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A State Feedback Linearization Controller for a Chemical Stirred Tank Reactor

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Abstract

This paper proposes a state feedback linearization control design for a highly nonlinear chemical process carried out within a continuous stirred tank reactor (CSTR). Characterized by severe parametric couplings and exothermic reaction kinetics, CSTR dynamics present severe challenges for conventional linear controllers. The primary objective of the developed control architecture is to regulate these complex, nonlinear behaviors by transforming the system into an equivalent, decoupled linear form. This transformation is achieved through an exact state feedback linearization technique utilizing coordinate changes and non-linear algebraic feedback laws. Based on this linearized framework, a robust feedback control law is synthesized to drive the critical system states specifically reactant concentration and reactor temperature precisely toward their target steady-state values, ensuring stable operation at the desired setpoints. The proposed strategy mitigates inherent process nonlinearities and thermal sensitivities without relying on conservative localized approximations. The performance of the developed controller is rigorously evaluated through comprehensive software-based numerical simulations. The resulting data demonstrate that the method achieves highly accurate setpoint tracking, rapid settling times, and minimal overshoot under nominal operating conditions. Ultimately, the simulation results confirm the effectiveness, reliability, and robustness of the feedback linearization approach in maintaining stable, optimized operation for the stirred tank reactor process.

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1. Introduction

One of the most utilised equipment in the process industries is the continuous stirred tank reactor (CSTR). It has the ability to transform reactants to products, making it an essential component in several chemical reactions. In Zhao, et al. [1] an optimised financial gain and a high conversion rate was achieved, CSTRs are often operated at a precise equilibrium point that is associated with the ideal output or productivity of a process. From a control perspective, CSTRs are characterised by their nonlinearity and dynamic behaviour. Control engineers in Rahmat, et al. [2] find the problem of controlling a CSTR as both contentious and intriguing due to its complicated nonlinear dynamics. The majority of conventional controllers are limited to linear time-invariant systems. In Hoang, et al. [3] the control and modelling of non-isothermal chemical reactors was studied, from the point of view of CSTR model, non-isothermal chemical reactors are irreversible thermodynamic systems, wherein, instabilities may arise due to the nonlinear association between energy domains and mass resulting from chemical reactions.

In Ekinci, et al. [4] a proposed study of a Quadratic Interpolation Optimization (QIO)-based Two-Degrees-of-Freedom PID (2DoF-PID) controller for temperature regulation in Continuous Stirred Tank Heater (CSTH) systems. Unlike conventional PID controllers, the proposed approach independently optimizes setpoint tracking and disturbance rejection, improving control performance in nonlinear and disturbance-prone environments. Simulation results show that the QIO-optimized controller achieves lower overshoot, faster settling time, and smaller steady-state error. Comparative evaluations against traditional tuning methods (Murrill and Rovira) and advanced optimization algorithms (DE, PSO, FLA, and MGO) demonstrate its superior robustness and effectiveness. The study highlights the potential of QIO as a scalable, computationally efficient, and cost-effective solution for industrial temperature control applications. A Joint-Opposition Artificial Lemming Algorithm was introduced in Ekinci, et al. [5] to optimally tune a Fractional-Order PID (FOPID) controller for temperature regulation in nonlinear Continuous Stirred Tank Reactor (CSTR) systems. The enhanced optimizer improves convergence and avoids local optima by increasing population diversity. Simulation results show that the JOS-ALA-based FOPID controller provides zero overshoot, faster response, lower steady-state error, and better disturbance rejection than several advanced optimization algorithms. Statistical tests confirm the superiority of the proposed method, making it a promising and reliable solution for high-precision industrial temperature control. In Mukherjee, et al. [6] a Fractional-Order Standalone Backstepping Controller is proposed for controlling the concentration of a nonlinear CSTR under noise and disturbances. Using a novel fractional-order approximation technique, the controller achieves accurate tracking, smooth control action, low overshoot, and strong robustness against disturbances and parameter variations. Simulation results demonstrate superior performance compared to existing control methods, with reduced control errors and improved stability. A dynamic decentralized event-triggered control method is presented in Yang, et al. [7] for cascade CSTR systems with input constraints. By combining adaptive dynamic programming, critic neural networks, and event-triggering mechanisms, the proposed approach achieves accurate tracking, reduces computational and communication costs, and maintains system stability. Simulation results confirm its effectiveness and robustness for real-time industrial reactor control.

In Siddiqui [8] a design introduces a Parallel Cascade Control Structure (PCCS) for temperature regulation in a Nonlinear Continuous Stirred Tank Reactor (NCSTR). The proposed approach models the NCSTR with a recirculating jacket heat transfer system as a third-order unstable process and employs a model-matching technique to determine the controller parameters. Within the PCCS framework, the secondary control loop is designed to improve disturbance rejection and regulatory performance, while the primary control loop focuses on enhancing setpoint tracking accuracy. Simulation results based on the nonlinear reactor model demonstrate that the proposed PCCS achieves superior temperature control compared with conventional Cascade Control Structure (CCS) and Parallel Control Structure (PCS) methods. Furthermore, the controller maintains robust and reliable performance under nominal operating conditions, parameter variations, and noise measurement. In Deifalla and Gasmelseed [9] research focuses on optimizing PID controller parameters for temperature regulation in a Continuous Stirred Tank Reactor (CSTR) used in ethyl acetate saponification. A Genetic Algorithm (GA) is employed, with Ziegler–Nichols tuning used to define the initial parameter boundaries. The controller is designed and tested in a SIMULINK environment by minimizing the Integral of Squared Error (ISE) to improve system performance. Compared to the conventional Ziegler–Nichols method, the GA-tuned PID controller shows significantly better results, including faster response, reduced overshoot, improved set-point tracking, and stronger disturbance rejection. Overall, the GA-based approach demonstrates enhanced stability, accuracy, and efficiency in handling the nonlinear behavior of the CSTR process. A new design was addressed in Cappelletti, et al. [10] that shows the challenge of controlling nonlinear systems by proposing a vertex-reduced multi-model (polytopic) representation of a Continuous Stirred Tank Reactor (CSTR). The method accounts for parameter variations within the operating region while maintaining convexity, resulting in a unified system representation. Using this model, an optimal control strategy is developed based on Linear Matrix Inequalities (LMI), allowing the computation of feedback gains while satisfying state, input, and operating constraints and ensuring closed-loop stability. Simulation results demonstrate that the proposed approach effectively captures the nonlinear behavior of the CSTR and enables robust controller design, achieving desirable performance despite uncertainties and parameter changes.

In Kumari, et al. [11] a nonlinear active disturbance rejection control (NL-ADRC) strategy was developed for stabilizing unstable time-delay processes, with application to a Continuous Stirred Tank Reactor (CSTR). The method uses an extended state observer to estimate and compensate for unknown disturbances and uncertainties in real time, while a nonlinear feedback law ensures control without requiring an accurate plant model. Performance is evaluated on benchmark unstable systems and a nonlinear CSTR case study. Additionally, an IMC-based frequency-domain analysis of the linearized model is used to assess robustness, and Lyapunov theory confirms uniform ultimate boundedness of the closed-loop system. Simulation results show improved tracking, faster disturbance rejection, and stronger robustness compared with conventional control methods, demonstrating the effectiveness of NL-ADRC for complex industrial processes. A sliding mode control (SMC) strategy was created in Qi, et al. [12] for a Continuous Stirred Tank Reactor (CSTR) under external disturbances using a dynamic self-triggered communication protocol. The reactor dynamics, including fluctuations in concentration and temperature, are modeled as a switched stochastic semi-Markov system. A Lyapunov-based framework is used to ensure asymptotic mean-square stability without requiring sojourn-time constraints, leveraging the stationary distribution of the embedded Markov chain. To improve communication efficiency and dynamic performance, a self-triggered mechanism is integrated with the SMC design to predict the next transmission time and reduce unnecessary sampling. The proposed SMC law guarantees finite-time reachability of the sliding surface, and sufficient conditions are derived for system stability. Simulation results validate the effectiveness of the method, showing robust performance and improved efficiency for CSTR control under stochastic disturbances. In Chen, et al. [13] limited research was shown on fixed-time stability and control of continuous stirred tank reactor (CSTR) systems, particularly under time-delay and state-constraint conditions. The study considers CSTR with a delayed recycle stream and asymmetric, time-varying full-state constraints, and develops an adaptive fixed-time fuzzy control strategy. An improved practical fixed-time stability criterion is first introduced to handle more complex nonlinear systems. To manage asymmetric constraints, time-varying integral barrier Lyapunov functions are constructed. Fuzzy logic systems are employed to approximate unknown nonlinearities, while a sliding mode differentiator is used to avoid the "explosion of complexity" problem in derivative calculations. Based on the proposed stability criterion, an adaptive fixed-time fuzzy controller is designed to guarantee convergence within a fixed time while ensuring all state constraints are satisfied. Simulation results confirm the effectiveness of the proposed approach in achieving accurate tracking and maintaining system constraints under nonlinear, delayed, and constrained conditions

This paper presents a state feedback linearization control approach for a chemical process operating in a stirred tank reactor, with the aim of improving the regulation and tracking performance of a nonlinear dynamic system. Stirred tank reactors typically exhibit strong nonlinear behaviour due to reaction kinetics, mixing effects, and varying operating conditions, which makes controller design challenging. To address these issues, the proposed method focuses on transforming the nonlinear system into an equivalent linear representation using feedback linearization techniques.

Initially, an error dynamic model is developed to explicitly describe the deviation between the actual system states and their desired reference values. This model serves as the foundation for the control design by defining how the system errors evolve over time and how they can be driven toward zero. By ensuring that the error dynamics are properly formulated, the control objective of achieving accurate tracking of the desired state variables becomes more structured and systematic.

Following this, a state transformation is introduced to facilitate the feedback linearization process. This transformation restructures the original nonlinear reactor model into a form that is more suitable for controller synthesis, effectively simplifying the complexity of the system dynamics. Through this approach, the nonlinear behaviour of the stirred tank reactor is compensated, allowing the design of a linear equivalent control law that governs the closed-loop behaviour of the system.

Based on the transformed model, a state feedback control law is derived to ensure that all system states converge to their desired steady-state values. The controller is designed to stabilize the closed-loop system while simultaneously improving tracking accuracy and reducing deviations caused by nonlinearities or disturbances. This guarantees that the reactor operates reliably at the required operating conditions.

To evaluate the performance and practicality of the proposed method, two separate simulation case studies are carried out on the nonlinear closed-loop system. These simulations examine the controller's ability to handle different operating scenarios and system conditions. The results clearly demonstrate that the proposed state feedback linearization approach provides effective regulation, improved transient response, and stable steady-state behaviour for the stirred tank reactor process under study.

The rest of the paper is organized as follows. Section II presents the problem formulation of the nonlinear model. The state transformation of the system variables is illustrated in section III. The design of the feedback linearization controller is presented in section IV. The effectiveness and the applicability of the proposed control scheme are demonstrated through software simulations in section V. The paper is finally concluded in section VI.

2. Problem Formulation

The model of the stirred tank reactor in which an isothermal, liquid-phase, multicomponent chemical reaction take place is given as Sira-Ramírez [14].

$$\begin{aligned} \dot{w}_1 &= (1-D_{a1})w_1 + u \\ \dot{w}_2 &= D_{a1}w_1 - w_2 - D_{a2}w_2^2 \end{aligned} \qquad (1)$$

Where w_1 is the normalized (dimensionless) concentration C_P / C_{P0} of a certain species P reactor ,w_2 is the normalized concentration C_Q / C_{P0} of a certain species Q reactor, C_P and C_Q are respectively the concentration a certain species P and Q reactors, C_{P0} is the desired concentration of species P and Q. The input control signal of the system is u. The parameter $D_{a1} = k_1 V / F$ and $D_{a2} = k_2 V C_{P0} / F$, where F is defined as the volumetric feed rate, k_1 and k_2 are the first order rate constants.

3. The State Transformation

It is desired for the state variables in (1) to reach a certain steady state. Let the desired state for w_1 to be w_{1d} and w_2 to bew_{2d} .

To get the desired error model, let us define the error between the state and the desired state as:

$$\begin{aligned} e_1 &= w_1 - w_{1d} \\ e_2 &= w_2 - w_{1d} \end{aligned} \qquad (2)$$

Then the error dynamics will be given as:

$$\begin{aligned} \dot{e}_1 &= (1-D_{a1})w_1 + u - \dot{w}_{1d} \\ \dot{e}_2 &= D_{a1}w_1 - w_2 - D_{a2}w_2^2 - \dot{w}_{2d} \end{aligned} \qquad (3)$$

To simplify the process of the control design for nonlinear systems, a change of variables is sometimes suggested to express the system in a controllable canonical form [12]. Let us assume that such a transformation,$v(t) = T(e(t))$, exists and leads to the state vector$v(t) \in R^n$as given by:

$$\begin{aligned} v_1 &= e_2 \\ v_2 &= D_{a1}w_1 - w_2 - D_{a2}w_2^2 - \dot{w}_{2d} \end{aligned}$$

Let us define $f_v$as:

$$\begin{aligned} f_v = {} & \frac{(1-D_{a1})}{D_{a1}}\left[v_1 + v_2 + w_{1d} + \dot{w}_{2d} + D_{a2}\left(v_1 + w_{1d}\right)^2\right] \\ & -\left[1 + 2v_1 + w_{1d}\right]\left[v_2 + \dot{w}_{2d}\right] - \ddot{w}_{2d} \end{aligned}$$

Finally, the transformed system dynamic is given by:

$$\begin{aligned} \dot{v}_1 &= v_2 \\ \dot{v}_2 &= f_v + u \end{aligned} \qquad (4)$$

4. The Feedback Linearization Control Design

The proposed state feedback linearization control action for system (1) is:

$$u = -f_v + k_1 v_1 + k_2 v_2 \qquad (5)$$

Then, system (5) will be given as:

$$\begin{aligned} \dot{v}_1 &= v_2 \\ \dot{v}_2 &= k_1 v_1 + k_2 v_2 \end{aligned} \qquad (6)$$

To guarantee the stability of modeled dynamics of (7), the controller gains are chosen as $k_1 < 0$ and $k_2 < 0$.

5. Simulation Results and Discussion

In this section, two case studies are presented to illustrate the applicability and the capability of the control design procedure to reach the desired states.

The system parameters are assumed as:

$$D_{a1} = D_{a2} = 1\,.$$

5.1. Case Study 1

In this case study we will consider the desired states variables to approach zero i.e. $w_d = [0 \quad 0]^T$, The initial conditions of the state variables are $w_0 = [0.1 \quad 0.1]^T$, the control gains are $k_1 = -2$ and $k_2 = -3$.

Figure 1 presents the time response of the system state variables after the implementation of the control law given in equation (6). From the results, it is clearly observed that all state variables gradually converge to zero as time progresses. This behavior confirms that the proposed control strategy is effective in stabilizing the system at the desired equilibrium point. The convergence of the states to zero also indicates that the controller successfully suppresses the effects of the system's nonlinear dynamics and ensures proper regulation of the process variables. Overall, Figure 1 demonstrates the strong performance of the designed control law in achieving accurate state stabilization and reliable closed-loop behavior.

Figure 2 shows the corresponding control signal generated by the system under the applied feedback control law. The control input exhibits the necessary adjustments during the transient phase in order to drive the state variables toward their desired values. Initially, the control effort responds actively to the system deviations, ensuring fast convergence of the states. As the system approaches steady state, the control signal gradually decreases and stabilizes, indicating that less corrective action is required once the desired equilibrium is reached. This behavior highlights the efficiency of the control design in terms of both performance and control effort, demonstrating smooth and stable operation of the closed-loop system.

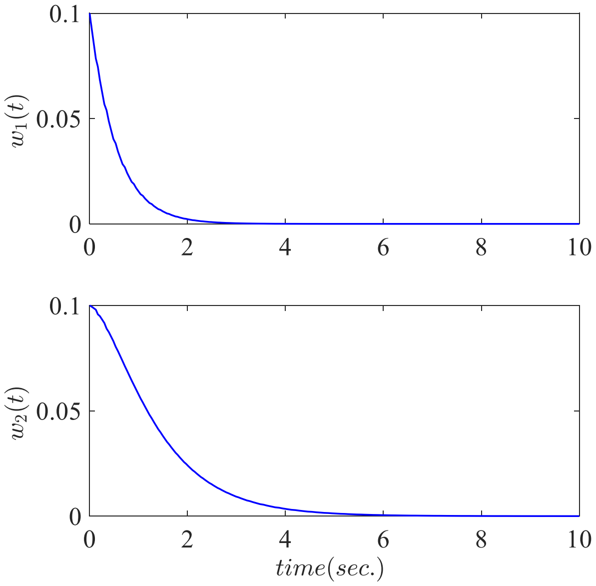

Figure 1. The state of the system $w_1(t)$ and $w_2(t)$.

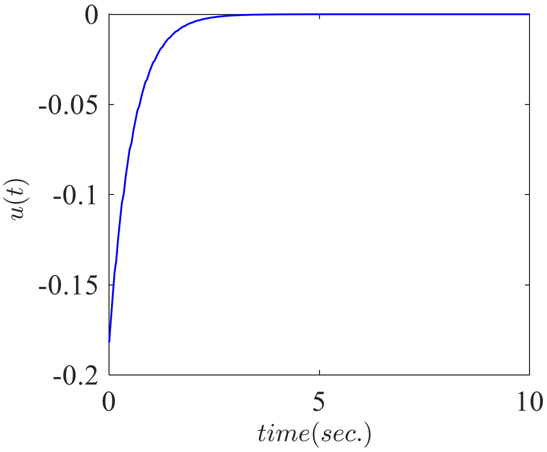

Figure 2. The input control signals for the system $u(t)$.

5.2. Case Study 2

In this case, it is demanded for the steady state variables to attain $w_d = [2 \quad 1]^T$, The initial conditions of the state variables are $w_0 = [0.1 \quad 0.1]^T$, the control gains are $k_1 = -7$ and $k_2 = -8$.

The time responses of the nonlinear system state variables are illustrated in Figure 3 showing the dynamic behavior of the system under the proposed control strategy. It can be observed that the state trajectories evolve smoothly over time and eventually converge to their desired values, indicating effective regulation of the nonlinear system dynamics.

Figure 4 presents the corresponding state feedback linearization controller response. This figure demonstrates the behavior of the controller action applied to the system, highlighting how the control input is adjusted over time to ensure proper stabilization and tracking performance. The results confirm that the proposed control law successfully governs the system states and achieves the desired closed-loop performance.

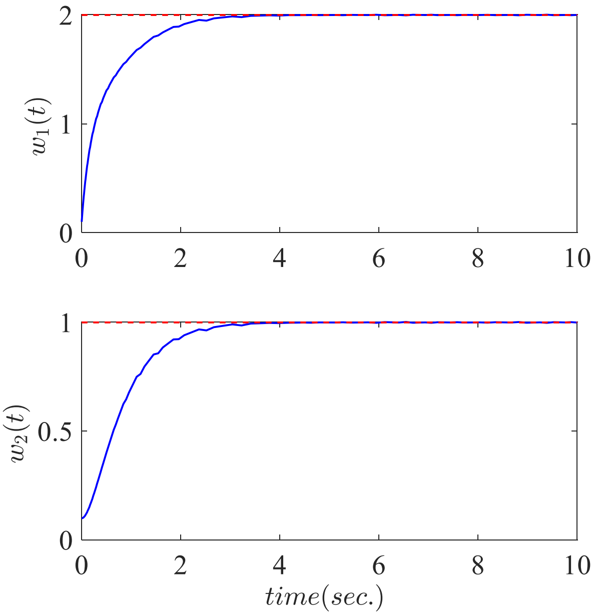

Figure 3. The state of the system $w_1(t)$ and $w_2(t)$.

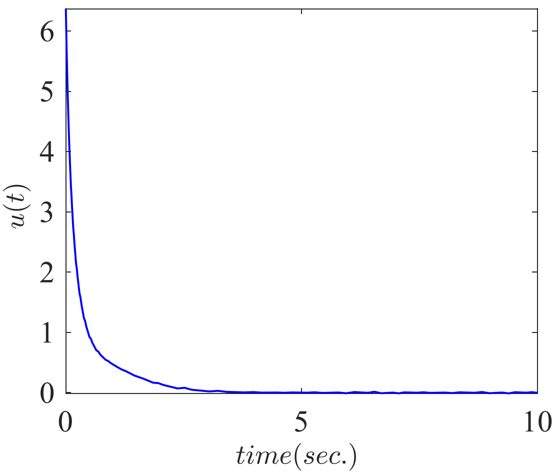

Figure 4. The input control signals for the system $u(t)$.

5.3. Discussion

1. From the first case study, it can be clearly observed that the performance of the proposed state feedback linearization controller is effective and satisfactory, as the system states are successfully driven toward and stabilized at the desired zero steady-state value within approximately 6 seconds, as illustrated in Figure 1. This relatively fast convergence time indicates that the controller is capable of ensuring rapid stabilization of the closed-loop system despite the nonlinear nature of the process dynamics, while maintaining acceptable transient performance.
2. Figure 3 further illustrates that the proposed control law is capable of accurately achieving and maintaining the required steady-state operating condition. The results confirm that the controller successfully regulates the system states to the desired reference value, demonstrating its effectiveness in handling different operating scenarios and ensuring precise tracking performance under the designed control strategy.
3. In both case studies, it is observed that the control input $u(t)$converges to zero after the transient response period. This behavior indicates that the controller does not require continuous or excessive control effort once the system reaches steady state, which is desirable from an energy efficiency and practical implementation perspective. The smooth decay of the control signal also reflects the stability and proper design of the feedback linearization approach.
4. A small overshoot can be noticed in Case 1 for both system states during the transient phase of the response. However, this overshoot is relatively minor and quickly attenuates as the system converges

to the desired steady-state value. Importantly, this transient deviation does not compromise the overall stability of the system or affect the long-term performance of the controller, indicating that the proposed method maintains robust and well-damped behavior.

6. Conclusion

In this paper we developed a a feedback linearization control strategy for a continuous-time chemical stirred tank reactor (CSTR) system, which is inherently nonlinear and challenging to control using conventional linear methods. The main objective of the proposed work is to design an effective control law that ensures accurate regulation of the reactor states and guarantees stable operation at desired steady-state conditions. Firstly, formulation of a transformed system model, where the original nonlinear dynamics of the stirred tank reactor are systematically restructured into a more suitable form for controller design. This transformation simplifies the complexity of the system and enables the application of feedback linearization techniques by effectively compensating for the nonlinearities present in the process. As a result, the control design becomes more structured and analytically manageable. Based on the transformed model, a feedback linearization controller is then designed. To validate the effectiveness and applicability of the proposed method, two simulation case studies are conducted. In the first case study, the controller is evaluated based on its ability to drive the system states to zero. This scenario demonstrates the stabilization capability of the proposed approach and confirms that the closed-loop system achieves asymptotic convergence to the origin. In the second case study, the controller is tested under a different operating condition where the objective is to reach and maintain a desired non-zero steady-state value. This case highlights the flexibility and adaptability of the proposed scheme in handling different reference targets and operating scenarios. The simulation results obtained from both case studies clearly demonstrate that the proposed feedback linearization control strategy provides reliable performance, accurate state regulation, and stable closed-loop behaviour for the continuous stirred tank reactor system. Overall, the study confirms that the developed approach is effective in managing nonlinear chemical reactor dynamics and achieving desired performance objectives under varying conditions.

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