) & \cdots & g_{n1}(s) \\ g_{12}(s) & g_{22}(s) & \cdots & g_{n2}(s) \\ \cdots & \cdots & \cdots & \cdots \\ g_{1n}(s) & g_{2n}(s) & \cdots & g_{nn}(s) \end{bmatrix} \cdot \begin{bmatrix} u_1(s) \\ u_2(s) \\ \cdots \\ u_n(s) \end{bmatrix} \tag{1}$$

For ij loop, we can rewrite the transfer function as

$$g_{ij}(s) = g_{ij}(0) \cdot \bar{g}_{ij}(s) \tag{2}$$

Thus the normalized output can be expressed as

$$\bar{y}_i(s) = \bar{g}_{ij}(s) \cdot u_j(s) \tag{3}$$

Here, the integrated square error criterion of step response is adopted to evaluate the process dynamics

$$\theta_{\mathrm{E},ij} = \int_0^\infty (\bar{y}_i(\infty) - \bar{y}_i(t))^2 \mathrm{d}t \tag{4}$$

where $\bar{y}_i(\infty)$ represents the final steady-state value of normalized output and $\theta_{\mathrm{E},ij}$ is defined as control energy consumption. Apparently, a small energy consumption value implies a fast dynamic response for output, while a large one indicates a slow process dynamic response. Generally, the original state is considered steady at $t = 0$ and $\bar{y}_i(0) = 0$. With the unit step input signal, the normalized output is shown in Fig. 1.

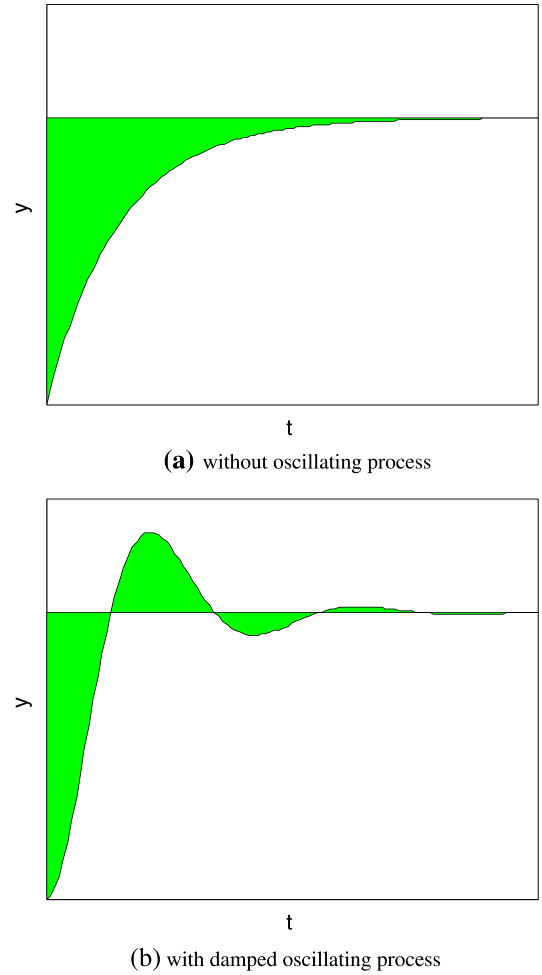

Fig. 1. The response curve of normalized output.

In Fig. 1 the square of the shaded area refers to the control energy consumption. For most industrial processes, the element of transfer function matrix can be described as first order plus delay time (FOPDT) model

$$g_{ij}(s) = \frac{k_{ij}}{T_{ij}s + 1} e^{-\tau_{ij}s} \tag{5}$$

or second order plus delay time (SOPDT) model

$$g_{ij}(s) = \frac{k_{ij}}{a_{2,ij}s^2 + a_{1,ij}s + 1} e^{-\tau_{ij}s} \tag{6}$$

When $g_{ij}(s)$ is described as FOPDT model or SOPDT model, $\theta_{\mathrm{E},ij}$ can be obtained as (Appendix A)

$$\theta_{\mathrm{E},ij} = \tau_{ij} + \frac{T_{ij}}{2} \tag{7}$$

or

$$\theta_{\mathrm{E},ij} = \tau_{ij} + \frac{a_{1,ij}^2 + a_{2,ij}}{2a_{1,ij}} \tag{8}$$

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