Research on Closed-Loop Identification of Time-Delay Systems Based on High-Frequency Test Signals

Lijie Wang, Shuzhong Song, Jingtao Huang and Wenbo Zhang

ABSTRACT

To get the accurate identification of time delay in closed-loop control systems widely existing in industry processes, a method is presented by using the auto regressive exogenous (ARX) model with high frequency test signals. The mean filtering is applied on the sampled data to eliminate the effects of the colored noise existed in the data. Simulation results show that the proposed method can obtain the system time delay effectively. Furthermore, to evaluate the performance of the proposed method in physical systems, a closed-loop control system of single-tank with obvious time-delay is constructed. The influences of white noise test signals with different frequencies on the identifiability of closed-loop systems are discussed. The results on experimental data show that the proposed method can effectively identify the time delay based on closed-loop data.

INTRODUCTION

Time-delay systems are widely found in industry processes, the system control performance cannot be guaranteed with unknown time delay. This issue has attracted much attention of academia and industry, as [1, 2], the academic community proposed the topic of parameter identification of closed-loop system. Achieving accurate estimation of time delay can contribute to realize the precise control, and help maintaining the product quality, ensuring production safety, reducing materials and energy cost.

Time-delay identification has been widely discussed. Liu et al., as [3], used the threshold orthogonal matching pursuit algorithm to estimate the system parameters

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and the amount of time delay of the MISO-FIR model with unknown time delay. However, this method requires to know the input order of the system when identifying the time delay. Yang et al., as [4], used the reorganized innovation analysis approach to study the optimal estimation problem of networked control systems with bounded random measurement delays. To solve the problem of time-delay estimation in industry without known information about the system, the ARX model is used to estimate the time delay based on closed-loop sampled data with high frequency test signals. A closed-loop control system of single-tank with obvious time-delay is constructed to verify the feasibility and accuracy of the proposed method.

SYSTEM DELAY PARAMETER IDENTIFICATION METHOD

As well known, the amount of delay in a closed-loop system usually cannot be estimated from the process data without external excitation or mutation, as [5]. Therefore, it is necessary to implement an appropriate test signal on the system to increase the identifiability of the closed-loop system data with minimal effects of additional interference on the system. Reference [6] analyzed the influences of different types of test signals on the identification results of closed-loop system. The results showed that high-frequency test signals or white-noise test signals can effectively improve the identifiability of closed-loop system data. In this paper, the white-noise test signal is used for time delay identification experiments. The closed-loop process data is obtained as in Fig. 1, where C(z) denotes the controller, G(z) denotes the process, uopt(t) is the white-noise test signal used to estimate the delay and e(t) is the noise. The high-order ARX model is used to estimate the amount of delay.

Figure 1. Closed-loop system structure.
The high-order ARX model is shown as Eq. (1):

\[ A_N^m(z)y(t) = B_N^m(z)u(t) + e(t) \]  

where \( m \) is the order of the model, \( N \) is the total number of samples, \( A_N^m(z) = 1 + a_1 z^{-1} + \cdots + a_m z^{-m} \), and \( B_N^m(z) = b_1 z^{-1} + b_2 z^{-T_d + 1} + b_{T_d + 1} z^{-T_d} + \cdots + b_m z^{-m+1} \).

Then Eq. (1) can be expressed as Eq. (2):

\[ y(t) = R(t)Q + e(t) \]  

where

\[ R(t) = \begin{bmatrix} u(t), \ldots, u(t-m+1), -y(t-1), \ldots, -y(t-m) \end{bmatrix} \]

\[ Q = \begin{bmatrix} b_1, \ldots, b_{T_d}, \ldots, b_m, a_1, \ldots, a_m \end{bmatrix}^T. \]

\( Q \) can be estimated by the least squares method as Eq. (3):

\[ \hat{Q} = \left( \sum_{t=1}^{N} R(t)R(t)^\top \right)^{-1} \left( \sum_{t=1}^{N} R(t)y(t) \right) \]  

If \( e(t) \sim N(0, \lambda^2) \), the estimated delay covariance should also fit Gaussian distribution. The covariance matrix of \( \hat{Q} \) is \( \Sigma = \text{cov}(\hat{Q}) \).

Therefore, \( Z_d \) can be selected as a statistics shown in Eq. (4), and \( Z_d \sim \chi^2(d) \):

\[ Z_d = \hat{Q}_D^\top \Sigma_D^{-1} \hat{Q}_D \]  

Based on the simulation, 99% confidence level is a good choice for time delay identification. As shown in Table 1, the thresholds of different dimensions at 99% confidence are determined by \( \chi^2 \) distribution.

The delay \( T_d \) can be known by comparing the value of \( \alpha_d \) and \( Z_d \) at different dimensions, as Eq. (5). Assuming that a system has five sampled-delay, \( d \) is from 2 to 5, \( Z_d \) is less than \( \alpha_d \); when \( d \) is from 6 to \( m \), \( Z_d \) is greater than \( \alpha_d \).

\[ T_d = k, \text{iff} Z_k < \alpha_k \text{ and } Z_{k+1} > \alpha_{k+1}, \quad k = 1, \ldots, m. \]
EXPERIMENTS AND RESULTS ANALYSIS

In order to study the identification effect of the proposed method on the actual system, a typical first-order inertia system single-tank is designed, as shown in Fig. 2 (only connecting and controlling the tank in the upper right of the figure), the structure of system is shown in Fig. 3. The flow meter is used to measure the flow rate of the inlet of the water tank, the drain tank is used to simulate the time-delay in the actual system, and the level sensor is used to measure the water level. The system is tested for time-delay and the timing is known to be 6 s.

<table>
<thead>
<tr>
<th>Dimension $d$</th>
<th>Threshold $\alpha_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.635</td>
</tr>
<tr>
<td>2</td>
<td>9.210</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>44</td>
<td>68.710</td>
</tr>
<tr>
<td>45</td>
<td>69.957</td>
</tr>
</tbody>
</table>

Figure 2. The physical device of the system.  
Figure 3. Structure of the system.
As shown in Fig. 4 and Fig. 5, the process data without test signals is obtained by data recording device. Owing to the influence of hardware devices and external interference, the collected data contains noise components, and such data is difficult to be directly used for identification of time-delay, as [7, 8]. The mean filtering is applied on the sampled data to eliminate the effects of the colored noise existed in the data, as [9, 10]. The processed data with mean filtering is shown in Fig. 6, and as shown in Fig. 7, the system delay cannot be estimated by the proposed methods.
In order to demonstrate and compare the effects of test signals with different frequencies on the identification results, white-noise test signals with frequencies of 200 Hz, 1 kHz and 9.6 kHz are added on the system respectively. The obtained identification results are shown in Fig. 8-Fig. 10. Adding three types of test signals on the system, the delay can be accurately estimated by the proposed ARX model. However, comparing the identification results, the result of Fig. 10 is more reliable, because there exists a noticeable rise between $d=6$ and $d=7$.

**CONCLUSIONS**

This paper mainly focuses on the time delay identification in closed-loop control system, and the identification performances of adding white-noise test signals with different frequencies are discussed. The experiment results show that the identifiability of the closed-loop system data can be improved, especially by adding the high-frequency signal. The time-delay of actual system can be accurately estimated from closed-loop sampled data by using the proposed method of high order ARX model with appropriate test signal. Therefore, when solving the time delay system control with unknown delay, the proposed method can identify the time-delay effectively.

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**REFERENCES**