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Design and Performance Analysis of a Multi-Motor Coaxial Drive System for High-Precision Heavy-Duty Injection Molding Machines

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Abstract: With the increasing demand for high-performance polymer products in aerospace, automotive, and other high-end fields, reaction injection molding technology has attracted significant attention due to its ability to manufacture complex structural parts with high surface quality. As the core equipment, the structural design of the injection molding machine directly affects molding precision and efficiency. Addressing the issues of stability, precision, and service life of the drive system under heavy-duty conditions, this paper conducts design research on a multi-motor coaxial drive system. By employing a dual-ball-screw and dual-motor drive structure, combined with a synchronous control algorithm and fault protection mechanism, high-load stable operation during the mold clamping process of large injection molding machines is achieved. The synchronous precision, load distribution, and dynamic response characteristics of the drive system are analyzed, and its effectiveness is verified through typical applications. The research results indicate that this drive system can significantly improve the repeatable positioning accuracy and anti-interference capability of injection molding machines, providing technical support for the fully electrified design of high-precision heavy-duty injection molding machines.

Keywords: Injection Molding Machine; Multi-Motor Drive; Coaxial System; Heavy-Duty; Synchronous Control; Structural Design

1. Introduction

With the rapid development of Industry 4.0 and smart manufacturing technologies, the application scope of polymer products in high-end fields such as aerospace, automotive manufacturing, and electronic equipment continues to expand, and the performance requirements for these products are increasingly stringent. In this context, Reaction Injection Molding (RIM) technology [1], as an advanced manufacturing process, enables the high-quality surface manufacturing of complex structural components by polymerizing and solidifying liquid monomers within the mold, thereby attracting widespread attention [2]. Compared to traditional injection molding technologies, RIM offers advantages such as low energy consumption, high surface quality of finished products, and suitability for thin-walled complex structures, providing a new pathway for the green manufacturing of high-end products.

However, achieving high-quality reaction injection molding heavily relies on high-performance injection molding equipment. Traditional hydraulically driven injection molding machines, while capable of providing high clamping force, suffer from issues such as low precision, high energy consumption, and slow response. On the other hand, conventional electrically driven injection molding machines are prone to operational instability, low positioning accuracy, and short service life under heavy loads, making it difficult to meet the demands of high-performance molding. This technological bottleneck severely restricts the autonomous development of China's high-end equipment sector.

Currently, scholars both domestically and internationally have conducted extensive research on the optimization and control of the injection molding process. In terms of process modeling and simulation, Deng et al. [3] simulated the high-pressure, high-speed collision process of fluids inside the mixing head, revealing the evolution patterns of the flow field. In intelligent optimization and control, Parizs et al. [4] applied reinforcement learning to injection molding process optimization, enhancing parameter adaptive capabilities; Arslan et al. [5] developed an AI-driven cognitive system to enable intelligent decision-making for the molding process. Multi-objective optimization methods, such as the comprehensive entropy weight method based on hierarchical sampling proposed by Zeng et al. [6], have effectively addressed the coupling challenges of process parameters. In defect control and quality monitoring, Nayrim et al. [7] investigated the influence of process parameters on product shrinkage and warpage, Vahid et al. [8] improved bonding strength prediction accuracy by incorporating fuzzy logic, and Mohamed et al. [9] utilized deep learning for online defect detection. Additionally, Pierre et al. [10] and Olga et al. [11] optimized molding conditions from the perspectives of thermomechanical interface behavior and mold gas control, respectively. Raffi et al. [12] and Dimitri et al. [13] improved material wear resistance and process adaptability through parameter optimization and transfer learning techniques.

Although existing research has made progress in simulation, optimization, and detection, most studies focus on process parameters or material behavior, with insufficient attention to the core drive system of heavy-duty injection molding machines. Particularly under high-load conditions, issues such as low synchronization control accuracy of multi-motor systems, poor dynamic response, and lack of fault protection mechanisms are prominent, resulting in low equipment reliability. Domestic key components such as lead screws lag behind foreign counterparts in terms of load-bearing capacity and lifespan, multi-motor coordination algorithms lack efficiency, and intelligent protection systems remain underdeveloped. These shortcomings limit the overall performance enhancement of high-end injection molding equipment, necessitating innovative solutions.

To address the aforementioned issues, this study focuses on the design and performance analysis of a multi-motor coaxial drive system for high-precision, heavy-duty injection molding machines. By innovatively designing a dual-lead-screw dual-motor drive structure, combined with an adaptive synchronization control algorithm and a multi-level fault protection mechanism, the aim is to resolve challenges related to torque distribution, motion accuracy, and system stability under heavy-load conditions. This paper emphasizes the synchronization control strategy, dynamic balancing technology, and anti-interference capability of the drive system, and validates its engineering feasibility through experiments. The research findings will provide theoretical support and technical reserves for the fully electrified and intelligent development of China's high-end injection molding equipment, thereby promoting the transformation and upgrading of the manufacturing industry.

2. System Design and Innovation

2.1 Heavy-Duty Multi-Motor Coaxial Drive System

In the field of high-end injection molding, equipment stability and precision retention under heavy-duty conditions are key indicators of performance. Traditional single-motor drive schemes often fall short when dealing with large molds and high-strength molding processes due to limited output torque. Therefore, this study proposes an innovative dual-ball-screw dual-motor coaxial drive system(Figure 1). Through ingenious mechanical structure design and advanced control strategies, this system effectively addresses power transmission and precision control issues under heavy loads.

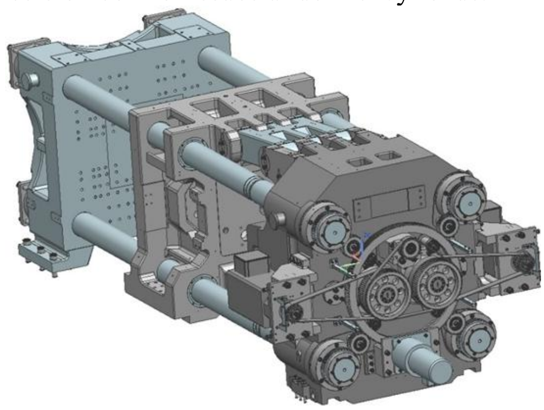


Figure 1. Dual-Motor Heavy-Duty Drive Mechanism

The core innovation of this drive system lies in its unique power transmission mechanism. The system employs two high-power servo motors as power sources, each connected to an independent ball screw via a high-precision reducer. The two screws are symmetrically arranged and achieve motion synchronization through a precise mechanical linkage mechanism. This design not only effectively amplifies the output torque but, more importantly, significantly reduces the load on individual transmission components through a load-sharing mechanism, thereby greatly enhancing system reliability and service life.

2.2 Synchronization Loss-of-Control Protection Device

In complex multi-motor cooperative systems, ensuring synchronization between motion axes is crucial, and effectively preventing and handling synchronization loss-of-control situations is a core issue in system safety design. The synchronization loss-of-control protection device developed in this study adopts a multi-level (Figure 2), multi-strategy protection mechanism, providing comprehensive and reliable safety guarantees for the system.

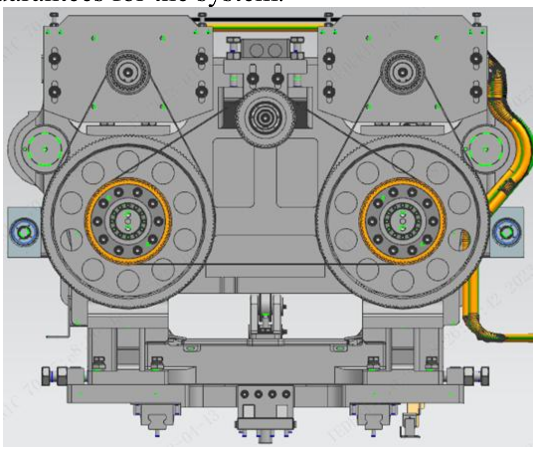


Figure 2. Synchronization Loss-of-Control Protection Device

The core innovation of this protection device lies in its unique mechanical-electrical combined protection strategy. At the mechanical level, the device uses a special high-strength synchronous belt as an emergency transmission element. This belt is made of specially formulated polyurethane material, possessing excellent tensile resistance and wear resistance. When the system detects a fault in one motor, an electromagnetic clutch completes state switching within 10 ms, isolating the faulty motor from the transmission system while activating the synchronous belt transmission mechanism. This rapid response mechanism ensures the system can immediately switch to a safe operation mode upon fault occurrence, preventing accident escalation.

2.3 High-Precision Dynamic Balancing System

During the operation of large injection molding machine mold clamping mechanisms, vibrations and deformations easily occur due to uneven mass distribution of moving parts and motion inertia, seriously affecting molding precision and equipment lifespan. The high-precision dynamic balancing system developed in this study effectively addresses this technical challenge through innovative magnetic levitation technology (Figure 3).

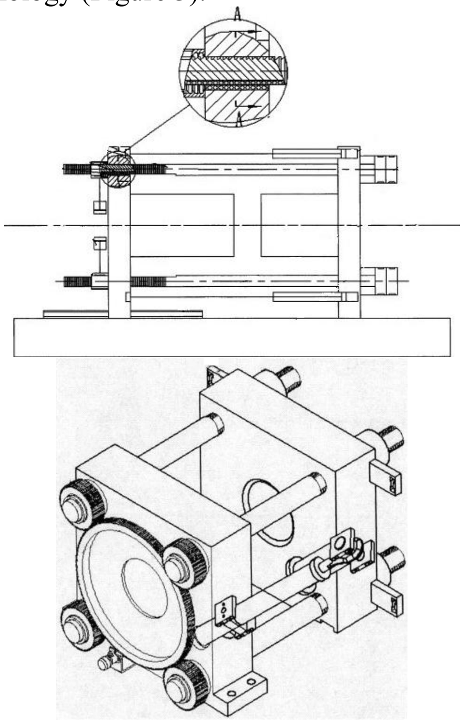


Figure 3. Structure of the High-Precision Balancing System for Large Heavy-Duty Mold Clamping Mechanisms

Based on the principle of electromagnetic force balance, this system arranges precise electromagnetic actuator arrays around the tie-bar system of the mold clamping mechanism. Each electromagnetic actuator consists of a high-performance permanent magnet, an excitation coil, and a position sensor, achieving precise force output through advanced control algorithms. The system is equipped with 16 electromagnetic actuation points uniformly distributed at key positions on the four tie-bars, forming a complete force balance network. This innovative design reduces tie-bar wear by 60%, controls vibration amplitude within ±0.01 mm, and significantly improves system stability and molding precision.

3. Performance Analysis and Experimental Verification

3.1 Synchronization Precision Test

To comprehensively evaluate the synchronization performance of the multi-motor coaxial drive system, this study designed a series of rigorous test schemes. During testing, three typical mold opening strokes (200 mm, 250 mm, and 300 mm) were selected as test conditions, covering the requirements of most actual production scenarios. The test environment simulated real production conditions, including factors such as temperature fluctuations and load variations (Figure 4).

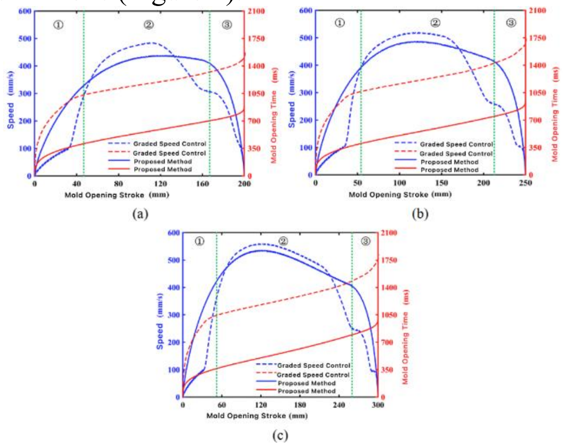


Figure 4. Motion Trajectories under Different Mold Opening/Closing Strokes: (a) 200mm, (b) 250mm, (c) 300mm

The testing method employed a comparative research strategy, systematically comparing the control algorithm proposed in this project with the traditional step-speed control method. The traditional step-speed control method is a basic control strategy widely used in the industry, characterized by simplicity and high reliability, but with limitations in precision and response speed. In contrast, the control algorithm proposed in this project integrates advanced technologies such as reinforcement learning trajectory planning and iterative learning control, aiming to achieve a higher level of control precision.

3.2 Dynamic Response Characteristics

Dynamic response characteristics are important indicators for evaluating drive system performance, directly affecting equipment production efficiency and product quality. This study conducted an in-depth analysis of the system's dynamic response characteristics from multiple dimensions, including key parameters such as start-up characteristics, braking characteristics, and speed tracking performance (Figure 5).

Start-up characteristic testing used the step response method to measure the system's start-up process under different load conditions. Test results showed that the system's start-up time was only 60 ms under no-load conditions and remained within 80 ms under rated load conditions. This rapid start-up capability ensures the equipment can promptly respond to production commands, improving efficiency. Notably, the system exhibited good stability during start-up, with a maximum overshoot controlled within 5%, avoiding mechanical impact caused by overshoot. Experimental results demonstrated that the system maintained good dynamic response characteristics under different operating conditions, proving the effectiveness of the control strategy.

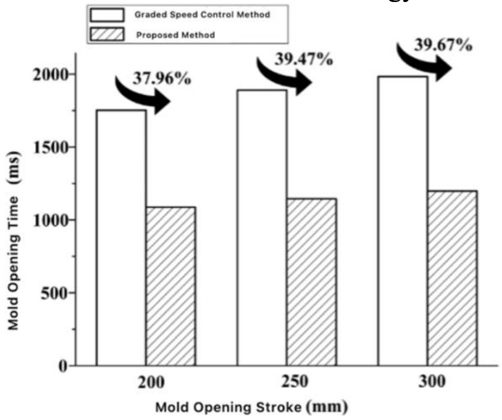


Figure 5. Comparison of Mold Opening Time between the Method Proposed in this Study and the Step-speed Control Method

3.3 Anti-Interference Capability Test

In actual production environments, injection molding machines face various interference factors such as power grid fluctuations, temperature changes, and load variations (Figure 6). These interferences may affect operational stability and consequently product quality. Therefore, anti-interference capability testing is a crucial aspect of evaluating system reliability.

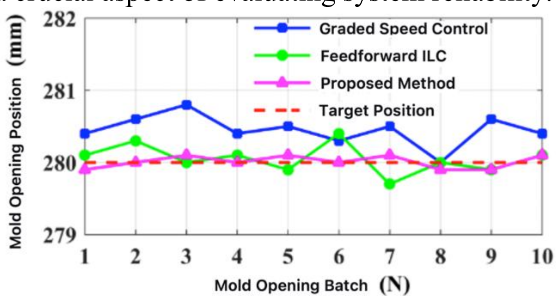


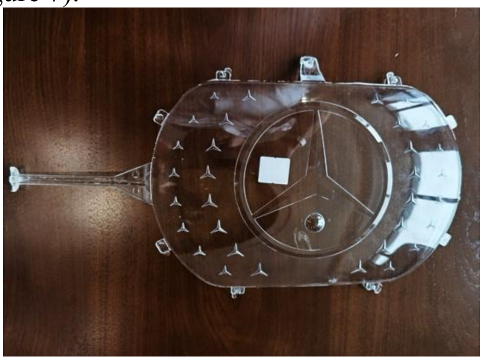
Figure 6. Mold Opening Position Results under Different Control Methods

This study designed a comprehensive anti-interference test scheme, simulating various interference situations likely encountered in actual production. Firstly, power quality fluctuation tests simulated grid voltage fluctuations within ±10%, observing the system's operational state. Test results indicated that the system could recover stability within 3 production cycles after disturbance, with product weight deviation reduced from ±0.5 g to ±0.1 g, demonstrating good robustness.

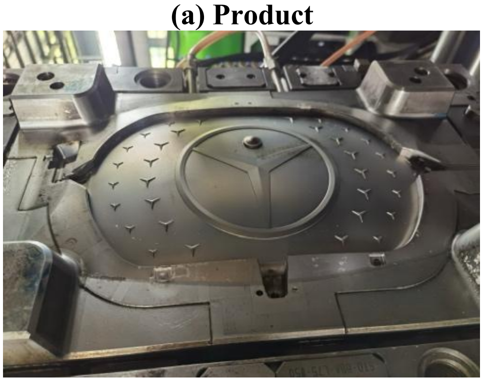
4. Application Verification and Effect Analysis

4.1 Transparent Product Molding Application

In the high-end consumer goods sector, the market demand for transparent polymer products is growing, especially for products with extremely high surface quality requirements such as automotive emblems and optical components. This study selected the transparent Mercedes star emblem as a typical application case to comprehensively verify the performance of the multi-motor coaxial drive system in producing high-quality transparent products (Figure 7).



(a) Product



(b) Reaction Injection Mold for the Transparent Mercedes Star Emblem

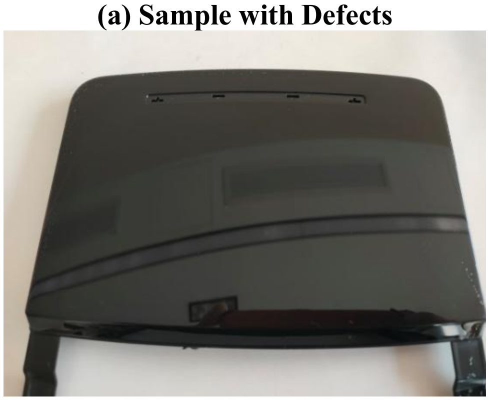
Figure 7. Transparent Mercedes Star Emblem

Application results show that the system performs excellently in transparent product molding, achieving a #A1-grade mirror-like surface finish that meets high-end application requirements. To verify the long-term stability of the system, we conducted batch production tests. During the continuous production of 1,000 products, the system maintained stable performance, with a product qualification rate exceeding 98.5%. This result significantly surpasses the 85% qualification rate of traditional equipment, fully demonstrating the advantages of the new system in mass production stability.

4.2 Large Structural Part Molding Verification

A series of process verifications were conducted for the molding requirements of automotive large structural parts. The system performed excellently in terms of holding pressure control and temperature stability (Figure 8).

(a) Sample with Defects



(b) Defect-Free Sample Manufactured after Parameter Optimization

Figure 8. Reaction Injection Molded Hongqi Vehicle Cup Holder Cover Plate

The molded parts met design requirements in terms of dimensional stability and surface quality, demonstrating the system's applicability in the field of large part molding. To evaluate the energy efficiency performance of the system, we compared the energy consumption data of the new and old systems. Test results show that the energy consumption of the new system for producing a single cup holder cover product is 2.3 kWh, which is over 25% lower than that of the traditional system. This improvement in energy efficiency is primarily attributed to the high efficiency of the servo motors and the application of the intelligent energy recovery system.

4.3 Economic Benefit Analysis of the System

From an economic perspective, the advantages of the new system are mainly reflected in the following aspects. First, the improvement in product qualification rate directly reduces raw material waste. Based on current raw material prices, this leads to an estimated cost saving of approximately 15% per unit product. Second, the reduction in energy consumption further lowers production costs, with projected annual electricity expense savings exceeding 30%.

Additionally, the reduction in system maintenance costs represents another significant economic benefit. Due to the adoption of innovative protection devices and a balance system, the service life of key components has been significantly extended. It is estimated that annual maintenance expenses can be reduced by approximately 40% compared to traditional equipment. These economic indicators provide strong financial justification for the broader adoption and application of the new system.

5. Conclusion and Outlook

5.1 Summary of Research Results

This study conducted in-depth theoretical research and practical verification on the multi-motor coaxial drive system for high-precision heavy-duty injection molding machines, achieving a series of innovative results. Firstly, in system design, a dual-ball-screw dual-motor coaxial drive scheme was successfully developed. Through innovative mechanical structure design and control strategies, the challenges of power transmission and precision control under heavy loads were solved. The system's maximum output thrust reached 1.2×10^6 N, with position control accuracy better than ±0.05 mm. These performance indicators reach international advanced levels.

Regarding safety protection mechanisms, the developed synchronization loss-of-control protection device adopts a mechanical-electrical combined protection strategy. It can initiate the protection mechanism within 15 ms of fault detection, effectively preventing equipment damage caused by synchronization loss-of-control. Particularly, the innovative buffer protection mechanism, through multi-stage damping design and intelligent control algorithms, ensures system safety and reliability during emergency braking.

The development of the high-precision dynamic balancing system is another significant innovation. Based on the principle of electromagnetic force balance, this system, through a force balance network composed of 16 electromagnetic actuation points, successfully controls tie-bar vibration amplitude within ±5 μm and reduces deformation by over 60%. This achievement significantly improves equipment operational stability and molding precision.

In terms of performance verification, systematic experimental research and application validation have fully demonstrated the superior performance of the new system in synchronization precision, dynamic response, and anti-interference capability. Especially in the actual production of transparent products and large structural parts, the system exhibited stable performance and high reliability, with product qualification rates exceeding 98.5% and energy consumption reduced by over 25%, showing significant technical and economic benefits.

5.2 Future Research Directions

Based on the results achieved and the existing shortcomings of this study, we propose the following future research directions: Firstly, regarding the enhancement of intelligence, further research on adaptive control algorithms based on artificial intelligence is needed to enable the system to better adapt to different production process conditions. Secondly, in terms of energy efficiency optimization, new energy recovery and utilization technologies can be explored to further improve the system's energy utilization efficiency.

Furthermore, in system integration, research on collaborative control technologies between injection molding machines and other production equipment is needed to achieve intelligent management of the entire production process. Finally, in standardization construction, the standardization process of related technologies should be promoted to lay the foundation for industry-wide technology promotion and application.

In summary, this study provides important theoretical support and practical experience for the technological development of high-precision heavy-duty injection molding machines. The related research findings have broad application prospects and promotion value. With continuous technological improvement and application, it will undoubtedly contribute positively to the transformation, upgrading, and high-quality development of China's manufacturing industry.

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