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IDENTIFICATION METHOD FOR SIMPLIFIED DECOUPLING CONTROL SYSTEM OF MULTIVARIABLE PROCESSES

PHƯƠNG PHÁP NHẬN DẠNG CHO HỆ THỐNG ĐIỀU KHIỂN PHÂN LY ĐƠN GIẢN HÓA CỦA CÁC QUÁ TRÌNH ĐA BIẾN

Vo Lam Chuong, Truong Nguyen Luan Vu
Ho Chi Minh City University of Technology and Education, Vietnam

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ABSTRACT

In this paper, a new method of system identification for a multivariable process is adopted to obtain system models from a pair of priori input/output data. Decoupling techniques are the suitable choice for most industrial processes wherein the interactions between process variables are significant. In this work, simplified decoupling is suggested for a two-input, two-output (TITO) process and then a method of controller design for multi-loop systems is proposed. A new analytical tuning method for a proportional-integral-derivative (PID) controller is also proposed for the second-order plus time delay (SOPTD) process model. The tuning parameters of the controller are calculated and simulated in Matlab. When the resulting PID characteristics confirm that the proposed controllers hold good responses, we implement the controller in real-time using PCI card to substantiate our proposed method in a real application.

Keywords**:** *Multiple input; multiple output (MIMO) control system; Identification method; Simplified decoupling; Reduced-order model; PID controller tuning.*

TÓM TẮT

Trong bài báo này, phương pháp nhận dạng hệ thống và quá trình đa biến được vận dụng để xác định mô hình thuật toán từ dữ liệu thực với việc ghép đôi tín hiệu vào và ra của hệ thống đa biến. Các kỹ thuật phân ly là sự chọn lựa phù hợp cho hầu hết các quá trình công nghiệp, trong đó tương tác bên trong của các biến quá trình là đáng kể. Trong nghiên cứu này, kỹ thuật phân ly đơn giản hóa được đề xuất cho các quá trình 2x2 cùng với phương pháp thiết kế thiết kế bộ điều khiển đa biến. Bộ điều khiển PID dạng phân tích được giới thiệu cho các quá trình bậc hai có thời gian trễ tiêu chuẩn. Các thông số điều chỉnh của bộ điều khiển được tính toán bằng qui luật điều chỉnh được đề xuất và sau đó hệ thống điều khiển được mô phỏng bằng phần mềm Matlab. Khi kết quả của bộ điều khiển PID chứng minh được có thể cung cấp đáp ứng tốt cho hệ thống điều khiển phân ly đa biến, nó sẽ được áp dụng trong thực tế ở chế độ thời gian thực thông qua card giao tiếp PCI.

Từ khóa: *Hệ thống điều khiển MIMO; Phương pháp nhận dạng hệ thống; Phân ly đơn giản hóa; Mô hình hạ bậc hệ thống; Điều chỉnh bộ điều khiển PID.*

1. INTRODUCTION

Multivariable processes are common in most industrial systems. However, control design of those encounters a large number of difficulties due to interactions between process variables. Advanced control strategies deal with that kind of problem by centralized and decentralized control [1], [2], [3]. The first one with a representative of model predictive control (MPC) that attracts many researchers because of its intuitive concepts and applicability to MIMO systems with constraints [4]. However, it is still complicated compared with the classical feedback controller. Therefore, the latter with decoupling techniques that allow us to use SISO controller design approaches is the appropriate choice for most industrial processes [5], [6], [7], [8].

Ideal, simplified and inverted decoupling are some of the widely used decomposition methods. In practice, the simplified decoupling is the favorite choice because of its simplicity of decoupling network, the unitary diagonal elements, and robustness [5], [7]. Another point of view is also considered when choosing the decoupling techniques, it is realizability with the three requirements of being stable, proper and causal [5]. To overcome this kind of issue, realizability, especially in the decoupled transfer function matrix which its elements are usually constituted by the sum of transfer functions with multiple time delays. Therefore, numerous approximation approaches or reduced-order models such as Laguerre expansion, Gaussian frequency domain, and coefficient matching (CM) were also proposed by many researchers [9], [10], [11]. The CM method is chosen in this work because of its simplicity and effectiveness for tuning a PID controller. An effective method of PI/PID controller design is then suggested for simplified decoupling control systems, where controller can be directly obtained in a general form [5], [12], [13].

The applicability and effectiveness of our proposed method is substantiated by a real model of a TITO process, a double-tank system. A system model needs to be obtained for the purpose of decoupling and tuning the controller. It is accomplished by using the empirical method of system identification with supporting of Ident Toolbox of Matlab [14], [15].

In general, the PID controller design has been frequently discussed in the huge literature, but the design of a simple and effective one for a MIMO system with the perfect improvement of performance has not been fully achieved for a variety of time-delay processes. Moreover, some controllers can provide good set-point response but poor disturbance response or inversely. Therefore, the present study is focused on tuning the PID parameters for decoupled systems in analytical form, and easy to implement in the practice with the excellent performance for both the regulatory and servo problems [5], [10], [12], [16].

This paper is organized as follows. Section 2 is briefly introduced the experimental model. The system identification is also discussed in this section. The simplified decoupling technique and PID controller design are presented in Section 3. In Section 4, all the results of evaluation of control algorithms are shown in simulation as well as real-time implementation. Finally, conclusions are given in Section 5.

2. SYSTEM IDENTIFICATIO

2.1. Experimental model

Fig. 1. *The experimental model of double-tank system*

The experimental model is a double-tank system where water is pumped by two centrifugal pumps into two series tank. The manipulated variables are two dc voltages (0÷10 VDC) which applied to the inverters to control the power of the two pumps and then manipulate flow rates of the inlet streams.

Figure 2 is a Pipe & Instrumentation Diagram (P&ID) that describes the operation of the system. The inlet streams with controlled flow rates (x_1, x_2). The level of each tank is measured by a sensor with standardized industrial voltage output, 0-10 VDC. The control unit of the system is constituted by a core i3-PC with a PCI card

6052E of National Instrument, and the control algorithms are implemented in Matlab with Real time Window Target.

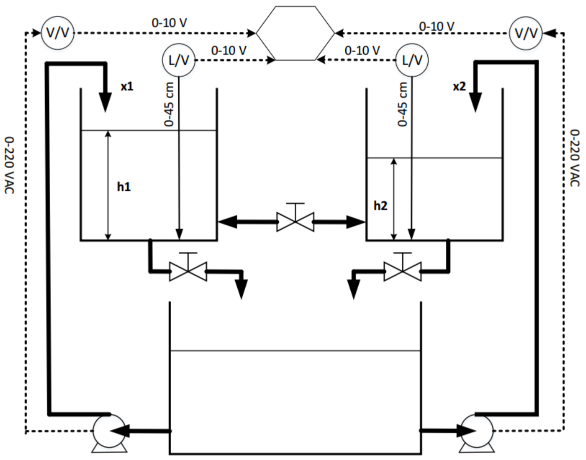


Fig. 2*. The Pipe & Instrumentation Diagram (P&ID)*

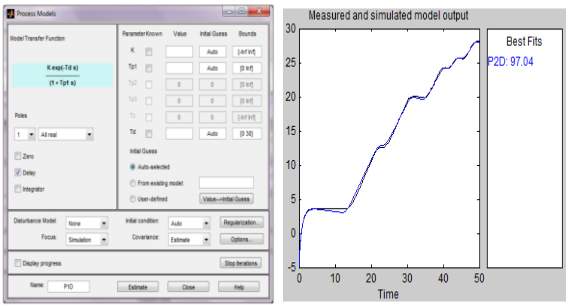
2.2. System identification

The PCI card is used for the data acquisition. From the figure 2, we perform the data acquisition by applying DC voltages from 0 to 10 and then measuring the level responses (h_1, h_2). These pairs of data are reserved and used for the system identification.

The Pseudo-Random Binary Signal (PRBS) is a periodic, deterministic signal. Its stochastic plays a quite crucial role in system identification [15]. In this paper, in order to identify the model of the system, we use a PRBS as a excitation signal. Number of data points collected are 2000 samples, wherein the first 1000 ones are adopted for identification, the others are used for the validation. The process model is chosen as the first/second order plus time delay for each pair of input and output. Our system is the two input, two output, therefore, we are supposed to have a 2x2 matrix of transfer functions

$$P(s) = \begin{bmatrix} P_{11}(s) & P_{12}(s) \\ P_{21}(s) & P_{22}(s) \end{bmatrix} \quad (1)$$

After several steps of trial and error, we draw out the transfer function of a pair of input/output. The other transfer functions could be obtained by the similar way.



(a) *(b)*

Fig. 3*. Choosing process model for each pair of input/output (a) and identification result (b)*

The transfer function of the input 1 (x_1) to the output 1 (h_1) is as follows:

$$P_{11}(s) = \frac{11.2e^{-0.65s}}{(160.99s+1)(0.42s+1)} \quad (2)$$

The final step of modeling, we justify the step response of the identified model and compare it with the actual response of the real system. From figure 4, we can see clearly that both responses have appropriate fit.

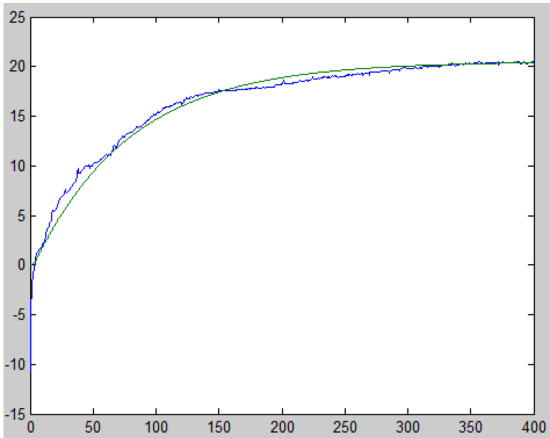


Fig. 4*. Step response of the actual model and the identified case.*

Similarly, we obtain the other transfer functions:

$$P_{12}(s) = \frac{0.92e^{-1.82s}}{(183.33s+1)(6.73s+1)} \quad (3)$$

$$P_{21}(s) = \frac{0.39e^{-1.85s}}{(140.4s+1)(5.12s+1)} \quad (4)$$

$$P_{22}(s) = \frac{10.84e^{-0.68s}}{(40.05s+1)(0.32s+1)} \quad (5)$$

3. DECOUPLING METHOD AND CONTROL DESIGN

The well-known block diagram of decoupling method of a TITO process is as figure 5. It is required to design a decoupler matrix D(s) so that P(s)D(s) is a diagonal matrix, T(s), where:

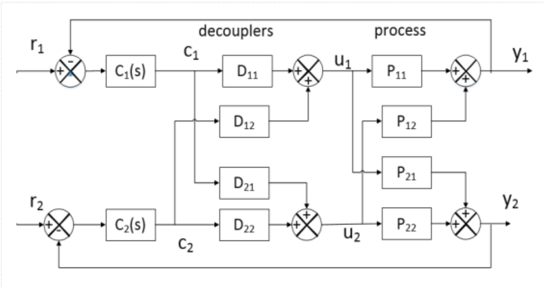


***Fig. 5**. Block diagram of a decoupler of a TITO process*

$$P(s)=\begin{bmatrix} P_{11}(s) & P_{12}(s) \\ P_{21}(s) & P_{22}(s) \end{bmatrix} \tag{6a}$$

$$D(s)=\begin{bmatrix} D_{11}(s) & D_{12}(s) \\ D_{21}(s) & D_{22}(s) \end{bmatrix} \tag{6b}$$

$$T(s)=P(s)D(s)=\begin{bmatrix} T_{11}(s) & 0 \\ 0 & T_{22}(s) \end{bmatrix} \tag{6c}$$

In the case of a simplified decoupler, which its most advantage is the simplicity of its element, we arbitrarily assign D_{11} = D_{22} = 1. In order to make the off-diagonal elements of the decoupled transfer function matrix equal to zero, we find out the other elements of the decoupler matrix:

$$D_{12}(s)=-\frac{P_{12}(s)}{P_{11}(s)} \tag{7a}$$

$$D_{21}(s)=-\frac{P_{21}(s)}{P_{22}(s)} \tag{7b}$$

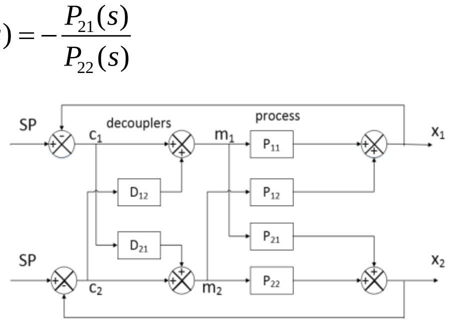


***Fig. 6**. Block diagram of a simplified decoupler of a TITO process*

This lead to the simpler decoupler transfer function:

$$T(s)=\begin{bmatrix} P_{11}-\dfrac{P_{12}P_{21}}{P_{22}} & 0 \\ 0 & P_{22}-\dfrac{P_{12}P_{21}}{P_{11}} \end{bmatrix} \tag{8}$$

In this study, the PI/PID tuning rules proposed by Vu and Lee (2013) are used for decoupled system because of its simplicity, robustness, and effectiveness [5]. From this method, we obtain the analytical form in a general formula of the controller:

$$g_{ci}(s)=\frac{C_{ii}}{|P|}\left(\frac{e^{-\theta_{ii}s}}{(\lambda_i s+1)^{m_i}-e^{-\theta_{ii}s}}\right) \tag{9}$$

where,

$$C(s)=\begin{bmatrix} C_{11}(s) & 0 \\ 0 & C_{22}(s) \end{bmatrix}=\begin{bmatrix} P_{22}(s) & 0 \\ 0 & P_{11}(s) \end{bmatrix} \tag{10}$$

The θ_{ii} denotes the time delay of *i*-th diagonal element of the process transfer function matrix. The time constant, λ_i, is an adjustable parameter that controls the tradeoffs between performance and robustness; m_i is the relative order of the numerator and denominator in $P_{ii}(s)$. $|P|$ is the determinant of transfer matrix P.

Using the identified models Eq. (2) - Eq. (5) to replace into Eq. (8), we realize that the obtained diagonal transfer matrix T(s) is complex since its elements are the sum of transfer functions with multiple time delays. Then if we adopt these for control design which makes it difficult for controller tuning. Therefore, we suggest an approximation method to overcome this issue. The coeffient matching (CM) approach, proposed by Vu and Lee (2010) [12], is chosen and extended to reduce order of decoupler elements:

$$P_{11}(s)=\frac{11.2e^{-0.65s}}{(160.99s+1)(0.42s+1)} \tag{11}$$

$$P_{11}(s)=d_{11}^{eff}\approx a_{11}\left(1+\frac{b_{11}}{a_{11}}s+\frac{c_{11}}{a_{11}}s^2\right)+O(s^3) \tag{12}$$

where,

$$a_{11} = d_{11}^{eff}(0) = 11.2 \quad (13)$$

$$b_{11} = \left. \frac{dd_{11}^{eff}(s)}{ds} \right|_{s=0} = -339.438 \quad (14)$$

$$c_{11} = \left. \frac{1}{2}\frac{d^2 d_{11}^{eff}(s)}{ds^2} \right|_{s=0} = 5190 \quad (15)$$

Similarly, we obtain the reduced-order models:

$$P_{11}(s) \approx 11.2 - 339.438s + 5190s^2 \quad (16)$$

$$P_{12}(s) \approx 0.92 - 63.011s + 2967.3s^2 \quad (17)$$

$$P_{12}(s) \approx 0.39 - 222.011s + 31205s^2 \quad (18)$$

$$P_{22}(s) \approx 10.84 - 85.008s + 3921.2s^2 \quad (19)$$

Then, from equation Eq. (10), we have

$$C_{11}(s) = P_{22}(s) \approx 10.84 - 85.008s + 3921.2s^2 \quad (20)$$

$$C_{22}(s) = P_{11}(s) \approx 11.2 - 339.438s + 5190s^2 \quad (21)$$

It is also selected as:

$$\theta_{11} = \theta_{P_{11}} = 0.65;\ \ \lambda_1 = \lambda_{P_{11}} = 160.99;\ \ \mathrm{m}_1 = 2 \quad (22)$$

$$\theta_{22} = \theta_{P_{22}} = 0.68;\ \ \lambda_2 = \lambda_{P_{22}} = 40.05;\ \ m_2 = 2 \quad (23)$$

Expanding $g_{c1}(s)$ as a Maclaurin series yields:

$$g_{c1}(s) \approx \frac{1}{s}(0.98 + 5.422s + 0.046s^2) \quad (24)$$

In the otherwise, the standard form of a PID controller

$$g_c(s) = \frac{1}{s}(K_i + sK_c + s^2 K_d) \quad (25)$$

It is noted that K_i, K_c, K_d represent the integral, propotional and derivative terms of the standard PID controller, respectively.

Comparing Eq. (24) with Eq. (25) yields the resulting PID controller parameters for the first control loop:

$$K_{i1} = 0.98;\ \ K_{c1} = 5.422;\ \ \mathrm{K}_{d1} = 0.046 \quad (26)$$

Similarly, we obtain the controller parameters of the second control loop:

$$K_{i1} = 0.64;\ \ K_{c1} = 2.078;\ \ \mathrm{K}_{d1} = 0.034 \quad (27)$$

4. RESULTS AND DISCUSSION

4.1. Simulation

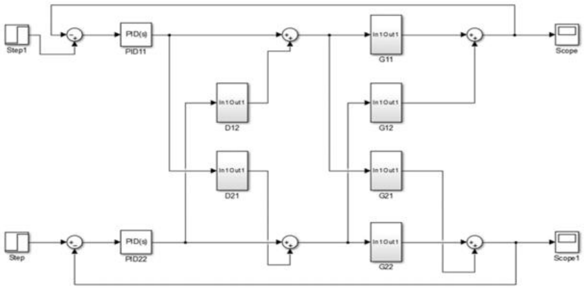


Fig. 7. *Simulation program in Simulink/Matlab*

Using identified models Eq. (2) - Eq. (5), simplified decoupler Eq. (7) and the PID controller parameters for the two control loop as shown at Eq. (26) and Eq. (27), we create a simulink program in Matlab to justify responses of the system adopting our proposed method.

The step responses of the level output of two tanks as Fig. 8.

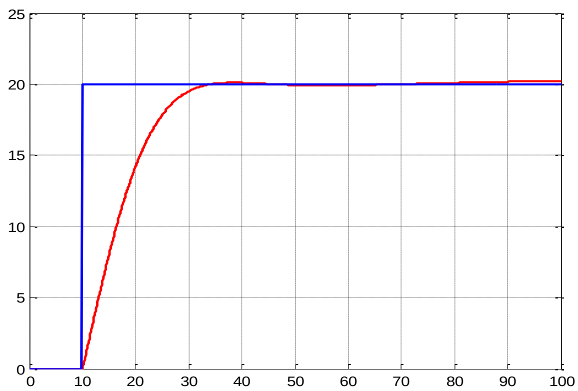


Fig. 8. *Step response of the level of tank 1 in simulation*

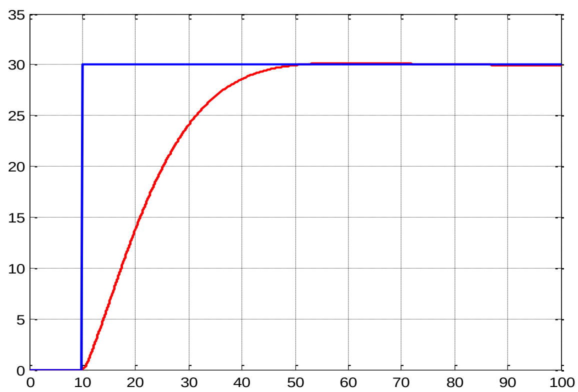


Fig. 9. *Step response of the level of tank 2 in simulation*

The simulation results indicate that the proposed method consistently affords more advanced performance with a fast and well-balanced closed-loop time response in both tanks.

4.2. Implementation

After that we implement the controller into the real model as Fig. 10.

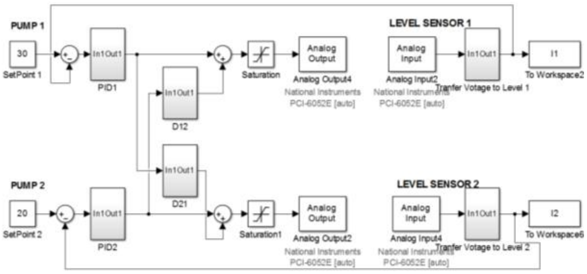


Fig. 10*. Implementing the controller into the real model*

These parameters Eq. (26) and Eq. (27) are incorporated into the simulink that runs in the real model using Real Time Window Target of Matlab software. Figure 11 and 12 show the responses of the system in both tanks.

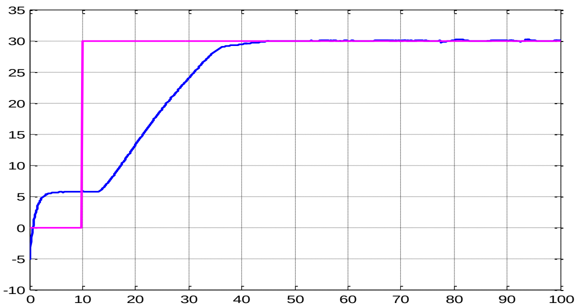


Figure 11. *Step response of level of tank 1 in real model*

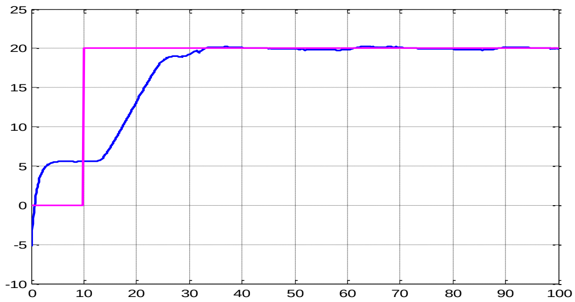


Fig. 12*. Step response of level of tank 2 in real model*

5. CONCLUSION

In this work, an empirical method of system identification for a multivariable process is proposed to obtain the transfer function matrix of the double-tank system. The decentralized approach is considered with simplified decoupling technique owing to its realizability. However, the decoupled system is still complicated for controller design. Therefore, a reduced-order method, CM method, is also applied to obtain a polynomial for easy calculation. The analytical form of the controller is drawn out and its parameters are obtained based on Maclaurin series expansion. The results show that all proposed methods have good responses in simulation as well as in the real model.

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Corresponding Author:
Assoc. Prof. Dr. Truong Nguyen Luan Vu
Ho Chi Minh City University of Technology and Education, Vietnam
Email: vuluantn@hcmute.edu.vn