CHEMICAL ENGINEERING TRANSACTIONS
VOL. 62, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Fei Song, Haibo Wang, Fang He

ISBN 978-88-95608- 60-0; **ISSN** 2283-9216
DOI: 10.3303/CET1762032

A Closed-loop Identification Method based on AIC and Its Application in the Distillation Column Reactor of Ethanol-Water System

Yimin Zheng[*a,b], Guoli Ji[a], Zhuoyun Nie[b], Jiansheng Guan[a]

[a] School of Aerospace Engineering, Xiamen University, Xiamen 361005,China.
[b] College of Information Science and Engineering, Huaqiao University, Xiamen 361021,China.
zh_even@sina.com

Considering process with time delay and limitations of traditional closed-loop identification methods, a new closed-loop identification method based on Akaike's information criterion (AIC) was proposed. Firstly, the time delay term is approximated by first-order Padé and the equivalent closed-loop transfer model structure of closed-loop system is calculated. Secondly, the actual closed-loop transfer function model was identified by open-loop identification methods (e.g. ARX). Here, a method to select model structure in determination of discrete identification based on AIC was put forward. The high-order discrete model structure which is determined by this method has high identification accuracy. Finally, the equivalent closed-loop transfer function which is similar with first-order Padé and is gained from after transformation and reduction of the high-order discrete model owns an identification model with same structure. Hence, solving methods of process parameters could be deduced by coefficient of same power and two typical time delay process. It achieves satisfying identification effect in the closed-loop system identification of temperature and liquid level in distillation column reactor of ethanol -water system.

1. Introduction

System identification is an effective way to gain system model. It has been one of the most active research fields in automatic control. In industrial control, it is difficult to gain mathematical models of research process (e.g. distillation column in industry) by existing theories, because they generally have complicated internal mechanisms (Kaymak et al., 2017). Instead, mathematical models of research process can only be determined by observation data. In-situ feature test is a simple way to acquire the control model. The simulation experiment can be simplified and dynamic characteristics of research process can be studied firstly by the identification method (Larsson et al., 2016).

Open-loop and closed-loop identification methods are widely used in actual industry. The least square method which is used mostly in engineering practice is characteristic of consistent estimation of process parameters (Shardt and Huang, 2015). Some industrial processes which are running actually can cut the feedback loop simply, or it will affect production significantly. Therefore, closed-loop identification method is one of main research directions of system.

In traditional closed-loop identification method, input signal is generally selected from controller output. This often needs some additional conditions to be used in closed-loop identification. Isermann stated that if the feedback channel model is known, the model order of the feedback channel must be higher than that of the forward channel and the feedback channel must own adequate orders of persistently exciting signal to identify the forward channel, so that estimation of forward channel parameters is consistent (Isermann and Münchhof, 2011). Yuchai Zhu studied the closed-loop identification effect when the input sampling time is different from output sampling time by using non-uniform sampling time in traditional closed-loop identification method (Fang et al., 2017). There are a number of research efforts concerning the use of a reactive distillation for identification (Komkrajang et al., 2014).

Please cite this article as: Yimin Zheng, Guoli Ji, Zhuoyun Nie, Jiansheng Guan, 2017, A closed-loop identification method based on aic and its application in the distillation column reactor of ethanol-water system, Chemical Engineering Transactions, 62, 187-192 DOI:10.3303/CET1762032

The proposed closed-loop identification method is different from traditional ones. Given a controller model, the closed-loop system can be approximated by the equivalent closed-loop transfer function model, so that the open-loop identification method can be used in the closed-loop identification. Firstly, the equivalent closed-loop transfer function of the closed-loop system can be identified by open-loop identification method. Secondly, the parameter model of actual process is deduced. Since it is impossible to get the analytic expression of equivalent closed-loop transfer function when there's pure time delay process, a reduced order closed-loop identification method based on AIC was proposed.

2. Closed-loop identification method based on AIC

Based on above mentioned limitations in actual engineering applications, a new closed-loop identification method was proposed in this study. A continuous closed-loop system which is equivalent to the open-loop system in Figure 1.

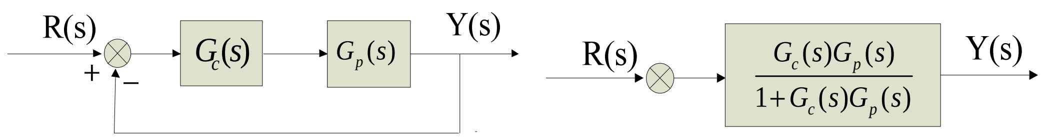


Figure 1: (a) Closed-loop system and (b) Equivalent closed-loop system Φ(s)

In Figure 1, $G_c(s)$ is the controller, $G_p(s)$ is the process, R(s) is the input signal and Y(s) is the output signal. The equivalent closed-loop transfer function Φ(s) In Figure 1(b) can be identified firstly by the open-loop identification method. The model of the identified closed-loop transfer function is recorded as Φi(s), it covers the controller model $G_c(s)$ which is often known. If the model structures (orders) of Φ(s) and Φi(s) are same, the parameter of the process $G_p(s)$ can be deduced by the coefficients of same power of Φ(s) and Φi(s), However, Φ(s) doesn't use the analytical expression because of influences of pure delay time τ in process. Here, the pure time delay term in process (e-τs) can be expanded by the k-order Padé approximation model, is shown in Eq(1).

$$P_{k,\tau}(s)=\frac{1-\tau s/2+p_2(\tau s)^2-p_3(\tau s)^3+\cdots+(-1)^{n+1}p_n(\tau s)^k}{1+\tau s/2+p_2(\tau s)^2+p_3(\tau s)^3+\cdots+p_n(\tau s)^k} \tag{1}$$

Since the closed-loop transfer function structure is complicated, the e-τs can be approximated by first-order Padé in the equation (1), which is shown in Eq(2). Then the equivalent closed-loop transfer function is recorded as $\Phi_a(s)$.

$$e^{-\tau s}\approx\frac{-\tau s+2}{\tau s+2} \tag{2}$$

Since the high-order Padé approximation in Eq(1) has good approximation to actual process, it is recommended to using high-order identification model in order to increase identification accuracy. As a result, higher-order model with higher identification accuracy shall be selected firstly and then reduced to $\Phi_i(s)$, $\Phi_i(s)$ and $\Phi_a(s)$ shall have the same model structures. Finally, the process model can be deduced from coefficients of same power in $\Phi_i(s)$ and $\Phi_a(s)$, because the continuous system identification is not very satisfying and even unstable, indirect method can be used to identify the high-order discrete model firstly and then convert it into the high-order model of a continuous system.
Before identification of the discrete closed-loop system ($G_\Phi(z^{-1})$), some basic hypotheses shall be determined. Firstly, suppose n, m and d which represent the model structure (orders) of the closed-loop system are known. According to above analysis, process with time delay term $e^{-\tau s}$ shall be recognized by using high-order model. Therefore, it has to determine n, m and d of the high-order model before discrete identification. In this study, a new method to select identification model orders based on AIC is proposed. Specifically, the delay steps (d) can be identified under the influence of input signal. If the observed output signal is at step N, it can get non-zero values or violent changes of steady state value of output signal ratio at step N are observed, d<N. Next, appropriate orders of the model shall be determined according Akaike's information criterion (AIC) (Akaike, 2014), Definition of AIC is shown in Eq(3).

$$AIC = \lg\left\{\det\left[\frac{1}{L}\sum_{i=1}^{M}\in(i,\theta)\in^{T}(i,\theta)\right]\right\} + \frac{k}{L} \quad (3)$$

Where L is the array of test data, θ is an identification parameter, and k is number of identification parameters. It can prove that when AIC=min, the corresponding model order is a relatively reasonable model structure. If the calculated AIC is small than (<-20), error might be corresponding to 10^{-10} of the loss function. Under this circumstance, n, m and d can be viewed as appropriate orders in discrete identification.
The closed-loop identification method based on AIC for two typical process is shown in Figure 2

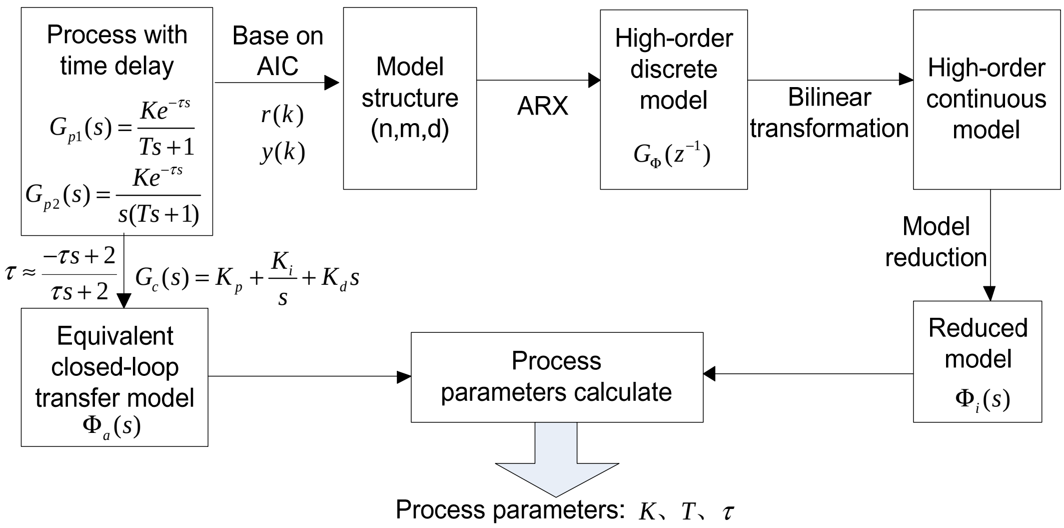


Figure 2: Closed-loop identification method based on AIC

3. Distillation process identification in the distillation column reactor

The distillation apparatus of ethyl alcohol is shown in Figure 3(a). This system distills the ethyl alcohol and water mixture (10% ethyl alcohol) to industrial ethyl alcohol with a purity of 95%. The hardware structure is composed of site equipment and DCS control station. Equipment includes distillation column, charging stock tank, product tank, reflux tank, raw material tubular heat exchanger and tubular condenser at top. The overall structure is shown in Figure 3(b).
Since the overall structure of the distillation column is complicated, the distillation column reactor model is identified firstly in this experiment. It is a multi-variable system which has two inputs and two outputs. One controlled variable is the reactor temperature (y_1). The executor is the reactor heater H101 which is a single-phase silicon controlled rectifier (SCR) voltage regulator. To maintain stability of the distillation process, the working point of reactor temperature ($97^{O}C$) must be kept stable. Feed flow and reflux at top tank are main influencing factors of the reactor temperature. Another controlled variable is liquid level in the reactor (y_2). The executor is the feed metering pump P105. The residual metering pump P104 return residual liquid to the heater and pre-heat the feeding liquid, thus saving energies. To maintain continuous feeding, the working point of liquid level is 40cm, which can distill products to the maximum extent, but avoid reactor drying and dry burning of the heating wire.
Heating furnace in the reactor is a typical temperature process. This process is a typical control process with pure time delay. The transfer function of this process can be described approximately as $G_{P1}(s)=Ke^{-\tau s}/(Ts+1)$. In the liquid level control loop, residual return from the reactor to the heater is controlled by a metering pump. Since the raw material tubular heat exchange has pure time delay τ, the model can be described by a typical single volume process without inherent regulation $e^{-\tau s}/Ts$. Here, influences of volatilization of light components in ethyl alcohol and water vapor as well as the reflux from top tank on the liquid level under the working temperature point ($97^{O}C$) shall be taken into account. Here, one first-order sub-derivation pole approximation is added in this model. Therefore, the process transfer function of liquid level can be described approximately as $G_{P2}(s)= Ke^{-\tau s}/s(Ts+1)$.

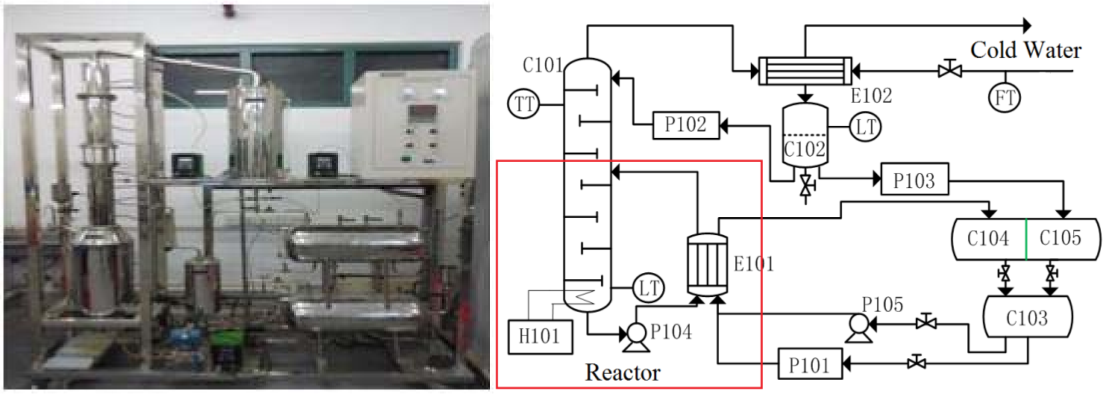


Figure 3: (a) Experimental apparatus of distillation column and (b) Overall structure of site equipment

The feedback loop couldn't be cut simply during the identification process of distillation column reactor, or it will lose control over the process. Hence, the identification must be carried out under closed-loop state. In this experiment, the closed-loop system identification steps under the pseudo random M sequence of the known input signal are:

(1) Selection of sampling time: sampling time was chosen $T_{95}/(5\sim15)$, where T_{95} is the transition time when the system step response reaches 95% steady value. Based on real model curves in Figure 5, sampling time for temperature and liquid level can be determined 10sec and 5sec, respectively.

(2) Selection of the input M sequence: the parameter N_p (M sequence period) and sampling time T must meet the Eq (4), where f_{max} is the highest working frequency of the system and T_s is the transition time of the system. Amplitude of M sequence shouldn't be too large or too small in order to ensure signal-to-noise ratio (SNR), in Figure 4.

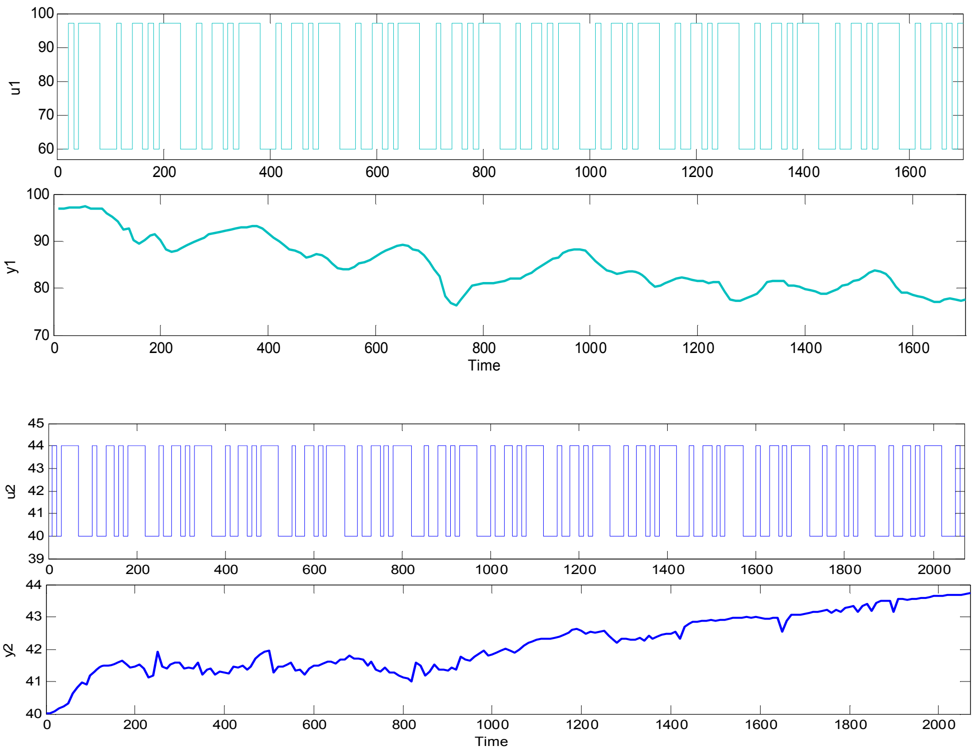


Figure 4: (a) Input and output data of temperature in distillation column reactor and (b) Input and output data of liquid level in distillation column reactor

$$\begin{cases} \dfrac{1}{3T} \geq f_{\max} \\ (N_P - 1)T > T_s \end{cases} \tag{4}$$

(3) This identification method uses ARX model. The model structure is shown in Eq (5), where $G_\Phi(z^{-1})$ is the discrete closed-loop system for identification.

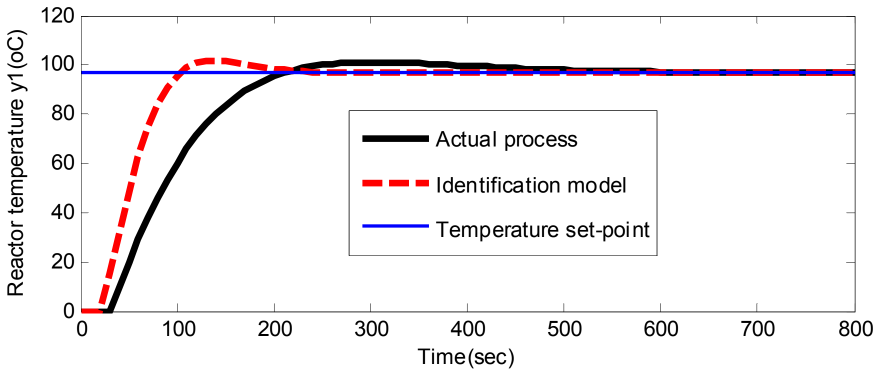
$$y(k) = G_\Phi(z^{-1})u(k) + \varepsilon(k) \tag{5}$$

The closed-loop identification of distillation column reactor of ethanol-water system uses the method in Section 2. The approximation models of temperature and liquid level can be calculated from coefficients of terminal closed-loop identification model (reduced model) and PID parameters, in Table 1.

Table 1: Identification parameters of temperature and liquid level in distillation column reactor

Loop	PID parameters	Model structure	Reduced model $\Phi_i(s)$	Process with parameters: K, T, τ
temperature	K_p=0.2 k_i=0.01	n=m=5 d=2	$\dfrac{0.0001399s^2 + 0.000009104s + 0.000007331}{s^3 + 0.06483s^2 + 0.003668s + 0.000007432}$	$G_{p1}(s) = \dfrac{2.02e^{-20s}}{27.18s + 1}$
Liquid level	K_p=0.1 k_d=0.05	n=m=6 d=2	$\dfrac{-0.002673s^2 - 0.0005027s + 0.00004028}{s^3 + 0.3387s^2 + 0.03465s + 0.00003746}$	$G_{p2}(s) = \dfrac{0.378e^{-10s}}{s(7.07s + 1)}$

Curves of the identification model and temperature and liquid level control curves which are collected by actual distillation column reactor under the same group of PID parameters are shown in Figure 5. The identification model has certain error with actual model, but it can reflect dynamic performance of the system well. It can provide approximate model for subsequent control studies (e.g. decoupling control and adaptive control) of distillation column.



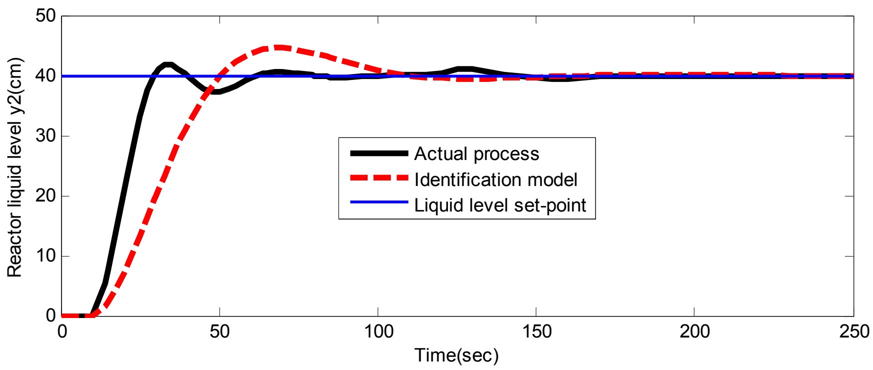


Figure 5: (a) Step response of temperature in the distillation column reactor and (b) Step response of liquid level in the distillation column reactor

4. Measurement units, numbers Conclusions

The closed-loop identification method based on AIC for process with pure time delay has certain universality. It is applicable to closed-loop identification of process with pure time delay and great inertia. In this study, identification methods and steps for two typical process structures are summarized. They are characteristic of strong identification, convenient input design, simple solving method of process parameters and high identification accuracy compared to traditional ones. It possesses strong engineering practices.it is used to experimental study of a distillation column reactor, identifying approximate models of temperature and liquid levels successfully. These two models can reflect dynamic characteristics of actual process well. The proposed method can provide appropriate control model for subsequent study of other control programs of the distillation column.

Reference

Akaike H., 1974, A new look at the statistical model identification, IEEE Transactions on Automatic 19(6), 716-723, DOI: 10.1109/tac.1974.1100705

Fang M., Zhu Y., 2017, Analysis of over-sampling based identification, Automatica, 79, 101-107, DOI: 10.1016/j.automatica.2017.01.006

Isermann R., Münchhof M., 2011, Identification of dynamic systems, an introduction with application, Springer-Verlag, Berlin Heidelberg, DOI: 10.1007/978-3-540-78879-9

Kaymak D.B., Ünlü H., 2017, Control of a reactive distillation column with double reactive sections for two-stage consecutive reactions, Chemical Engineering and Processing, 113, 86-93, DOI: 10.1016/j.cep.2016.09.010

Komkrajang T., Kheawhom S., Paengjuntuek W., Arpornwichanop A., 2014, Design of model predictive control for butyl acetate production in reactive distillation, Chemical Engineering Transactions, 39, 427-432, DOI:10.3303/CET1439072.

Larsson C.A., Ebadat A., RojasC.R., Bombois X., Hjalmarsson H., 2016, An application-oriented approach to dual control with excitation for closed-loop identification, European Journal of Control, 29, 1-16, DOI: 10.1016/j.ejcon.2016.03.001

Shardt Y.A.W, Huang B., 2015, Minimal required excitation for closed-loop identification: Some implications for data-driven system identification, Journal of Process Control, 27, 22-35, DOI: 10.1016/j.jprocont.2015.01.009