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Specific growth rate estimation in (fed-)batch bioreactors using second-order sliding observers

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ABSTRACT

This paper addresses the estimation of specific growth rate of microorganisms in bioreactors using sliding observers. In particular, a second-order sliding observer based on biomass concentration measurement is proposed. Differing from other proposals that only guarantee bounded errors, the proposed observer provides a smooth estimate that converges in finite time to the time-varying parameter. Stability is proved using a Lyapunov approach. The observer exhibits also robustness to process uncertainties since no model of the reaction is used for its design. In addition, the off-surface coordinate of the sliding observer is useful to determine the convergence time as well as to identify sensor faults and unexpected behaviors. Because of the structure of the output error injection, chattering phenomena of conventional sliding mode algorithms are substantially reduced. The features of the proposed observer are assessed by numerical and experimental data.

1. Introduction

Bioprocesses are characterized by complex dynamic behavior, nonlinearities, model uncertainty, unpredictable parameter variations, etc. Furthermore, most representative variables are typically not accessible for on-line measurement. In this context, the development of robust and reliable algorithms to estimate key variables and parameters is of prime interest, both for process control and monitoring [1].

The existing algorithms differ from each other with respect to the measured and estimated variables, the parameters which are assumed to be known, the type of convergence, robustness issues, etc. A summary of several approaches under different scenarios can be found in [1,2]. Asymptotic observers for state and parameter estimations appeared for the first time in [3]. Adaptive high-gain observers for the same purposes were presented in [4]. Applications of high-gain observers to bioreactors were treated also in [5,6]. More recently, hybrid observers combining asymptotic with exponential observers to estimate states and identify confidence of the kinetic model were developed [7,8]. A proportional-integral observer based on the exact transformation of the nonlinear dynamical system into its multi-model form has been developed in [9]. Sliding mode observers have been proposed also to deal with model uncertainties [10,11]. An observer that estimates the substrate consumption rate based on substrate concentration measurement was designed in [10]. In [11], sliding mode techniques were exploited to estimate kinetic rates and concentration variables from biomass measurement.

In this paper we focus on the estimation of reaction rates and, particularly, of specific growth rates. The motivation is that, in many cases, specifications are related with the growth rate of microorganisms, whether the objective is to maximize biomass production or to maintain a metabolic steady state [12]. Besides, growth rate provides valuable information to monitor the development of microorganisms in the broth.

Substrate concentrations are the key variables in the kinetic models. So, by measuring them, good estimates of the specific growth rate can be obtained by using high-performance observers. However, substrates are usually very difficult to measure on-line and with good precision, particularly when they are in low concentrations.

Alternatively, there currently exist reliable biomass sensors (see for example [13,14]). That is why much research has been oriented to develop observers based on biomass sensors, although biomass is a much less informative signal from the point of view of kinetics than substrate. In this approach, the kinetic rate is traditionally treated as an unknown parameter. Advances in the field can be traced back to the work of [4], where an adaptive Luenberger-like observer is designed so that it achieves bounded error under the assumption that the specific growth rate has bounded time derivative. These results were extended and improved by further work of the authors and contributions of other colleagues.

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