Scholar Publishing Group
International Journal of Engineering Exploration and Construction
https://doi.org/10.38007/IJEEC.2025.040101
ISSN: 2789-8385 Vol. 4, Issue 1: 1-9

Research on Driving and Controlling Technology of High Speed and High Precision Based Flexible Material Cutting System

Bin Zhou[1], Tiesheng Liu[1], Zongwang Cai[1], Shufeng Zhang[2]

[1]*Jingwei Systemtechnik Ltd.,Ningbo City,China*

[2]*Ningbo City College of Vocational Technology*

Keywords: Flexible material; Cutting process; Synchronous control system

Abstract: Aiming at the problems of high reliance on manual labor and insufficient precision in the flexible material cutting process of the textile and garment industry, this paper proposes a driving control technology for a high-speed, high-precision and intelligent flexible material cutting system. By integrating multi-field coupling modelling, multi-objective electromagnetic optimization design and thrust fluctuation suppression technology, the thrust performance and temperature rise characteristics of the motor are optimized. Furthermore, a dual-motor synchronous control system was developed based on the deviation coupling and fuzzy PID algorithm, reducing the synchronous error to the sub-micron level and improving the control accuracy. This research achievement is of great significance in promoting the transformation of the textile and garment industry towards small-batch, high-precision and flexible production.

1. Introductions

Flexible materials cutting technology has long been a cornerstone of the textile and garment industry, involving the precise patterning and cutting of diverse materials such as fabric and leather. However, traditional cutting process, which rely heavily on manual labour, not only constrain production efficiency but are also prone to process fluctuation due to human error, making it challenging to achieve the product consistency demanded by modern standardised manufacturing. In labour-intensive textile and garment enterprises, cutting workers account for over 40% of the workforce, underscoring the critical role of the cutting process within the overall production workflow. Such reliance on low-precision manual cutting methods results in significant material wastage and high labour intensity for workers, while also failing to meet the growing consumer demand for superior garment quality. With technological advancements and evolving market dynamics, the garment industry is progressively shifting from a single, high-volume production model towards a more diverse, personalised, high-quality, and small-batch one.

Against this backdrop, traditional cutting methods, due to their inherent limitations such as low cutting precision, inconsistent quality, lengthy update cycles, limited added value, and low production efficiency, have significantly impeded the development of the garment industry. To address these challenges, the development of the high-speed, high-precision intelligent cutting system for flexible materials has emerged as a timely solution. The system has not only markedly enhanced cutting speed and accuracy but also substantially improved material utilisation and shortened product development cycles, delivering greater cost-effectiveness and production capacity for businesses. Therefore, research into the high-speed, high-precision cutting system for flexible materials holds profound theoretical significance and offers substantial practical value in advancing technological progress and industrial transformation within the textile and garment industry.

2. Overall Technical Route for Flexible Material Cutting Systems

Flexible material cutting systems need to deliver both high-speed, high-precision movement and intelligent functionality, with their foundation rooted in a deep understanding and innovative advancement of the cutting process for flexible materials. By integrating high-speed, high-precision design and control technologies, computer vision, big data, and Internet of Things, we have undertaken a series of critical technological developments to enhance existing flexible material cutting systems.

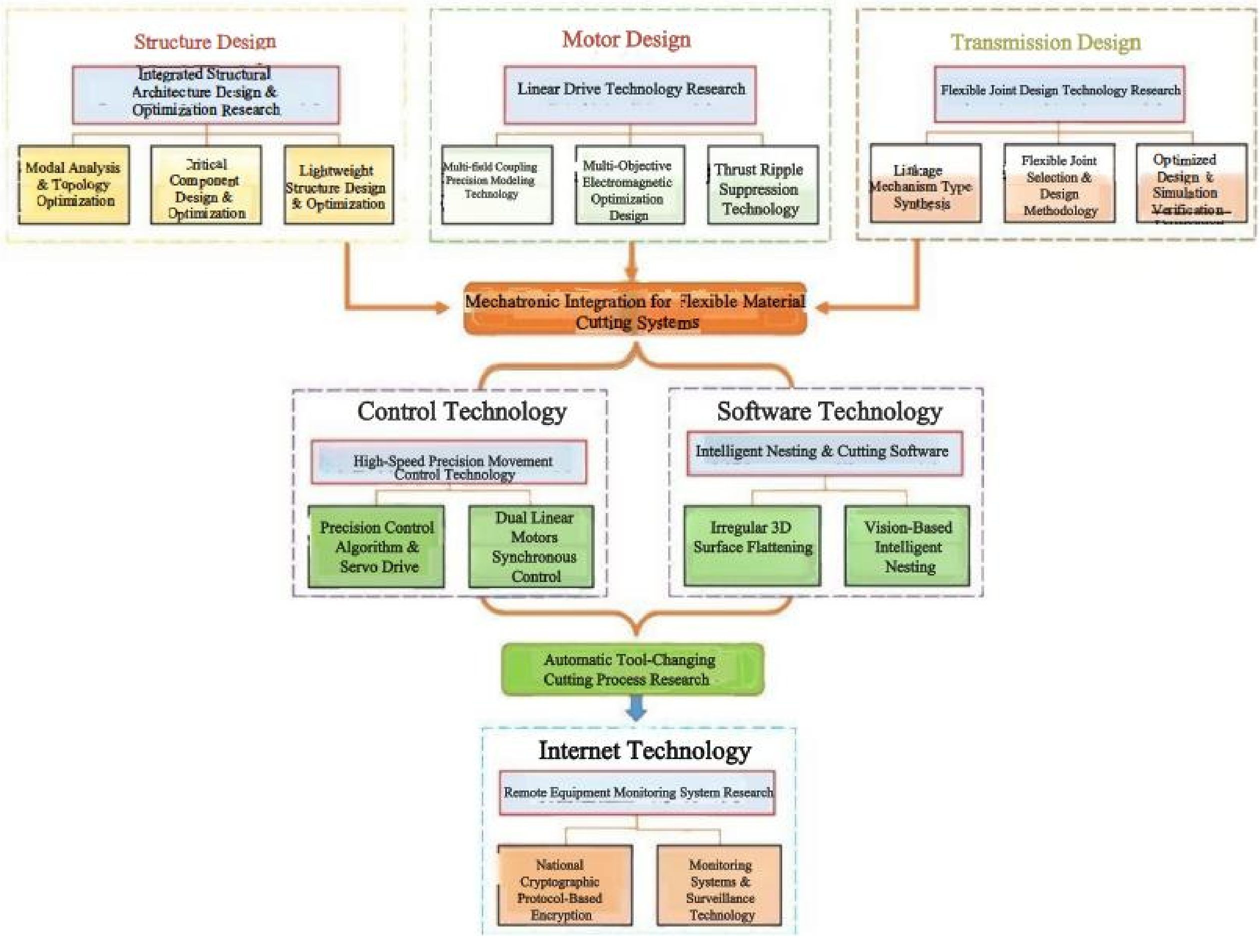

Figure 1. Overall Technical Route Diagram

The objective is to achieve high-speed moving, precise cutting, and intelligent, networked production management, thereby comprehensively improving product processing quality, increasing production efficiency, and effectively reducing costs. In this process, the drive control technology for high-speed, high-precision flexible material cutting systems plays a pivotal role. This technology not only directly determines the precision of the cutting equipment and the final product quality but also serves as a critical factor in achieving key performance indicators such as high speed, high precision, and rapid response. The overall technical route for the development of a high-speed, high-precision, intelligent flexible material cutting system is illustrated in Figure 1.

The primary development focus of this flexible material cutting system includes structural design, drive technology, and transmission design, with control technology and software technology serving as its core components. The structural design and optimisation of the flexible material cutting system involve studies on overall structural performance analysis and topology optimisation of the system, design and optimisation of critical components, and lightweight design and optimisation, all aimed at enhancing the system's reliability and stability. The drive design requires precise multi-field coupling modelling, multi-objective electromagnetic optimisation, and thrust fluctuation optimisation to provide high-speed, high-precision, and cost-effective linear drives for the cutting system. The transmission design, specifically flexible joint design technology, requires research into linkage synthesis, selection and design of flexible joints, optimisation design, and simulation verification to address redundancy issues in double linear drives and improve the smoothness and reliability of the cutting system's high-speed, high-precision movement. Furthermore, research into high-speed, high-precision movement control technology, including precision control algorithms, servo driver design, and synchronous control technology, is conducted to elevate the cutting system's movement control capabilities.

As evident from the overall technical route diagram, continuous optimisation of drive control technology can further enhance the comprehensive performance of the flexible material cutting system, thereby meeting the growing production demands of the textile and garment industry.

3. Linear Drive Technology for Cutting Systems

3.1 Precision Multi-Field Coupling Modelling Technology

For the special topology structure of permanent magnet linear motors within the high-performance flexible material cutting system, a three-dimensional transient electromagnetic field model was developed using the finite element method. This model incorporates characteristics of the cutting systems under actual extreme working conditions, enabling the precise calculation of copper losses in the armature winding, iron losses in the primary iron core, and eddy current losses within the permanent magnets.

Based on the heat transfer theory, a three-dimensional transient temperature field model was developed for the permanent magnet linear motor. Within this model, the determination of the heat dissipation coefficient is critical, as it directly affects the precision of the temperature field distribution profiles. The hot source data incorporated into the model is derived from previously established loss values obtained via finite element analysis. This framework enables the acquisition of detailed temperature field distribution profiles throughout motor operation.

To further enhance calculation accuracy, the calculated temperature data were reintroduced into the electromagnetic field model for iterative computation. The interactive iteration between the electromagnetic and temperature field models simulates the motor's electromagnetic properties and thermal performance more precisely.

The motor's mechanical strength was evaluated using a finite element stress model. This step is crucial for ensuring the structural resilience of the motor under diverse mechanical stresses during actual operation.

This multi-field coupling model not only facilitates a thorough study into how the motor structure and working state influence electromagnetic thrust and temperature rise, but also provides a robust theoretical foundation for lightweight motor design. Through motor structure optimisation, this approach achieves weight and cost reduction without compromising performance, thereby satisfying the high-speed, high-precision requirements of flexible material cutting systems.

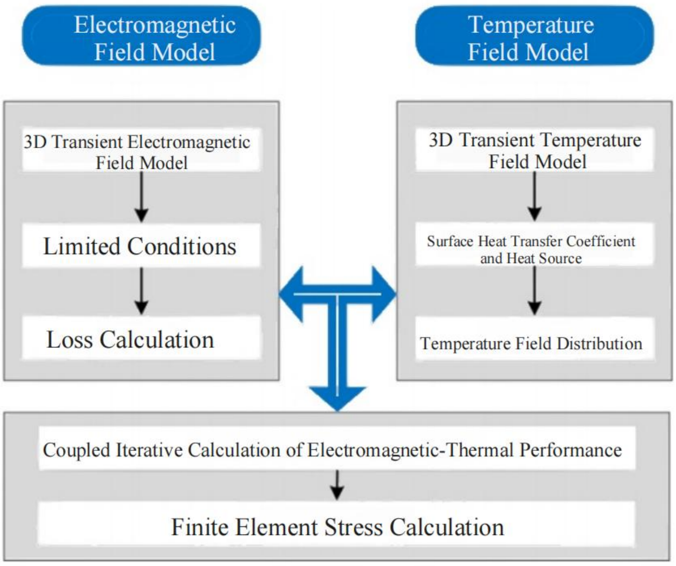

Figure 2. Linear Motor Multi-field Coupling Modelling Technology

3.2 Multi-objective Electromagnetic Optimisation Design Technology

To facilitate multi-objective electromagnetic optimisation design, the procedure begins by computing the motor's equivalent circuit parameters via the coupling of subdomain models and finite element models. This methodology explicitly accounts for the saturation and coupling of magnetic circuits and temperature influences. Subsequently, the equivalent circuit parameters are calculated to obtain the equivalent circuit, enabling the determination of target functions, optimisation variables, and electromagnetic constraint conditions. The multi-target optimisation problem can be summarised as:

$$\begin{aligned}
&\min y = f(x) = [f_1(x), f_2(x), \cdots, f_n(x)] \\
&n = 1, 2, \cdots, N \\
&s.t. \quad g_i(x) \le 0, i = 1, 2, \cdots, m \\
&h_j(x) = 0, j = 1, 2, \cdots, k \\
&X = [x_1, x_2, \cdots, x_d, \cdots, x_D] \\
&x_{d\ \min} \le x_d \le x_{d\ \max}, d = 1, 2, \cdots, D
\end{aligned}$$

where x is a D-dimensional decision vector; y denotes the target vector; N represents the total number of optimisation targets; gi (x)⩽0 and hj (x)=0 denote condition constraints (as a known and defined feasible region); X is the decision space formed by the decision vector; Y represents the target space form by the target vector; while xd_max and xd_min define upper and lower search limits for vectors in each dimension.

In the design of the high-performance flexible material cutting system, a three-tier optimisation target system was established, comprising the speed-precision ratio, processing cost coefficient, and yield threshold. Through multi-generational evolution, individuals in the population progressively converged towards the Pareto optimal solution set for this multi-objective optimisation problem. This approach simultaneously satisfied the cutting system's mechanical property requirements while achieving dual objectives of cost reduction and noise suppression. Such optimisation results not only enhance the service life and operational stability of the motor system but also provide critical theoretical guidance for determining rational motor structural parameters. The methodology ensures that the high-performance flexible material cutting system delivers both efficiency and cost-effectiveness in practical applications, offering robust support for the technological advancement and industrial upgrading of the textile and garment sector.

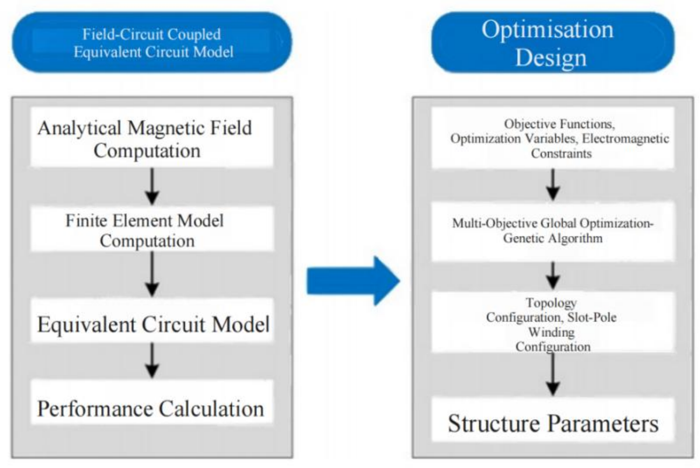

Figure 3. Linear Motor Multi-objective Electromagnetic Optimisation Design Technology

3.3 Thrust Fluctuation Suppression Technology Study

Linear motors suffer from the drawback of significant thrust fluctuations, which, in the absence of buffering or damping mechanisms typically provided by intermediate mechanical transmission components, act directly on the motor itself.

This severely impairs the motor’s operational performance and degrades its control characteristics, creating a significant conflict with the objectives of high-speed, high-precision servo transmission applications. To address the critical technical challenge of minimising thrust fluctuations, research was conducted focusing on the specific characteristics of this issue in linear motors. Theoretical analysis and digital simulation studies were performed on the minimisation design methods for the primary components of static thrust fluctuations, including end forces, cogging forces, and electromagnetic pulsations, establishing a theoretical foundation and prediction method for optimal parameter design.

To comprehensively eliminate the impact of thrust fluctuations on linear motor performance, an innovative motor body structure was proposed. Its characteristics and application methods were systematically analysed and validated, with its underlying principles experimentally verified.

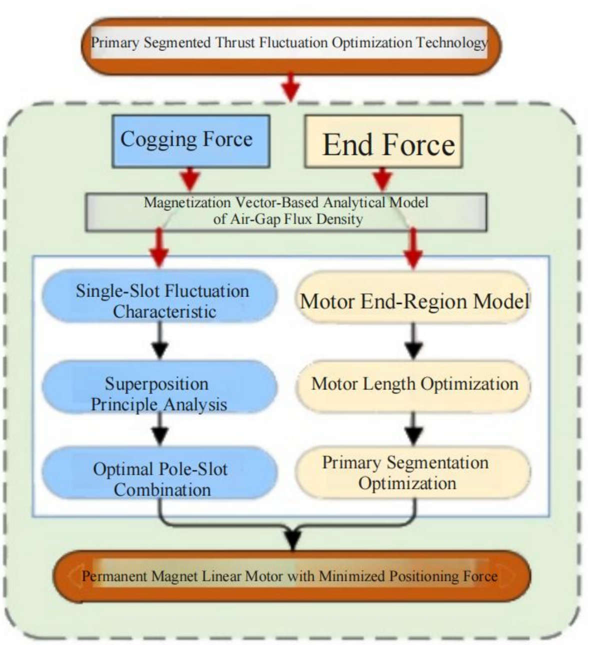

Figure 4. Linear Motor Thrust Fluctuation Optimisation Technology

4. Flexible Driving Technology

This cutting system innovatively incorporates direct-drive technology, with a symmetrical design in the X-direction employing two linear motors operating simultaneously. This configuration not only significantly enhances the machine’s movement speed and precision but also reduces wear by minimising transmission components, thereby extending the equipment’s service life. However, the rigid connection between the X-direction linear motors and the Y-direction beams may introduce a redundant drive issue, where asynchrony between the two motors causes movement interference, consequently affecting the movement stability of the system.

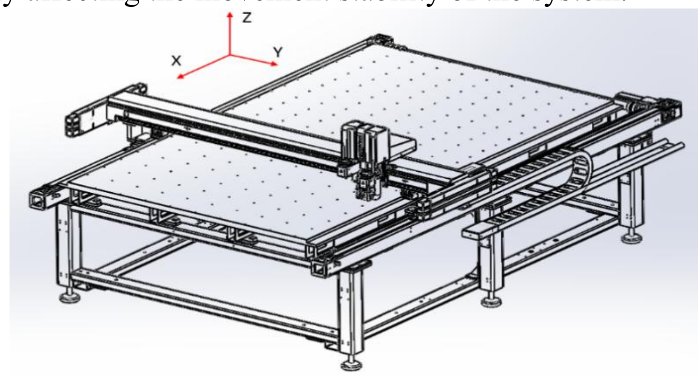

Figure 5. Schematic Diagram of the Cutting System with Linear Motor Drives

To address this issue and enhance movement stability, flexible joints were innovatively adopted, transforming the original rigid connection with redundant drive into a flexible drive with deterministic movement. This approach successfully eliminated the movement interference, achieving more stable and efficient cutting operations.

4.1 Linkage Synthesis Design

To address the redundant drive issue in the X-direction of the cutting system driven by dual linear motors, a thorough analysis was conducted on the characteristics and degrees of freedom of planar movement in the cutting process. Recognising that introducing an additional degree of freedom could eliminate redundancy, research focused on linkages. As the five-bar linkage represents the simplest form with two degrees of freedom, it was selected to mitigate the redundant drive issue.

In the topology analysis of the five-bar mechanism, a comprehensive study was conducted, starting from the basic five revolute joints (RRRRR) and progressively replacing revolute joints with prismatic joints, ending up in a five-bar mechanism with five prismatic joints (PPPPP). By replacing R and P joints in order, various types of five-bar mechanisms were obtained. From these, a five-bar mechanism was identified whose topology aligns with the movement requirements of the cutting system in the X-direction.

In the flexible material cutting system described herein, the two linear motors in the X-direction, which perform reciprocating linear movement, can be turned into two prismatic joints, namely linear reciprocating movement joints. Consequently, within the five-bar mechanism's five joints, the first joint on the left is a prismatic joint, and the first joint on the right is also a prismatic joint. Meanwhile, the rigid connections between the Y-direction beam and the two X-direction motors can be modelled as joint combinations such as PPP, PRP, or RRR, collectively forming a five-bar mechanism akin to a PRPRP mechanism. The three intermediate joints in this mechanism offer multiple configuration possibilities.

Analysis of the actual movement of this cutting system under conditions of redundant drive revealed that, when movement anomalies such as jamming occur in the two linear motors in the X-direction, coupling arises between the movement of the X-direction motors and the Y-direction beam. This coupling manifests as both minor deformation along the beam's direction and slight rotation about the Z-axis, necessitating a decoupling design. By replacing the rigid connection on one side with a PR joint and on the other side with an R joint, combined with two additional P joints, a PRPRP five-bar mechanism is formed, as illustrated in Figure 6. This innovative design not only resolves the redundant drive issue but also further enhances the movement stability and precision of the cutting system.

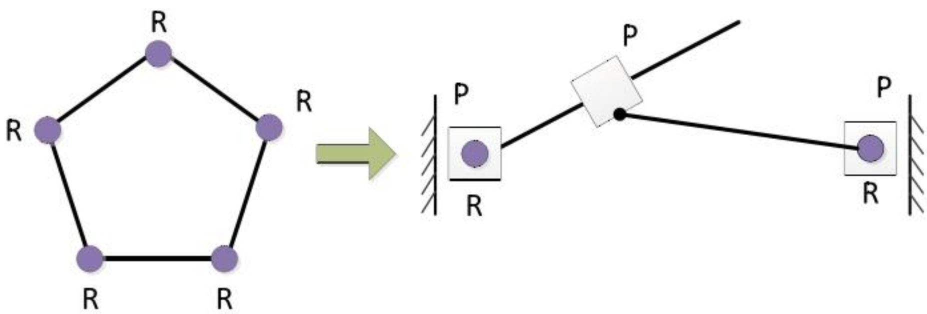

Figure 6. Diagram of Five-bar Mechanism Topology Analysis

4.2 Flexible Joints Design

Based on the comprehensive analysis of the model, structural design can be undertaken for the PRP joint, specifically by embodying the PR and R joints within the five-bar mechanism. Given that the rigid connection between the linear motor in the Z-direction and the Y-direction beam exhibits both slight rotation and minor displacement during unsteady movement, a flexible mechanism based on a cross-reed configuration (as shown in Figure 7) was selected as the design solution. This enables the establishment of a preliminary design model for the flexible joint (as depicted in Figure 8).

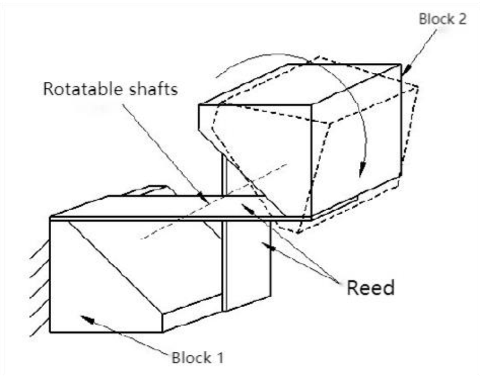

Figure 7. Cross-reed Flexible Mechanism

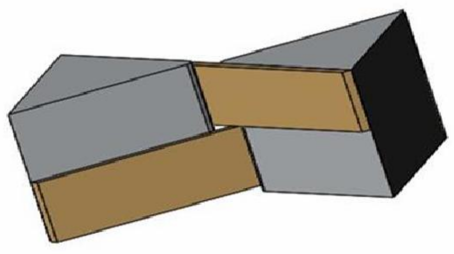

Figure 8. Diagram of Flexible Joint Primary Design

4.3 Optimisation Design and Verification

The design of flexible joints involves several critical parameters, including length, width, and thickness. The selection of these parameters is paramount to the overall movement performance of the system. Inadequate design or improper selection of parameter sizes will directly impair the system's speed and precision, failing to meet the intended design objectives.

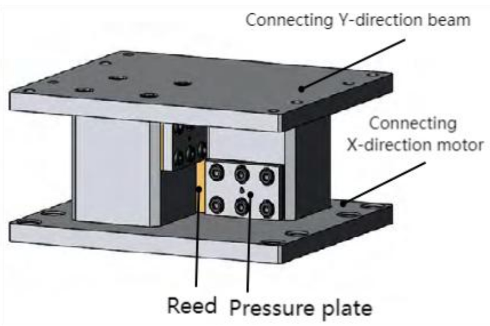

Figure 9. Diagram of Optimised Flexible Joints

Therefore, the objective of the optimisation design is to carefully select the optimal structural parameter sizes to develop a flexible joint best suited to the entire system. By employing an orthogonal optimisation algorithm, coupled with meticulous calculations and analysis, a set of optimal design parameter sizes for the flexible joint was successfully determined.

Based on the optimisation results, a precise simulation model was developed and validated through ANSYS finite element simulation experiments. By comparing the experimental results with the design requirements, the performance of the optimised flexible joint was evaluated against the established standards. Ultimately, following a rigorous validation process, an optimised flexible joint design was achieved, providing robust assurance for the overall system performance.

5. Conclusion

1) To achieve the core objectives of high speed, high precision, and rapid response in the flexible material cutting system, this study adopted linear drive technology. This technology, which eliminates the need for middle switching mechanisms, offers significant advantages, including high speed, high efficiency, high acceleration, and high precision. By employing advanced technologies such as multi-field coupling precision modelling, multi-objective electromagnetic optimisation design, and thrust fluctuation suppression, a stable linear drive was successfully realised for the cutting system, thereby meeting the stringent requirements of flexible material processing.

2) To address the issue of diminished control performance due to thrust fluctuations in linear motors, this study proposes a new motor structure. Through the coordinated optimisation of end forces, cogging forces, and electromagnetic pulsations, thrust fluctuations are significantly suppressed, thereby enhancing the motor’s operational stability and the precision of cutting control.

3) To address the redundant drive issue arising from the rigid connection between the X-direction linear motors and the Y-direction beam, this study innovatively introduces a flexible joint design. This new approach transforms the redundant drive caused by the rigid connection into a flexible drive with deterministic movement, effectively eliminating movement interference and significantly enhancing the stability of the cutting system’s operation.

4) The servo driver and open movement control system developed in this study not only provide a robust platform for optimising the overall performance of the cutting system but also offer a versatile reference for motion control optimisation in high-dynamic electromechanical systems through their coordinated design philosophy of "custom hardware plus open software".

Reference

[1] Yang Guojun. Optimization design of redundantly driven Cartesian robot based on flexible mechanisms. North University of China, 2015.

[2] Ma Mengna. Collaborative control research of multi-linear motor servo systems. China Jiliang University, 2014.

[3] Cheng Yuanxiong. Research on thrust fluctuation optimization design of permanent magnet linear synchronous motors. Huazhong University of Science and Technology, 2011.

[4] Deng Lanmei. Research on ideal point method based on relative effectiveness. Southwest Jiaotong University, 2018.

[5] China Galvanized Layer Passivator Industry Market Analysis Forecast and Investment Prospect Evaluation Report (2024-2034), 2024.