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Brief paper

Analysis of over-sampling based identification[☆]

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ABSTRACT

In this work, firstly, an asymptotic variance expression is derived for the transfer function estimates in the over-sampling based identification scheme. Then the result is used to analyze the over-sampling scheme. The asymptotic variance expression says that the joint covariance matrix of the transfer function estimates is proportional to the "generalized" noise-to-signal ratio. It is an application of the result in Ljung (1985); and it covers both open-loop and closed-loop tests. Using the result, one can show that informativity of the closed-loop tests without external excitation can be attained by using the over-sampling scheme, but only when the output disturbance has high frequency content beyond the bandwidth of the plant. Moreover, when the output disturbance has high frequency content and when test signal is used, the result points out that the over-sampling scheme can increase model accuracy, and, it will outperform conventional method with anti-aliasing filtering. Numerical examples are used to illustrate the asymptotic variance expression and the analysis about over-sampling scheme of identification.

1. Introduction

System identification plays the most important role in model-based control applications such as model predictive control (MPC) and robust control. In last decades, many identification algorithms have been developed and analyzed, see Ljung (1999) and Söderström and Stoica (1989). The basic requirement for system identification, especially in large-scale control applications, is to obtain good quality models at a low cost. In most industrial applications, the cost of identification is related to the disturbance caused by the test signals and to the identification test time. Hence to reduce the cost of identification implies the reduction of the disturbance of identification test and the test time. The test signal is generally restricted to a considerably low level in many practical systems, especially for MPC identification of large and capital intensive industrial processes such as distillation columns and power plants where the identification excitation should not cause any off spec of the products, or, disturb normal operation, see Zhu (2001), and this may lead to poor model quality and control performance. The situation can be improved when identification test is carried out in closed-loop under feedback control because the controller can reduce the output variations considerably. The cost of computing power and computing time can be neglected in off-line model identification.

Inspired by the over-sampling technique used in signal processing area, in Sun, Wen, and Sano (1997) and Sun, Ohmori, and Sano (2001) the over-sampling based identification scheme has been proposed, and it is proved in time domain that this scheme can attain informative experiments[2] in closed-loop identification without external excitation, which means informative data can be obtained from noise excitation only and the open-loop plant can be identified with no test signals applied. Sun, Ohmori, and Sano (2000) proposed a frequency domain closed-loop identification algorithm using the over-sampling scheme which can also attain informative closed-loop experiments without external excitation. In Sun and Sano (2009) and Wang, Chen, and Huang (2004), the authors make use of the cyclo-stationarity of the over-sampled signals to prove in frequency domain that the observed data in over-sampling based closed-loop identification without external excitation is informative. In Sun and Zhu (2012), an over-sampling based closed-loop identification

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2 For definition of informative experiments, see Definition 8.1 in Ljung (1999).

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algorithm is investigated which can reduce the influence of sensitivity to the noise model estimation and initial values in the numerical optimization.

We would like to mention that the over-sampling technique is practically costless. In industrial MPC (model predictive control) systems, the controller sampling frequency is much lower than the sampling frequency of the lower level DCS (distributed control system). For example, the sampling time of a typical refinery DCS system is 1 s or shorter, while the sampling time of a typical MPC control system is 60 s. This means that in MPC identification, the sampling frequency can be made 60 times as high if necessary. The situations in other industries are similar. Because no test signal is used, the over-sampling scheme is the most economical test approach, namely, the cost is practically zero.

However, the over-sampling based identification scheme has its shortcomings and the model quality is not guaranteed: the quality of identified plant model is strongly dependent on controller parameters, the positions of plant poles and the property of unmeasured disturbance. In Sun and co-workers' works, the external excitation is set to zero in the identification tests. In industrial applications, external test signals are permitted although they should be kept small in amplitudes.

Here, in order to achieve high model quality and low disturbing test, we propose the use of external test signal in the over-sampling scheme in identification tests. We start by analyzing the asymptotic properties of the transfer function estimates in over-sampling based identification where external excitation is used, which includes the situation without excitation as a special case. Variance expression asymptotic both in the number of observed data and in the model order is derived and has an explicit form. This is an application of Ljung (1985) to the over-sampling based identification. The results cover open-loop tests which has not been considered in the previous study of Sun and co-workers. Using the result, we can give the exact condition for informative closed-loop test without excitation for the over-sampling scheme which is previously unknown. Moreover, we can show that, when test signal is used, under the same condition, the over-sampling scheme can increase model accuracy in both open-loop and closed-loop identification.

The outline of this paper is as follows. In Section 2, the over-sampling technique is briefly introduced; the asymptotic variance expression in over-sampling based identification is derived in Section 3; Section 4 gives the analysis of the over-sampling based identification using the asymptotic variance expression; numerical illustrations are given in Section 5 and Section 6 contains the conclusion and perspective.

2. Over-sampling technique

Fig. 1 displays how the over-sampling technique is used in closed-loop identification. Same as in conventional closed-loop identification, the closed-loop system contains a linear continuous-time plant $G_c(s)$ and a digital controller $K(z^{-1})$ of which the control period is T, and z^{-1} is a backwards shift operator corresponding to T. $K(z^{-1})$ is followed by a zero-order holder to generate piecewise control input. The difference is that the output is sampled at a period of $\Delta = T/p$ to generate the signal $y_\Delta(k)$ used for identification while in conventional identification the sampling time for output signal equals T. Here p is a positive integer indicating the over-sampling rate. Notice that the input is also over-sampled. But due to the zero-order holding, the input signal $u_\Delta(k)$ for identification is actually generated as

$$u_\Delta(k) = u(m), \quad k = mp, mp+1, \ldots (m+1)p-1. \tag{1}$$

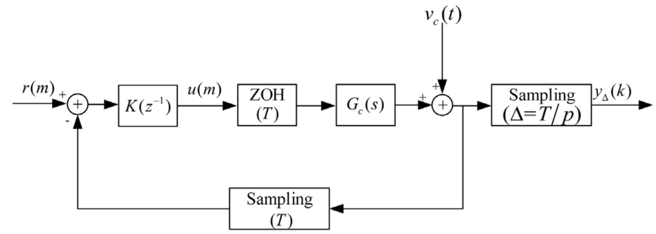

Fig. 1. Over-sampling technique in closed-loop identification.

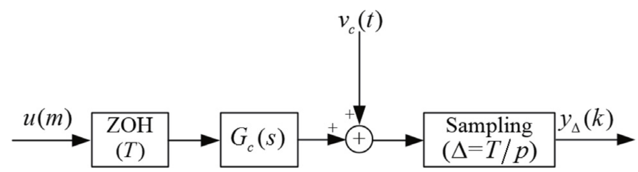

Fig. 2. Over-sampling technique in open-loop identification.

Due to the zero-order holding, the over-sampled input and output, i.e. $u_\Delta(k)$ and $y_\Delta(k)$, are cyclo-stationary signals for which the cyclo-stationary correlation function is defined as

$$C_{x_1,x_2}(\alpha_l, \tau) = \frac{1}{p}\sum_{k=mp}^{mp+p-1} e^{i\alpha_l k} E\{x_1(k+\tau)x_2(k)\} \tag{2}$$

where either $x_1(k)$ or $x_2(k)$ is cyclo-stationary signal and $\alpha_l = 2\pi l/p$, see Sun and Sano (2009). The cyclo-stationary spectrum is further defined as

$$S_{x_1,x_2}(\alpha_l, \omega) = \sum_{\tau=-\infty}^{\infty} C_{x_1,x_2}(\alpha_l, \tau) e^{-i\omega\tau}. \tag{3}$$

The over-sampling technique can also be applied in open-loop identification, see Fig. 2.

2.1. Plant models and model conversion

Denote the discretized plant model with respect to sampling time T as

$$y(m) = G(z^{-1})u(m) + v(m) \tag{4}$$

where $u(m)$ and $y(m)$ are the plant input and output at sampling instant mT respectively. $v(m)$ is considered as the sample of a continuous stationary stochastic process $v_c(t)$ at mT. The transfer function $G(z^{-1})$ will be indicated as T-model in the sequel.

Denote the discretized plant model with respect to sampling time Δ as

$$y_\Delta(k) = G_\Delta(q^{-1})u_\Delta(k) + v_\Delta(k) \tag{5}$$

where $u_\Delta(k)$ and $y_\Delta(k)$ are the input and output at instant $k\Delta$ respectively. Here q^{-1} is a backward shift operator corresponding to the interval Δ. $v_\Delta(k)$ is the sample of $v_c(t)$ at instants $k\Delta$. The transfer function $G_\Delta(q^{-1})$ will be indicated as Δ-model in the sequel.

When $G_\Delta(q^{-1})$ is identified, $G(z^{-1})$ is uniquely determined by

$$G(z^{-1}) = z^{-\frac{\tau_\Delta - 1}{p} - 1} c_\Delta \cdot (I - A_\Delta^p z^{-1})^{-1} \sum_{j=0}^{p-1} A_\Delta^j b_\Delta \tag{6}$$

where A_Δ, b_Δ and c_Δ are the matrices and vectors in the state-space realization of $G_\Delta(q^{-1})$, τ_Δ is the delay time of $G_\Delta(q^{-1})$, see Sun and Sano (2009).