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Adaptive Robust Micro-Displacement Control Strategy for the Servo System of Lithium Battery Electrode Rolling Mills

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Abstract. The electrode rolling process critically determines the consistency and performance of lithium-ion batteries, where precise micro-displacement control of the rolling mill servo system governs electrode thickness uniformity and energy density. Conventional PID or model-based controllers often encounter limitations due to parameter uncertainties, nonlinear friction, and external disturbances during high-precision rolling operations. To address these challenges, this paper proposes an adaptive robust control (ARC) strategy that combines parameter adaptation with robust compensation. The proposed controller enables stable and accurate micro-displacement tracking under uncertain conditions, enhancing reliability and robustness. Simulation and experimental studies on a prototype rolling mill validate the effectiveness of the method, confirming its capability to improve system stability and reduce sensitivity to variations and disturbances. The results highlight the potential of ARC to provide a practical and reliable control solution for intelligent manufacturing equipment in next-generation lithium-ion battery production.

Keywords: adaptive robust control, micro-displacement precision, servo system, electrode rolling process, lithium-ion battery manufacturing

1 Introduction

The rapid development of electric vehicles, renewable energy storage systems, and portable consumer electronics has significantly increased global demand for high-performance lithium-ion batteries [1]. As the core of energy storage technology, the performance and consistency of lithium-ion batteries depend heavily on manufacturing precision [2]. Electrode manufacturing, in particular, is a fundamental step that directly impacts battery capacity, energy density, and long-term reliability. Electrode rolling plays a crucial role in various electrode manufacturing processes [3], as electrode thickness uniformity not only determines electrode packing density but also influences ion transport kinetics and interfacial stability during charge-discharge cycling. Even slight thickness deviations can lead to local current density variations, non-uniform solid electrolyte interface (SEI) growth, and premature battery failure, thereby reducing cycle life and safety [4]. Therefore, achieving microscale precision in electrode rolling has become a core requirement for manufacturing next-generation smart batteries. Despite its critical importance, high-precision electrode rolling remains a challenging task. Rolling mill servo systems are inherently susceptible to dynamic load disturbances caused by nonlinear mechanical properties, material inhomogeneities, and rolling force variations. Furthermore, uncertainties in system parameters introduce additional complexity to control design. Traditional control strategies, such as proportional-integral-derivative (PID) [5], sliding mode control (SMC) [6], and classical adaptive control [7], are widely used in industrial servo systems due to their simplicity and practicality. However, these approaches also have significant limitations: PID controllers are sensitive to parameter variations and lack robustness; SMC is effective under uncertain conditions but suffers from severe jitters, which can damage the actuator; and traditional adaptive controllers often have slow convergence and insufficient stability in the face of sudden disturbances. These shortcomings collectively hinder the realization of high-precision electrode thickness adjustment in real-world production lines, where both robustness and

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adaptability must be ensured [8]. Recent research has attempted to improve servo system accuracy by integrating model-based compensation, nonlinear observers, and disturbance rejection techniques. While these approaches have achieved some performance improvements, they often rely on precise modeling assumptions and are susceptible to time-varying uncertainties and un-modeled dynamics. Furthermore, balancing real-time adaptability and robustness under dynamic operating conditions remains an unresolved issue in electrode rolling mill applications. With the growing demand for smart manufacturing, advanced control strategies are urgently needed to ensure high-precision micro-displacement adjustment while maintaining stability and resilience to uncertainty and disturbances. To address these challenges, this study proposes a micro-displacement adaptive robust control (ARC) strategy for the servo system of a lithium battery electrode rolling mill. The proposed ARC framework combines real-time parameter estimation with robust compensation, thereby combining the adaptability of adaptive control with the interference rejection capability of robust control. This unified design enables accurate micro-displacement tracking under uncertain and time-varying conditions while suppressing the effects of nonlinear friction and external load fluctuations. Simulation studies and prototype rolling mill tests confirm the effectiveness of the proposed strategy, demonstrating improved stability, reduced sensitivity to parameter variations, and strong resilience under dynamic load conditions. Results demonstrate that the ARC-based approach provides a reliable, high-performance control solution for intelligent manufacturing equipment, bringing practical benefits to the production of next-generation lithium-ion batteries.

2 Literature Review

In the realm of advanced manufacturing and precision engineering, the control strategies employed significantly influence the system's performance, including accuracy, robustness, and adaptability to disturbances and uncertainties. This literature review delves into recent developments in control systems for manufacturing, focusing on servo control in rolling mills, advanced control strategies in precision manufacturing, and adaptive robust control theory. Servo control systems in rolling mills have traditionally relied on conventional PID and feedforward strategies to regulate the process and ensure precision. However, these conventional methods sometimes struggle with the complexities of modern manufacturing demands, such as non-linearities, parameter variations, and external disturbances. To enhance performance in precision manufacturing, advanced control strategies have been explored. Sliding mode control, disturbance observers, model predictive control (MPC), and adaptive robust control techniques have gained attention for their potential to offer superior control performance under uncertainty and disturbances. For instance, the development of a redundancy dynamic model incorporating rotation and pitch vibration caused by the change in the center of gravity's position demonstrates an innovative approach to dual-driving feed system control. The introduction of a dynamic model-based cross-coupled sliding mode control (CCSMC) signifies strides towards addressing the intricate dynamics of manufacturing processes [9]. Likewise, the implementation of the GTCF-LARC contouring motion controller for an industrial X–Y linear motor stage underscores the progression towards integrating advanced model predictive control and adaptive robust control frameworks to achieve excellent transient and steady-state contouring accuracy, showcasing the capacity for these advanced controls to enhance both the efficiency and output quality in manufacturing settings [10]. Furthering the exploration into model predictive control, a feedforward MPC approach has shown promise in controlling continuous pulp digesters by leveraging the lignin content variation, a novel concept prioritizing precision and adaptability online [11]. This highlights the evolving landscape of manufacturing control systems towards more data-driven, predictive methodologies that can dynamically adjust to the process variations. The literature also reflects a growing interest in adaptive robust control theory, emphasizing the need to integrate adaptation mechanisms for handling parametric uncertainties with robust designs capable of mitigating the effects of unmodeled dynamics. The observation-based higher-order sliding mode control for large optical astronomical telescopes presents an example where robust control theory is applied in high-precision contexts, ensuring stability and performance even in the face of significant disturbances and uncertainties [12]. On another front, the convergence of robust control strategies with advanced observer designs is evident in the development of the PID integral sliding mode observer for the sensorless control of permanent magnet synchronous motors (PMSM). This approach achieves rapid convergence and enhanced tracking precision while effectively mitigating system jitters, illustrating the fusion of robust control and observer-based strategies for improved system performance [13]. In the context of disturbance observer-based control, new results have been introduced, emphasizing the application to advanced manufacturing. For example, the adaptive vibration rejection achievable through disturbance observation techniques offers a testament to modern control systems' evolving sophistication in combating real-world disturbances, further promoting precision and sustainability in robotic manipulators and other manufacturing devices [14]. In conclusion, the recent literature shows a palpable shift towards more sophisticated control strategies that balance precision, adaptability, and robustness in manufacturing. By advancing beyond traditional PID and feedforward controls towards more intricate architectures like modular predictive control, sliding mode control, and adaptive robust controls, the field is poised to meet the increasingly complex requirements of modern manufacturing processes. These advancements underline the critical role of control engineering in the ongoing evolution of industrial automation and precision manufacturing.

3 System Modeling

The electrode rolling mill used in lithium-ion battery manufacturing is a complex electromechanical system in which precise control of roller displacement is critical for ensuring electrode thickness uniformity [15]. To accurately describe its behavior and provide a foundation for controller design, the system can be modeled by integrating the dynamics of the servo motor, the ball screw transmission mechanism, and the nonlinear electrode compression process, while also considering the uncertainties that arise from friction, material variability, and sensor imperfections [16]. As shown in Fig. 1.

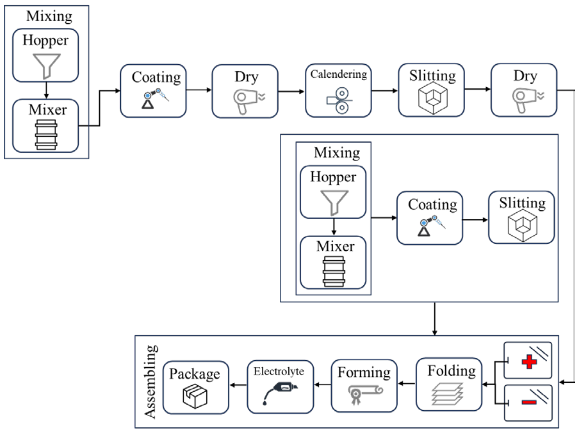

Fig. 1. Lithium battery production process

The servo motor is the main actuator in the electrode rolling mill and the key interface for converting electrical energy into mechanical torque to drive the roller shaft. The dynamic behavior of the motor can be described by a pair of coupled electromechanical equations, which simultaneously describe the mechanical motion of the rotor and the electrical processes in the armature winding:

$$J_m\dot{\omega}_m + B_m\omega_m + \tau_f = K_t i_a - \tau_L, \tag{1}$$

$$L_a\frac{dia}{dt} + R_a i_a + K_e\omega_m = u_a, \tag{2}$$

Where the mechanical dynamics describe how the electromagnetic torque K_t accelerates the rotor with inertia J_m, against viscous damping B_m, nonlinear friction τ_f, and the external load torque τ_L transmitted from the rollers. The electrical dynamics reflect the balance of input voltage u_a across the inductive and resistive elements of the armature winding and the back EMF term proportional to angular velocity. These equations highlight the tight coupling between the electrical and mechanical domains, where current directly influences torque, and rotor velocity induces voltage feedback. In industrial practice, the electrical time constant is usually much smaller than the mechanical time constant, but in high-precision applications such as electrode rolling, the full-order model must be retained to capture transient effects and to ensure robustness against parameter uncertainty. The motor torque is transmitted to the rolling mill through a ball screw mechanism, which performs rotary-to-linear motion conversion [17]. The kinematic relationship between the motor angle and the roller displacement is:

$$x = \frac{p}{2\pi}\theta_m, \dot{x} = \frac{p}{2\pi}\omega_m \tag{3}$$

Indicating that the displacement and velocity of the rollers are directly proportional to the motor's rotation, scaled by the screw lead p. The force transmission can be described as:

$$Fs = \frac{\eta}{r}\tau_m, r = \frac{p}{2\pi}, \tag{4}$$

Where Fs is the axial thrust force, η is the transmission efficiency accounting for mechanical losses, and r is the effective pitch radius. This subsystem introduces additional dynamics such as compliance, backlash, and varying transmission efficiency, all of which act as sources of uncertainty and nonlinear disturbance in the displacement control loop. The rolling process itself imposes nonlinear compression forces on the electrode material [18]. The rolling force can be approximated by the empirical model:

$$F_r = k_r(h_0 - h)^{\alpha}, \tag{5}$$

Where h_0 is the initial electrode thickness, h is the compressed thickness, and the coefficient k_r characterizes the effective stiffness of the electrode stack. The nonlinearity exponent $\alpha>1$ reflects the fact that compaction resistance increases nonlinearly with deformation. Since roller displacement reduces the electrode thickness:

$$h = h_0 - x, \tag{6}$$

This relation leads to a displacement-dependent rolling force:

$$F_r = k_r x^{\alpha}. \tag{7}$$

This expression shows that small deviations in displacement can cause large variations in rolling force, especially at high compression ratios, which makes precise displacement control essential for uniform electrode production. In practical operation, the system is affected by multiple sources of uncertainty. The motor friction torque is not purely viscous but strongly nonlinear, and can be modeled as:

$$\tau_f = F_c sgn(\omega_m) + B_m\omega_m + \Delta f(\omega_m), \tag{8}$$

Where F_c is the Coulomb friction, the second term represents viscous damping, and $\Delta f(\omega_m)$ captures unmodeled phenomena such as Stribeck friction or temperature-dependent effects. Similarly, electrode stiffness is not constant but varies with manufacturing conditions such as porosity, binder content, and calendaring history, and can be expressed as:

$$k_r = k_{r0} + \Delta k_r, \tag{9}$$

Where Δk_r represents batch-to-batch or time-varying uncertainty. Moreover, measurement noise is inevitable in high-resolution displacement sensors, which can be represented as:

$$y = x + n(t), n(t) \sim N(0, \sigma^2), \tag{10}$$

Indicating that the measured signal contains Gaussian-distributed noise. To facilitate controller synthesis, the above dynamics can be expressed in a nonlinear state-space form. By defining the state vector and input, the system dynamics are given as:

$$\ddot{x} = \frac{p}{2\pi J_m}(K_t i_a - B_m \omega_m - \tau_f - \frac{2\pi}{p} F_r), \tag{11}$$

$$\dot{i}_a = \frac{1}{L_a}(u_a - R_a i_a - K_e \omega_m), \tag{12}$$

With the measured output:

$$y = x + n(t). \tag{13}$$

This representation can be compactly written as:

$$\dot{x} = f(x) + g(x)u_a + d(t), \tag{14}$$

Where $f(x)$ describes the nominal nonlinear dynamic, $g(x)$ denotes the input mapping, and $d(t)$ aggregates the uncertain and disturbance terms, including nonlinear friction, stiffness variations, and measurement noise. The entire servo system utilizes a closed-loop control architecture, as shown in Fig. 2. Input commands are processed by the system controller and servo driver, converted into torque by the servo motor, and then output by the electro-hydraulic actuator. Sensor feedback signals are corrected in real time, enabling precise regulation even in the presence of interference.

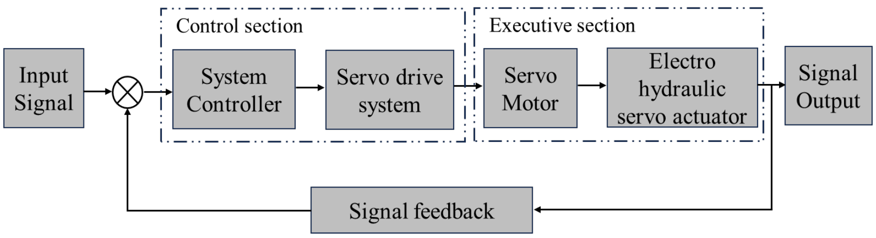

Fig. 2. Control system schematic diagram

4 Control Strategy Design

To achieve high-precision micro-displacement control of an electrode rolling mill servo system under parameter uncertainty and external disturbances, this paper develops an ARC scheme. This controller integrates two complementary components: an adaptive component for online parameter estimation and a robust component for compensating for unmodeled dynamics and bounded disturbances [19]. Together, these two components ensure accurate trajectory tracking and stability. The output tracking error is defined as:

$$e = y - y_d, \tag{15}$$

Where y_d is the desired displacement trajectory. The control objective is to design such that e→0e or remains bounded within a small neighborhood under all admissible uncertainties.