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Multi-scale control scheme: Stabilization of a class of fourth-order integrating-unstable systems

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Abstract

Even when based on simple models, a fed-batch fermentation process can demonstrate several different forms of complex dynamic behaviours throughout the course of its operation. One of the most intriguing forms of dynamic behaviours that can occur at some points during the fed-batch operation is represented by a fourth-order integrating-unstable system with multiple RHP zeros. To deal with the stabilization of this complex dynamics, a new triple-loop multi-scale control (TL-MSC) scheme is proposed. This scheme aims to first decompose the complex dynamics into three simpler sub-systems which are then separately addressed in a multi-scale structure. This paper presents both the fundamental of TL-MSC scheme and the details of its design. A typical fed-batch alcoholic fermentation is shown as an example to demonstrate the applicability of the new scheme.

1. Introduction

A fed-batch fermentation process is commonly used in biotechnological industries because it can overcome substrate inhibition responsible for low productivity in the process [1,2]. The fed-batch bioreactor can be represented by a set of mass balance equations and sometimes coupled with energy balances when the thermal generation is significant. In the simplest case under isothermal conditions, the fed-batch process can be represented by a set of

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differential-algebraic equation (DAE) as follows

$$\frac{dZ}{dt} = f(Z, U, R_r, T) \tag{1}$$

$$R_r = g(Z) \tag{2}$$

where $Z \in \Re^n$, $U \in \Re^m$ and $R_r \in \Re^q$ are vectors of state variables, input variables and reaction rates; f and g are nonlinear functions of their arguments, respectively. In the simplest case, a realistic model of the fed-batch bioreactor should have minimum of four state variables and complemented with at least three kinetics or rate equations. In many cases, only one input variable is available for manipulation, i.e., the fresh feed flow rate.

It is interesting to note that based on the simplest model, a linearization of the nonlinear system at any given operating point shall lead to a fourth-order integrating transfer function. Depending on the point at which the system is linearized, the fourth-order integrating system can take several different forms of challenging dynamic behaviours. One of the particular forms which can be very difficult to stabilize is given by

$$P = \frac{z_i}{u} = \frac{K_p \prod_{j=1}^{3} (\tau_{zj} s + 1)}{s(\tau_p s + 1)\left(\tau_u^2 s^2 + 2\zeta \tau_u s + 1\right)} \tag{3}$$

with the following assumptions:

- A.1: two RHP zeros, $\tau_{z1} < 0$, $\tau_{z2} < 0$ and $\tau_{z3} > 0$.
- A.2: unstable-oscillatory, $\tau_p > 0$, $\tau_u > 0$ and $-1 < \zeta < 0$.

Here, z_i and u denote one of the state variables (e.g., substrate concentration) and input variable (e.g., fresh feed flow rate). It should be emphasized that not all fed-batch processes demonstrate such complex dynamic behaviours. In some common cases, the linearized process can be simplified to a second- or even first-order system with time-delay. However, the nature of fermentation dynamics depends on the types of applications and microorganisms involved.

The novelty of the present work lies in a new control structure, called the triple-loop multi-scale control (TL-MSC) scheme for the stabilization of a complex dynamic system such as Eq. (3), which is difficult or even impossible to stabilize using the standard single-loop feedback control structure, e.g., a single-loop PID control. This complex dynamic system can arise from some fermentation processes, e.g., during a fed-batch fermentation operation. Interestingly, the present work suggests that three conventional PID-type controllers can be used in the TL-MSC scheme in order to stabilize and give satisfactory control performance for a class of fourth-order integrating-unstable-oscillatory NMP system. In term of academic contributions, this paper presents a systematic procedure to assist in the tunings of these three PID-type controllers, hence providing complete design of the TL-MSC scheme. It is worth noting that this procedure is simple and easy to implement.

Significantly, the present work shows that one of the possible approaches to analyzing complex behaviours that can emerge from a nonlinear system (e.g., a fed-batch fermentation), is through linearization analysis of the system at various points along its possible operating trajectory. Although in some reported studies that simple PID controllers can be used to control fed-batch fermentation processes [3,4], it is important to note that this cannot be generalized to all fed-batch or batch fermentation processes, for examples, fermentation that uses engineered microorganisms (with enhanced performance for specific products) and complex substrates