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Discrete-time frequency response identification method for processes with final cyclic-steady-state

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ABSTRACT

A new non-parametric process identification method is proposed to obtain the discrete-time frequency response model from the process input and output data. The existing discrete-time Fourier transform approach can be applied to only the case that the initial part and the final part of the process data are zero-steady-state to estimate perfect frequency response data without modeling errors. The proposed method using a new transform can estimate the exact frequency response model from more various process excitation cases including initial-steady-state/final-steady-state and initial-steady-state/final-cyclic-steady-state. It can estimate exact frequency response model because no approximations are used in developing the proposed algorithm. Also, the proposed method can still provide exact model even in the case of static disturbances and sinusoidal disturbances of which the frequencies are multiples of the cyclic-steady-state frequency.

1. Introduction

Nonparametric process identification methods to estimate frequency responses can be categorized into two types of continuous-time approach and discrete-time approach. In recent years, a number of new continuous-time nonparametric process identification methods have been developed while no remarkable progress in discrete-time nonparametric process identification methods has been achieved.

The describing function analysis method has been widely used to identify the ultimate frequency response from the relay feedback signal [1–5]. The method was derived by neglecting the harmonics of the Fourier series and approximating the process signal to the fundamental term. It shows serious modeling errors for asymmetric signals because of the approximation. The Fourier analysis method can overcome the inaccuracy problem of the describing function analysis [6]. But, the describing function analysis and the Fourier analysis can provide only one or two frequency response data for the relay feedback signal. To overcome the weakness, several improved versions of continuous-time nonparametric process identification methods have been developed [7–13]. Luyben proposed a modification of the continuous-time Fourier transform to estimate the frequency responses of continuous-time processes of which the initial part is zero-steady-state and the final part is nonzero-steady-state [7]. Although it can provide all the frequency responses of the process without errors, it is valid only in the case that the initial part and the final part of the process are steady-state. Two nonparametric continuous-time process identification algorithms applicable to the case of zero-initial-steady-state and final-cyclic-steady-state were developed [8,9]. Recently, remarkable continuous-time process identification methods [10–13] were proposed. They can theoretically extract all the frequency responses of the process and provide exact estimates. Moreover, it can be applied to all the three types of process excitation of initial-steady-state/final-steady-state, initial-steady-state/final-cyclic-steady-state and initial-cyclic-steady-state/final-cyclic-steady-state.

Note that all the above-mentioned approaches [1–13] are for continuous-time processes. Until now, many application studies using the classical discrete-time Fourier transform have been published [14–23]. But, no novel nonparametric process identification methods for discrete-time processes applicable to all the cases of initial-steady-state/final-steady-state, initial-steady-state/final-cyclic-steady-state can estimate perfect frequency response data without any modeling errors from the theoretical point of view. The existing discrete-time Fourier transform approach [23] in system identification and control textbooks can be applied to only the case that the initial part and the

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final part of the process data are zero-steady-state if we want to estimate all the frequency responses of the process without modeling errors. Even though the accuracy of the exiting discrete-time Fourier transform approaches could be better as increasing the number of the samples, the modeling errors can never be completely avoided [14,22,23].

In this paper, a new discrete-time frequency response model identification method for discrete-time processes is developed to overcome the limitation of the existing discrete-time Fourier transform approach. It can estimate all the frequency responses of the process without modeling errors. Also, it can be applied to more various types of process excitation including initial-steady-state/final-steady-state and initial-steady-state/final-cyclic-steady-state.

2. Process excitation

Three types of process excitation are considered in this research: (Type 1) – both the initial part and the final part of the excited process data are zero-steady-state (Fig. 1a), (Type 2) – both the initial part and the final part of the excited process data are steady-state (Fig. 1b), (Type 3) – the initial part is steady-state and the final part is cyclic-steady-state (Fig. 1c).

The process data in Fig. 1a and b are obtained by a proportional controller with the step setpoint change. And, the relay feedback method with changing the reference value for the relay on-off is used to obtain the process data in Fig. 1c.

Various forms of process excitation can be designed within the category of the above-mentioned three types. Any types of process excitation can be inserted between the initial part and the final part because the three types in this paper restrict the state of only the initial and final part and no restrictions are given to the other part between the initial part and the final part. For examples, it is possible to increase the amount of the frequency information in the excitation signal by combining a step signal and a biased-relay feedback signal as shown in Fig. 2a (Type 3) or a biased-relay feedback signal and a proportional control signal as shown in Fig. 2b (Type 2).

The proposed method can estimate all the frequency responses of the process without modeling errors from any process excitation data belong to the above-mentioned three types. On the other hand, previous discrete-time Fourier transform approaches cannot provide exact frequency responses theoretically for the process excitation cases mentioned in this paper because the ratio of the discrete Fourier spectra of the process input and the process output is not equal to the transfer function due to the appearance of the initial and final process input and output terms [14]. So, the application range of the proposed method is much wider than the previous discrete-time Fourier transform approaches.

3. Proposed nonparametric process identification method

The previous discrete-time Fourier transform approach to estimate the frequency responses of the process cannot be applied to the excitation types of Fig. 1b (Type 2) and c (Type 3). The objective of this research is to develop a new discrete-time frequency response identification method applicable to all the three types of process excitation.

3.1. New transform

Consider the following assumptions and definition of a new transform before developing the proposed identification method.

Assumption 1. The process input and output after the n_{ss}th sample of Type 3 (Fig. 1c) are cyclic-steady-state of which the period is P.

Assumption 2. The dynamics of the discrete-time process is described by the following transfer function:

$$G(z) = \frac{y(z)}{u(z)} = \frac{b_1 z^{-1} + b_2 z^{-2} + \cdots + b_{m-1} z^{-(m-1)} + b_m z^{-m}}{1 + a_1 z^{-1} + \cdots + a_{n-1} z^{-(n-1)} + a_n z^{-n}} \tag{1}$$

It is equivalent to the following difference equation:

$$y(k) + a_1 y(k-1) + a_2 y(k-2) + \cdots + a_n y(k-n) = b_1 u(k-1) + b_2 u(k-2) + \cdots + b_m u(k-m) \tag{2}$$

where $G(z)$ is the discrete-time transfer function of the process. $y(k)$ and $u(k)$ denote the process output and the process input at the kth sample. $a_i, i = 1, 2, \ldots, n$ and $b_i, i = 1, 2, \ldots, m$ are the parameters of the discrete-time process.

Definition 1. Let us define a new transform, $Q_{P,T}\{y(k)\} = y_{P,T}(q)$ as follows:

$$Q_{P,T}\{y(k)\} = \sum_{k=-P}^{-1}(y(k+1) - y(k)) + \sum_{k=-P+1}^{0}(y(k+1) - y(k))q^{-1} + \cdots + \sum_{k=T}^{P+T-1}(y(k+1) - y(k))q^{-(P+T)} = \sum_{i=-P}^{T}\left[\sum_{k=i}^{i+P-1}(y(k+1) - y(k))q^{-(i+P)}\right] \tag{3}$$

Property 1. The transform of Eq. (3) satisfies Eq. (4) if the initial part of $y(k)$ is steady-state and the final part of $y(k)$ after $(T-j)$th sample is cyclic-steady-state.

$$Q_{P,T}\{y(k-j)\} = Q_{P,T}\{y(k)\}q^{-j} = y_{P,T}(q)q^{-j} \tag{4}$$

Proof. Consider the following transform of $y(k-j)$.

$$Q_{P,T}\{y(k-j)\} = \sum_{k=-(P+j)}^{-(1+j)}\{y(k+1) - y(k)\} + \cdots + \sum_{k=-P}^{-1}\{y(k+1) - y(k)\}q^{-j} + \sum_{k=-P+1}^{0}\{y(k+1) - y(k)\}q^{-(j+1)} + \cdots + \sum_{k=T-j}^{P+T-1-j}\{y(k+1) - y(k)\}q^{-(P+T)} \tag{5}$$

Note that Eq. (6) is valid because the initial part of $y(k)$ is steady-state (that is, $y(k)$ for $k \le 0$ is a constant).

$$\sum_{k=i}^{i+P-1}\{y(k+1) - y(k)\}q^{-(i+P)} = 0 \quad \text{for} \quad i \le -P \tag{6}$$