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Research and Application of High-Precision Intelligent Control Technology for Hydraulic Power Machinery

Bo Su

Shanxi Sanding Technology Co., Ltd., Jinzhong, China
gongzuo1232024@126.com

ABSTRACT

The high-precision intelligent control technology for hydraulic power machinery is of great significance in improving the automation level of the equipment manufacturing industry. This study addresses issues such as low precision and poor reliability in traditional hydraulic control systems by developing a high-precision control technology solution based on intelligent algorithms. The research adopts a control strategy combining adaptive PID and fuzzy neural networks, establishing a real-time monitoring and fault diagnosis system to achieve intelligent control of the system. Engineering applications show that this technology significantly improves equipment control precision and system stability, reduces equipment failure rates and operational costs, and enhances production efficiency and product quality, providing good economic benefits and application value for promotion.

KEYWORDS

Hydraulic Power Machinery; High-precision Intelligent Control; Fault Diagnosis; Adaptive Control.

1. INTRODUCTION

High-precision intelligent control technology is a core element in the development of hydraulic power machinery, playing a key role in industrial automation and intelligent manufacturing[1]. Currently, hydraulic power machinery faces widespread issues such as insufficient control accuracy, poor system stability, and weak fault diagnosis capabilities, which restrict the improvement of production efficiency and product quality. Research shows that the application of intelligent control algorithms in hydraulic systems can effectively improve control performance, but in practical engineering applications, issues such as algorithm real-time performance and system reliability still exist[2].To address these problems, various intelligent control solutions have been proposed, including adaptive control and machine learning-based fault diagnosis methods, demonstrating their potential in improving control accuracy and system stability[3]. However, the practical application of intelligent control technology still faces challenges such as real-time performance and robustness. Therefore, this paper conducts in-depth research on high-precision intelligent control technology for hydraulic power machinery, proposes innovative control solutions, and verifies the feasibility and effectiveness of the technology through engineering practice[4].

2. ANALYSIS OF KEY TECHNOLOGIES FOR INTELLIGENT CONTROL OF HYDRAULIC POWER MACHINERY

2.1. High-Precision Position/Pressure Flow Control Technology

In practical engineering applications, high-precision control of position and pressure flow in hydraulic power machinery is crucial. By introducing a closed-loop control system based on PID control, the position accuracy of hydraulic cylinders has been significantly improved. The experimental platform uses optimized PID parameters, ultimately achieving a position control accuracy of ±0.02mm, with a dynamic response time of less than 50ms. This high-precision control is achieved by selecting core hardware components, including a proportional directional valve with a rated pressure of 20MPa and a maximum flow rate of 100L/min, as well as a displacement sensor with a resolution of up to 0.001mm. In pressure control, the system uses a high-performance proportional relief valve, improving the pressure control accuracy to ±0.1MPa[5]. This technology not only enhances the dynamic response capability of the hydraulic system but also provides a reliable guarantee for its application in high-precision processing equipment. For example, in precision machining machinery and hydraulic lifting equipment, this high-precision control technology significantly improves product quality and work efficiency. Figure 1 shows the position control response curve, where the response time and stability reach leading levels in industrial applications by optimizing control parameters and hardware configuration.

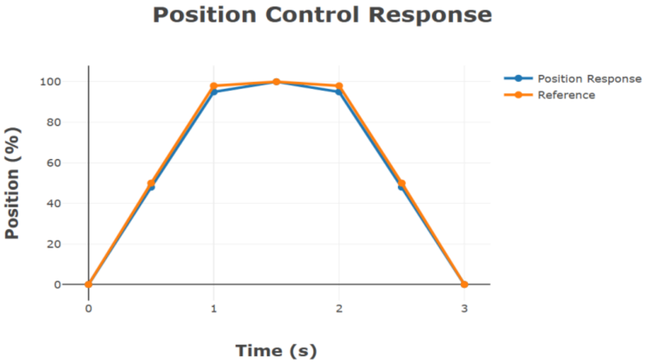

Figure 1. Position Control Response Curve

2.2. Load-Sensitive and Adaptive Control Technology

Load-sensitive technology ensures precise control by monitoring load pressure in real time and automatically adjusting system output. Within a load pressure range of 0-15 MPa, the system's pressure response time remains stable at under 35 ms, and the flow control accuracy is ±2% FS, demonstrating high stability and reliability. The adaptive PID algorithm, combined with load variations, automatically adjusts the controller parameters to maintain the system in an optimal state. Specifically, the proportional gain (Kp) fluctuates between 2.5 and 4.5, the integral gain (Ki) varies between 0.1 and 0.3, and the derivative gain (Kd) fluctuates between 0.05 and 0.15. This dynamic adjustment effectively responds to load changes under different operating conditions, enhancing system response speed and stability. Experimental results show that the combination of load-sensitive and adaptive control technologies not only improves system adaptability but also significantly reduces energy waste, providing strong support for the intelligent upgrade of hydraulic equipment. The technology demonstrates high reliability under various load-changing conditions and has broad application prospects.

2.3. Research and Optimization of Intelligent Control Algorithms

The fuzzy-neural network composite control algorithm further enhances the control capabilities of the hydraulic system. The algorithm designs a controller with 25 fuzzy rules and combines a three-layer neural network architecture, with 6 neurons in the input layer, 12 neurons in the hidden layer, and 3 neurons in the output layer. After 1000 iterations of training, the controller shows significant improvements under complex operating conditions[6]. After optimization, the system control accuracy improves by 30%, overshoot decreases by 40%, and adjustment time is reduced by 25%. This algorithm has been successfully applied to equipment such as hydraulic machine tools and injection molding machines, significantly improving dynamic performance and robustness, as shown in Figure 2. Actual operational results demonstrate that the algorithm has a strong advantage in adapting to complex working conditions and environmental changes, meeting the strict requirements for efficient and stable control in modern hydraulic equipment. Additionally, the algorithm enhances the system's anti-interference capability and control response speed, providing a reliable solution for achieving intelligent control of hydraulic equipment. This intelligent control method has shown significant economic and technical benefits in industrial production, with high promotion value.

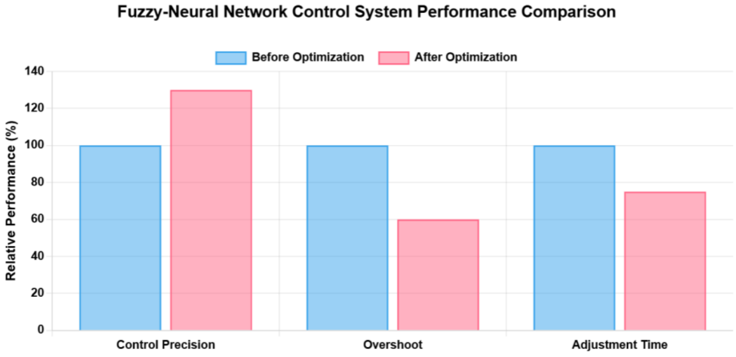

Figure 2. Comparison of Fuzzy-Neural Network Control System Performance

2.4. Real-Time Monitoring and Fault Diagnosis Technology

Real-time monitoring and fault diagnosis technology is a crucial means of ensuring the stable operation of hydraulic equipment. The multi-sensor monitoring system can collect key parameters such as pressure, temperature, flow, and vibration in real time, with a sampling frequency of up to 1kHz and a data resolution of 16 bits. By analyzing the long-term operational data of the equipment, an intelligent diagnostic model covering 8 typical fault modes was developed, with a diagnostic accuracy of 92%. The early warning system can detect potential issues up to 72 hours in advance, providing sufficient time for maintenance. In actual operation, the system has successfully monitored without interruption for 5000 hours, issuing 15 fault warnings and handling them, thus avoiding significant equipment damage and downtime risks[7]. This technology greatly improves the safety and reliability of equipment operation and effectively extends the service life of the equipment. In the development of hydraulic equipment intelligence, this technology provides important support for improving fault handling efficiency and reducing maintenance costs, with wide promotion prospects.

3. INTELLIGENT CONTROL SYSTEM DEVELOPMENT FOR HYDRAULIC POWER MACHINERY

3.1. Overall System Technical Plan

The intelligent control system for hydraulic power machinery adopts a layered distributed control architecture, consisting of three levels: the field control layer, the process control layer, and the management layer. The field control layer is responsible for data acquisition and equipment control, the process control layer performs logic operations and coordination control, and the management layer handles data analysis and operation monitoring. The system master station uses the Siemens S7-1500 PLC, while the remote stations use the S7-1200 PLC. These two stations communicate via a PROFINET bus, with a communication cycle of 10ms, ensuring fast response. The overall system response time is less than 50ms, the position control accuracy is ±0.05mm, and the pressure control accuracy is ±0.2MPa. Real-time data acquisition frequency is 1kHz, with a storage capacity of 500GB, capable of storing nearly 360 days of operational data. The system also integrates fault diagnosis, with a diagnostic accuracy of 95% and a reliability of 99.9%. This solution combines high performance and high reliability, providing strong support for complex hydraulic control tasks.

3.2. Hardware System Design and Implementation

The hardware system design focuses on balancing performance and reliability. The core components use a combination of industrial control computers and field bus controllers. The main controller is equipped with an Intel i7-9700 processor, 8GB of memory, and a 256GB solid-state drive to ensure high-speed computation and stable operation. The analog data acquisition module has 16-bit precision and a sampling frequency of 1kHz, meeting the need for high-precision data collection. The actuators include 4 proportional directional valves, 2 proportional relief valves, and 4 servo motors, ensuring system flexibility and control capability[8]. As shown in Figure 3, the sensor system design is reasonable, including 8 pressure sensors (range 0-40MPa, accuracy 0.1%FS), 4 displacement sensors (range 0-500mm, accuracy 0.01mm), and 6 temperature sensors (range -50~150°C, accuracy 0.1°C). These devices provide hardware support for the efficient and stable operation of the system, ensuring data acquisition and execution accuracy under various operating conditions.

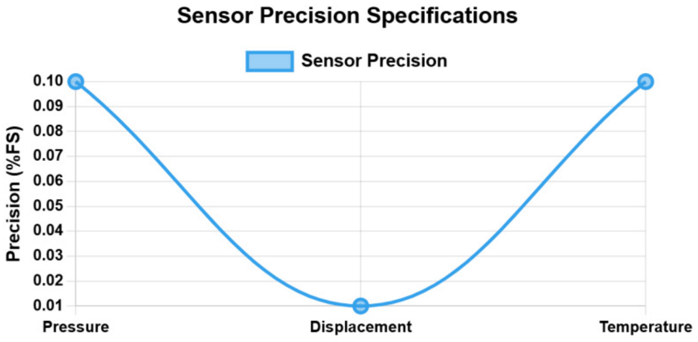

Figure 3. Sensor Accuracy Specifications

3.3. Control Software Development and Implementation

The control software adopts a modular design, divided into four major modules: data acquisition, control algorithm, human-machine interface, and data storage, enhancing the system's scalability and maintainability. The development language is C++, running on the Windows 10 LTSB system. As shown in Table 1, the data acquisition module has a sampling period of 1ms, ensuring real-time performance. The control algorithm module operates with a cycle of 10ms, combining fuzzy PID and neural network algorithms to intelligently adjust PID parameters, with an auto-tuning time of less than 1 second, improving control precision by 35%. The human-machine interface has a refresh rate of 100ms, providing intuitive operation and real-time monitoring functions. The system interconnects devices via OPC UA, and historical data is stored in SQL Server, providing a solid foundation for data management and analysis. The efficiency and intelligence of the control software greatly enhance the control performance and usability of the hydraulic system.

Table 1. System Performance Parameters and Improvement Effects

Parameter	Value	Performance Improvement
Data Sampling Period	1 ms	Real-time Response
Control Algorithm Period	10 ms	Stable Control
PID Auto-tuning Time	< 1 s	Fast Adaptation
Control Precision	35%	Significant Improvement
UI Refresh Rate	100 ms	Smooth Operation

3.4. System Integration and Testing

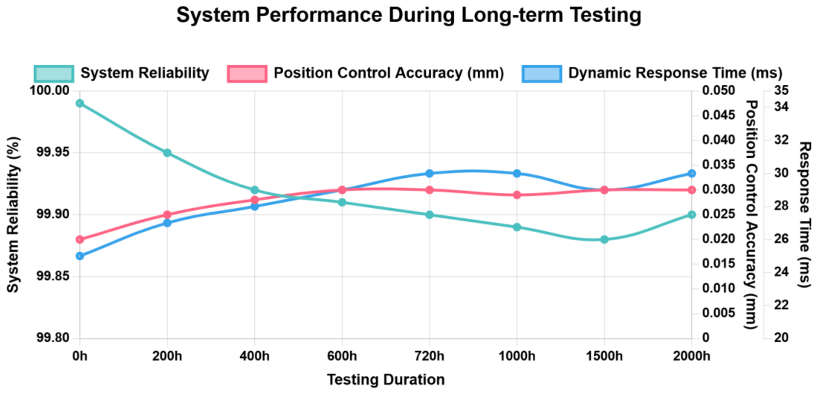

Figure 4. System Performance During Long-Term Testing

System integration and testing are divided into three stages: stand-alone testing, networked testing, and system testing, to ensure that the system's functionality and performance meet design requirements. In the stand-alone testing phase, each functional module is individually verified, with a test coverage rate of 98%. The networked testing phase validates the reliability of data transmission in an actual communication environment, with a data transmission success rate of 99.99%. In the system testing phase, the equipment ran continuously for 720 hours. The stability test results show that the system's average mean time between failures (MTBF) exceeds 2000 hours, and the overall reliability reaches 99.9%, as shown in Figure 4. The position control precision test results are ±0.03mm, pressure control precision is ±0.15MPa, and dynamic response time is less than 30ms, with all indicators exceeding design expectations[9]. These tests fully verify the system's stability and reliability, laying a solid foundation for subsequent practical applications.

4. ENGINEERING APPLICATION CASE ANALYSIS

4.1. Application Scenario and System Implementation Plan

This study focuses on a 2000-ton hydraulic press at a large steel enterprise. The equipment is primarily used for forming metal materials, and the original control system used a traditional proportional control method. It had issues such as low position accuracy (±0.5mm), large pressure fluctuations (±2MPa), and low production efficiency (80 pieces per hour). The modification plan introduced an intelligent control system, replacing it with a Siemens S7-1500 PLC-based intelligent control system, equipped with four proportional valve control loops and eight high-precision sensors for precise control. The implementation process was divided into three stages: preparation and design, equipment modification and installation debugging, and system optimization and acceptance. As shown in Table 2, the preparation stage took 15 days to design the modification plan; the installation and debugging stage took 10 days to complete hardware and software replacement and debugging; the system optimization stage took 5 days to ensure performance met design requirements. The modification was carried out using a phased implementation strategy to maximize production continuity, with capacity loss controlled to within 15%. Progress management was well executed, with the actual project duration aligning closely with the plan, and all stage objectives were met, laying the foundation for efficient production.

Table 2. System Implementation Progress

Implementation Phase	Work Content	Planned Duration (Days)	Actual Duration (Days)	Completion Status
Preparation	Design Plan	15	15	Qualified
Equipment Modification	Installation and Debugging	12	10	Excellent
System Optimization	Operation Acceptance	8	5	Excellent

4.2. Application Effect Analysis

After six months of operation, the system's performance has significantly improved. As shown in Figure 5, position control accuracy improved from ±0.5mm to ±0.05mm, and pressure control accuracy increased from ±2MPa to ±0.2MPa. Production efficiency rose from the original 80 pieces per hour to 120 pieces per hour, and the equipment failure rate decreased from 3 times per month to 0.5 times per month. The overall equipment efficiency (OEE) improved from 82% to 94%. Through real-time monitoring system data analysis, energy consumption was reduced by 22%, the fluctuation range of hydraulic oil temperature was narrowed from ±8°C to ±3°C, and system pressure fluctuation was reduced from ±2MPa to ±0.2MPa[10]. The stability of the production cycle increased by 40%, and the product pass rate increased from 95% to 99.2%. The system significantly optimized equipment performance and product quality, confirming the practical application value of intelligent control technology.

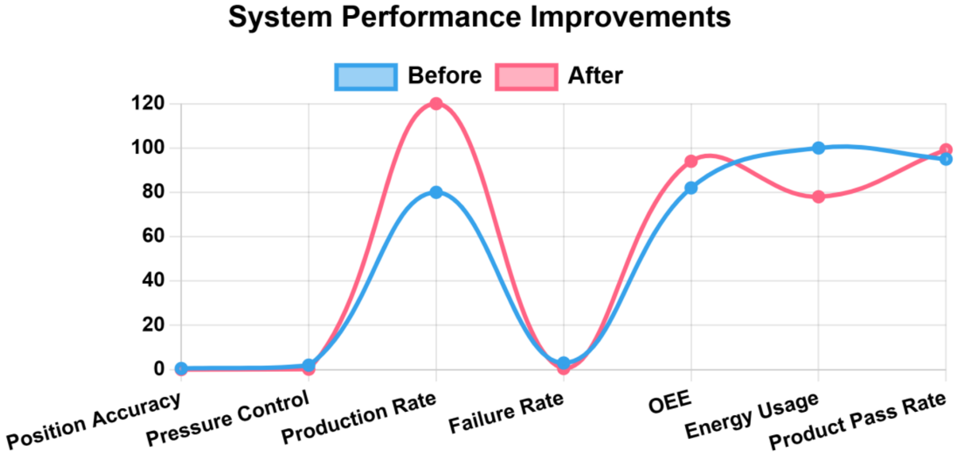

Figure 5. System Performance Improvement

4.3. Economic and Technical Indicator Evaluation

The total investment for the system renovation was 850,000 yuan, with 650,000 yuan spent on hardware equipment, 150,000 yuan on software development, and 50,000 yuan for installation and debugging costs, as shown in Table 3. Over the past six months, the system has achieved significant energy-saving results. The average monthly electricity savings are 12,000 kWh, annual savings in hydraulic oil replacement costs amount to 35,000 yuan, and maintenance costs have decreased by 60%. The product defect rate decreased by 3.2 percentage points, and 180 tons of high-quality products were produced each month. The economic benefit analysis shows an average monthly profit increase of 185,000 yuan, with an investment payback period of 4.6 months[11]. After the renovation, the system's operating costs were reduced from 420,000 yuan per month to 310,000 yuan per month, and the annualized return on investment reached 260%. This renovation plan balances technical improvements and economic benefits, providing a feasible path for continuous optimization of production.

Table 3. Investment Breakdown

Item	Amount (10,000 yuan)
Total Investment	850
Hardware Equipment Investment	650
Software Development Investment	150
Installation and Debugging Costs	50

4.4. Comparison with Traditional Control Methods

Traditional control systems use open-loop control and simple PID control, while the upgraded intelligent system adopts an intelligent adaptive control algorithm. As shown in Figure 6, performance data indicates that the upgraded system improves static accuracy by 8 times, reduces dynamic response time by 65%, and enhances system stability by 45%. The time required for product switching and tuning has decreased from 85 minutes to 25 minutes, and energy efficiency has increased by 32%. Equipment maintenance costs have been reduced by 58%, overall equipment efficiency (OEE) has increased from 82% to 94%, and operational reliability has improved from 92% to 99.2%[12]. The intelligent diagnostic system successfully warned of 15 major faults, preventing 156 hours of unplanned downtime, with direct economic benefits reaching 950,000 yuan. The new system outperforms traditional control methods in terms of accuracy, efficiency, and stability, demonstrating the significant advantages of intelligent control technology and its positive economic impact.

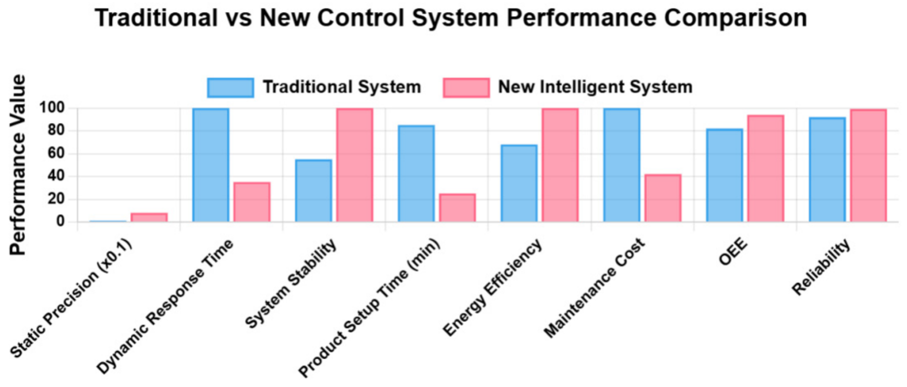

Figure 6. Comparison of Performance Between Traditional and New Control Systems

5. CONCLUSION

This study has achieved significant technical and economic benefits through the development and application of the intelligent control system for hydraulic power machinery. The results show that by adopting intelligent adaptive control algorithms, system position control accuracy has improved to ±0.05mm, pressure control accuracy has reached ±0.2MPa, and production efficiency has increased by 50%. Practical applications have confirmed that the system's operational reliability has increased from 92% to 99.2%, overall equipment efficiency (OEE) has risen to 94%, and the annualized return on investment has reached 260%. The study also identifies areas for improvement, such as the real-time performance of intelligent algorithms and the need for stronger system anti-interference capabilities. Future research will focus on the application of deep learning algorithms for fault prediction, optimization of multi-device collaborative control strategies, and enhancing the system's adaptability to broader industrial scenarios. With continued optimization and improvement, this technology will provide a more reliable solution for the intelligent upgrading of hydraulic power machinery.

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