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A robust control scheme for nonlinear non-isothermal uncertain jacketed continuous stirred tank reactor

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ABSTRACT

A Non-isothermal Jacketed Continuous Stirred Tank Reactor (CSTR) is extensively used in chemical as well as in other process industries to manufacture different products. The dynamics of non-isothermal CSTR are highly nonlinear and open-loop unstable in nature. Moreover, it may have parametric uncertainties, disturbances and un-modeled side reactions which may cause the reactor temperature to deviate from the reference value. This deviation may degrade quality of the product because the chemical reaction inside the CSTR depends on reactor temperature. For such a nonlinear, unstable and uncertain process, designing a control scheme with the ability to reject the effects of disturbances along with a good reference tracking capability is a challenging control engineering problem. In this work, a novel robust sliding mode control technique named as Improved Integral Sliding Mode Control (IISMC) has been presented for uncertain non-isothermal jacketed CSTR process. Moreover, a variety of recently developed sliding mode control techniques such as Classical Integral Sliding Mode Control (CISMC) and Super Twisted Algorithm based Sliding Mode Control (STA-SMC) have also been devised and compared with the proposed approach in order to investigate the effectiveness of the proposed scheme. A Lyapunov based analysis has also been provided to assure the robust stability of the closed loop process. Furthermore, in order to extend the state feedback approach to the output feedback scheme, two robust observers; High Gain Observer (HGO) and Extended High Gain Observer (EHGO), are also designed for the very process. They have also been compared with each other and have been investigated for robust stability using Lyapunov based approach. Finally, an output feedback control scheme using IISMC and EHGO has been presented and its performance has been examined and compared with the IISMC based state feedback approach. The simulation results show that the proposed control scheme effectively rejects the uncertainties and disturbances without leading the process to instability and offers good reference tracking capabilities.

1. Introduction

Continuous Stirred Tank Reactor (CSTR) is one of the widely used reactors in chemical plants [24,10] as well as in other process industries. It possesses highly nonlinear with unstable characteristics due to which the design of high performance control scheme would become a challenging problem. Moreover, the process model may have parameters uncertainties, input disturbance and un-modeled side reactions and nonlinearities due to poor knowledge of the process, may lead the process to instability. Some industrial applications such as alkylation of benzene with ethylene process, etc., may require robust and fast response control scheme in order to maintain the quality of the product [10]. Therefore, the problem for designing the control scheme for uncertain process would become more interesting for the control engineers.

If the classical control techniques are used to design a control scheme, it is very difficult to meet the performance requirements for the control of highly nonlinear process. Indeed, conventional linear control schemes involve the linearization of the process model around an operating point, which poses two major limitations: First, it can only predict the local behavior of the process around an operating point; secondly, the dynamics of linear processes is not much rich as compared to dynamics of nonlinear processes [3].

During past few years, control engineers and researchers have proposed a variety of nonlinear control schemes. Some of them are based on differential geometric concepts [1–3], adaptive linearization [6,8], robust linearization [7] and asymptotically exact

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linearization [9,5]. Others are based on sliding mode control (SMC), adaptive SMC, lyapunov redesign and Nonlinear Model Predictive Control (NMPC). Among them, SMC is one of the widely used schemes due to its ability to reject disturbances and its insensitivity to parameter variations [18]. Many researchers have proposed different combinations of sliding mode control schemes together with other approaches. One such scheme is a differential geometric approach with sliding mode scheme which has provided a potential way of designing a robust control scheme for the control of uncertain nonlinear process [1,19]. A Dynamical Sliding Mode Control (DSMC) strategy is another scheme, which is presented in [21] for the Fliess's generalized observability canonical form based system. A robust SMC based feedback linearization technique and deterministic approach is presented in [22]. A control scheme, by combining the differential geometric feedback linearization technique together with SMC and adaptive state feedback techniques, is presented in [19]. Some researchers combined SMC scheme with fuzzy logic control scheme, which is known as Fuzzy Sliding Mode Control (FSMC). One such scheme is employed in [23] where authors have used the sliding surface and rate of change of sliding surface as inputs to design a fuzzy logic control for chemical processes.

Recently, an output feedback exact linearization control scheme has been designed for non-isothermal jacketed CSTR [11]. In this scheme, nonlinear observers have been designed to estimate the states as well as disturbances in some parameters of the process. The performance of such control scheme may degrade if disturbance occurs in the parameters that are not estimated by the observer or if there is an input disturbance or un-modeled side reaction. More recently, a Terminal Sliding Mode Controls (TSMC) along with finite time stability observer have been proposed in [10] for non-isothermal CSTR process neglecting the dynamics of the cooling jacket.

Physical state variables are required in order to monitor the process. Moreover, state feedback control techniques require all states of the process to generate control signal(s). But, in real practice, not all the state variables are measured because the instruments required to measure the state variables are either too expensive or does not exist. Therefore, an observer is required which estimates the unmeasured states from the available measurement of the process. The classical linear observer only provides local estimation for state variables of the process having intrinsic nonlinearity. But, a finite time stable nonlinear observer may provide global estimation of state variables of highly nonlinear process and may give the desired performance specification. In addition to compensate for nonlinearity, the observer must converge the estimated states to the unmeasured states of the process in finite time in the presence of parametric uncertainties. Different types of nonlinear observers such as Luenberger like Nonlinear Observer (LNO), Extended Kalman Filter (EKF) and Sliding mode observers (SMO) are proposed in [11] for the CSTR process.

The aim of present work is to propose a high performance and simple robust control scheme, Improved Integral Sliding Mode Control (IISMC), for the regulation of nonlinear non-isothermal uncertain jacketed continuous stirred tank reactor. In this work, different existing control techniques which have proven to be robust such as Classical Integral Sliding Mode Control (CISMC)[1] and recently proposed Super Twisted Algorithm (STA) are also devised for the very process. These control techniques are compared with the proposed approach for reference tracking, parameter uncertainties and un-modeled side reaction and input disturbance. The robust stability analysis of the closed loop system is also carried out using Lyapunov stability technique. Moreover, for designing an output feedback scheme, two nonlinear robust observers; High Gain Observer (HGO) and Extended High Gain Observer (EHGO) are also devised, compared and investigated. The stability analyses of these observers are also presented.

The rest of the paper is organized as follows: In Section 2, a brief introduction of the CSTR process is presented. In Section 3, robust control techniques, CISMC, STA-SMC and IISMC are devised for the uncertain CSTR process. The performance of the controllers is also discussed in the same section. The robust observers, HGO and EHGO, are designed and discussed in Section 4. In Section 5, output feedback control scheme is developed by combining IISMC and EHGO for the CSTR process. Performance comparison between the IISMC based state feedback control technique and IISMC and EHGO based output feedback control scheme is also carried out in the same section. Finally, in Section 6, conclusion of the work is presented.

2. Non-isothermal jacketed continuous stirred tank reactor (CSTR)

We have considered a non-isothermal jacketed continuous stirred tank reactor problem in which exothermic irreversible first order reaction takes place. This problem has been extensively used in the area of control research due its highly nonlinear behavior. Before discussing the process model dynamics, consider the following assumptions:

Assumption 1. The temperature inside the reactor is uniformly distributed by assuming perfect mixing in the reactor.

Assumption 2. A constant volume inside the reactor is assumed.

By considering the above mentioned assumptions, following dynamic equations, described the physical model of the reactor, are derived [12,11].

$$\dot{x} = f(x) + g(x)q_c + \Delta f(x) \tag{1}$$

where,

$$f(x) = \begin{bmatrix} q\left(x_{1f} - x_1\right) - \phi x_1 \kappa(x_2) \\ q\left(x_{1f} - x_2\right) - \delta(x_2 - x_3) + \beta\phi x_1 \kappa(x_2) \\ \delta_1 \delta \delta_2 (x_2 - x_3) \end{bmatrix} \tag{2}$$

$$g(x) = \begin{bmatrix} 0 \\ 0 \\ \delta_1 \left(x_{3f} - x_3\right) \end{bmatrix} \tag{3}$$

$$\Delta f(x) = \begin{bmatrix} \Delta f_1(x) \\ 0 \\ 0 \end{bmatrix} \tag{4}$$

where, *f(x)* and *g(x)* are locally Lipschitz in *x*, state variable x_1, x_2 and x_3 is the dimensionless reactant concentration, reactor temperature and cooling jacket temperature, respectively, q denotes the reactor feed flow rate, x_{1f}, x_{2f} and x_{3f} is the dimensionless reactor feed concentration, reactor feed temperature and cooling-jacket feed temperature, respectively, β is the dimensionless heat of reaction, δ is the dimensionless heat transfer coefficient, δ_1 is the reactor to cooling-jacket volume ratio, δ_2 is the reactor to cooling-jacket density heat capacity ratio, ϕ is the nominal Damköhler number based on the reactant feed, the controlled variable q_c denotes the cooling jacket flow rate ranges from 0 to 1 [11], Δf_1 denotes the un-

[1] In order to differentiate Integral Sliding Mode Control Scheme (ISMC) presented in [3] with the proposed ISMC, we named the preceding scheme as CISMC and the later scheme as IISMC.