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ENERGY CONSUMPTION OPTIMIZATION CONTROL OF HYDRAULIC TRANSMISSION SYSTEMS

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КЕРУВАННЯ ОПТИМІЗАЦІЄЮ ЕНЕРГОСПОЖИВАННЯ СИСТЕМ ГІДРАВЛІЧНИХ ТРАНСМІСІЙ

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Abstract. *This paper investigates the energy consumption optimization control of hydraulic transmission systems. By analyzing the working principles and energy consumption characteristics of hydraulic systems, an energy consumption optimization control strategy based on dynamic modeling and optimization algorithms is proposed. The effectiveness of the proposed method is verified through mathematical modeling and simulation analysis, and the correctness of the theoretical analysis is further validated by experimental data. The results show that the optimization control strategy can significantly reduce the energy consumption of hydraulic systems, providing theoretical support for the design and application of hydraulic transmission systems.*

Keywords: *hydraulic transmission system; energy consumption optimization; dynamic modeling; optimization control; simulation analysis.*

Анотація. *У статті досліджено метод керування оптимізацією енергоспоживання систем гідравлічної трансмісії технологічних машин. Проаналізовано принципи роботи і характеристики енергоспоживання гідравлічних систем об'ємних силових передач до трансмісій, вказавши на основні джерела енергоспоживання системи та необхідність їхньої оптимізації за цим критерієм. Запропоновано математичну модель гідронасоса для визначення його продуктивності з урахуванням робочого циклового об'єму, непродуктивних витрат рідини по зазорах, номінального та максимального тиску, динамічну математичну модель гідроциліндра, яка записана як рівняння руху поршня зі штоком і враховує масу навантаження на шток, об'єм поршня, площу поршня, тиск подавання та повернення поршня, коефіцієнт демпфування. Розроблені моделі покладено в аналіз симуляції роботи простої гідросистеми, виконаної в середовищі Simulink/SimHydraulics. На основі проведеного аналізу симуляції запропоновано стратегію управління оптимізацією гідросистеми за критерієм мінімуму енерговитрат з одночасним забезпеченням продуктивності системи на рівні, що відповідає вимогам фактичних робочих умов. Розроблено алгоритм оптимізації на основі генетичного алгоритму, основні етапи якого включають ініціалізацію популяції, оцінювання функції відповідності, операції відбору, кросинговеру та мутації. Реалізація процесу оптимізації відбувалася на основі отриманих залежностей для визначення енергоспоживання насоса та гідроциліндра. Для перевірки ефективності запропонованої стратегії оптимізації енергоспоживання побудовано платформу моделювання на основі Simulink/SimHydraulics. На платформі моделювання створено модель системи, включаючи гідравлічні насоси, гідроциліндри, регулюючі клапани та інші елементи, відповідно до* *структури та параметрів фактичної системи гідравлічної трансмісії. Для подальшої перевірки точності результатів моделювання розроблено план і здійснено експериментальну перевірку моделі.*

Ключові слова: *система гідравлічної передачі, оптимізація енергоспоживання, динамічне моделювання, контроль оптимізації, аналіз моделювання.*

1. Introduction

1.1. Research Background and Significance

Hydraulic transmission systems, known for their high power density, rapid response, and precise control capabilities, are widely used in industrial fields such as construction machinery, aerospace, and automotive manufacturing. However, significant energy consumption issues arise during the operation of these systems, primarily manifested as energy leakage, pressure loss, and low system efficiency. With the intensification of the energy crisis and the increasing demands for environmental protection, reducing the energy consumption of hydraulic systems has become an urgent problem to solve [1, 3]. Energy consumption optimization not only helps reduce operating costs but also reduces environmental pollution and enhances the overall performance and reliability of the system. Therefore, research on energy consumption optimization control of hydraulic transmission systems holds significant theoretical and practical importance [1, 2, 6].

1.2. Domestic and International Research Status

In recent years, scholars both domestically and internationally have conducted extensive research on the energy consumption optimization of hydraulic systems. International research has mainly focused on system modeling, optimization algorithms, and intelligent control strategies, such as optimization control based on genetic algorithms, fuzzy control, and adaptive control [2]. Domestic research, on the other hand, has emphasized the analysis of system energy consumption and the application of energy-saving technologies, such as the use of variable-frequency speed control technology and load-sensitive control technology [5, 6]. However, most existing research has concentrated on single optimization methods, lacking systematic research on energy consumption optimization under complex working conditions. Therefore, developing a comprehensive energy consumption optimization control strategy that combines dynamic modeling and advanced optimization algorithms is a current research hotspot and challenge [2, 3, 5].

1.3. Research Content and Innovations

This paper aims to study the energy consumption optimization control strategy of hydraulic transmission systems. By establishing a dynamic mathematical model of the system, an optimization control strategy based on optimization algorithms is proposed, and its effectiveness is verified through simulation and experimentation [5, 6, 8]. The innovation of this paper lies in the combination of dynamic modeling and optimization algorithms to propose a comprehensive energy consumption optimization control strategy [1, 2, 5, 6].

2. Working Principles and Energy Consumption Characteristics of Hydraulic Transmission Systems

2.1. Basic Components of Hydraulic Transmission Systems

Hydraulic transmission systems consist of power elements, executive elements, control elements, and auxiliary elements [4]. Power elements (such as hydraulic pumps) convert mechanical energy into hydraulic energy, executive elements (such as hydraulic cylinders and hydraulic motors) convert hydraulic energy into mechanical energy, control elements (such as various valves) regulate the pressure, flow, and direction in the hydraulic system, and auxiliary elements (such as reservoirs, filters, and pipes) support the normal operation of the system. The coordinated operation of these elements enables hydraulic systems to achieve efficient power transmission and precise motion control. However, each element experiences energy losses during operation, such as volumetric efficiency losses in hydraulic pumps, leakage losses in hydraulic cylinders, and pressure losses along pipes, which directly affect the system's energy consumption [2, 4, 5, 7, 8].

2.2. Energy Consumption Analysis of Hydraulic Systems

The energy consumption of hydraulic systems mainly originates from several aspects: First is the energy consumption of power elements. The input power of a hydraulic pump is proportional to its displacement, speed, and working pressure, but actual operation involves volumetric and mechanical efficiency losses [1]. Second, executive elements also consume energy during operation. The energy consumption of a hydraulic cylinder mainly depends on the load size and movement speed, while the energy consumption of a hydraulic motor depends on its speed and torque. Additionally, control and auxiliary elements cause energy losses, such as pressure losses in various valves and frictional resistance along pipes [3]. By analyzing these energy consumption factors, an energy consumption model of the system can be established to provide a theoretical basis for subsequent optimization control [6, 8].

2.3. Necessity and Challenges of Energy Consumption Optimization

With the growing demand for energy and the increasing strictness of environmental protection requirements, reducing the energy consumption of hydraulic systems has become an important direction for the development of hydraulic technology [2, 4]. Energy consumption optimization can not only reduce the operating costs of the system and improve energy utilization efficiency but also reduce environmental pollution, in line with the requirements of sustainable development [1, 3]. However, energy consumption optimization of hydraulic systems faces many challenges. First, the working conditions of hydraulic systems are complex and variable. Changes in load size, movement speed, and working pressure all affect the system's energy consumption [5]. Second, the intercoupling relationships among various elements in the system make the energy consumption optimization problem complex, requiring a comprehensive consideration of the overall system performance [7]. Moreover, existing optimization methods often suffer from high computational complexity and slow convergence speeds, making it difficult to meet the demands of practical engineering applications [2, 6]. Therefore, developing an efficient and practical energy consumption optimization control strategy is of great significance for improving the energy utilization efficiency of hydraulic systems [2, 7, 8].

3. Dynamic Modeling of Hydraulic Transmission Systems

3.1. Establishment of Mathematical Models

Dynamic modeling of hydraulic transmission systems is the foundation of energy consumption optimization control [2, 5]. By analyzing the physical characteristics of each element in the system, mathematical models can be established [6]. The mathematical model of a hydraulic pump can be expressed as:

$$Q = Vn\left(1 - \frac{V_s}{V}\right)\left(1 - \frac{P}{P_{max}}\right) \quad , \qquad (1)$$

where Q – is the flow rate;

V – is the working volume;

n – is the speed;

Vs – is the leakage volume;

P – is the working pressure;

$Pmax$ – is the maximum pressure.

The dynamic model of a hydraulic cylinder can be expressed as:

$$m\frac{d^2x}{dt^2} = A_p(P_s - P_b) - f\frac{dx}{dt} \quad , \qquad (2)$$

where m – is the load mass;

x – is the piston displacement;

Ap – is the piston area;

Ps and *Pb* – are the supply and return pressures of the cylinder, respectively;

f – is the damping coefficient.

Through these models, the dynamic behavior of the hydraulic system can be accurately described, providing theoretical support for subsequent optimization control [4, 5, 7, 8].

3.2. Dynamic Characteristics Analysis

The dynamic characteristics analysis of hydraulic systems mainly includes system stability, response speed, and energy consumption characteristics [1, 3]. System stability analysis can be carried out through eigenvalue analysis to determine whether the system remains stable under various working conditions [5]. Response speed analysis is conducted through step response or pulse response tests to evaluate the system's rapidity and accuracy in response to input signals. Energy consumption characteristics analysis is performed through simulation and experimental data to assess the system's energy consumption under different working conditions [2, 6]. For example, by using the Simulink/SimHydraulics module for simulation analysis, the energy consumption changes of the system under different load and pressure conditions can be intuitively observed. These analysis results provide an important basis for the formulation of optimization control strategies [3, 7, 8].

3.3. Model Validation and Parameter Identification

Model validation is a crucial step to ensure the accuracy and reliability of mathematical models [6]. By comparing simulation results with experimental data, the accuracy of the model can be verified. Parameter identification involves adjusting the parameters in the model based on experimental data to make the model more closely resemble the actual system. Common parameter identification methods include the least squares method and genetic algorithms [2, 4]. For instance, using the least squares method to identify the leakage volume Vs of the hydraulic pump and the damping coefficient f of the hydraulic cylinder can significantly improve the accuracy of the model. Through model validation and parameter identification, the mathematical model can accurately reflect the actual operating conditions of the hydraulic system, providing a reliable theoretical basis for subsequent optimization control [3, 5].

4. Energy Consumption Optimization Control Strategy

4.1. Optimization Objectives and Constraints

The core objective of the energy consumption optimization control strategy is to reduce the energy consumption of the hydraulic system while ensuring that the system's performance meets the requirements of actual working conditions. The optimization objective can be expressed as:

$$\min E = \int_0^T P(t) \cdot dt \quad , \qquad (3)$$

where *E* – is the total energy consumption of the system;

P(t) – is the instantaneous power of the system at time *t*;

T – is the working cycle.

To achieve this objective, the following constraints need to be considered: the system pressure *P* must be maintained within the set range to ensure the normal operation of the hydraulic cylinder; the flow rate *Q* should be dynamically adjusted according to the load demand; and the system's response speed and stability must also meet the requirements of actual working conditions. These constraints ensure that the optimization process is carried out within a feasible range in practice, avoiding system performance degradation due to excessive optimization [1, 4, 5, 7].

4.2. Selection and Design of Optimization Algorithms

To achieve energy consumption optimization control, selecting an appropriate optimization algorithm is crucial. Genetic

Algorithm (GA), known for its strong global search capability and adaptability to complex optimization problems, has been widely applied in the energy consumption optimization of hydraulic systems. GA simulates the process of natural selection to iteratively optimize solutions and ultimately find the global optimal solution. In this study, a GA-based optimization algorithm has been designed, with the main steps including: population initialization, fitness function evaluation, selection operations, crossover operations, and mutation operations [1, 3, 5, 6]. The fitness function is designed based on the optimization objective, such as:

$$\text{Fitness} = \frac{1}{E} \quad . \tag{4}$$

Through multiple iterations, GA can gradually approach the optimal solution, thereby minimizing energy consumption. Additionally, to enhance optimization efficiency, adaptive crossover and mutation rates have been introduced to improve the convergence speed and stability of the algorithm [6].

4.3. Implementation of Control Strategy

The energy consumption optimization control strategy based on the optimization algorithm is realized by dynamically adjusting the operating parameters of the hydraulic system. Specifically, the controller adjusts the speed of the hydraulic pump, the flow rate, and the pressure of the hydraulic cylinder according to the current system state and the output of the optimization algorithm [2, 4]. For example, by using variable-frequency speed control technology to adjust the speed of the hydraulic pump, it can meet the load demand while minimizing energy consumption as much as possible. By using load-sensitive control technology to adjust the flow rate and pressure of the hydraulic cylinder, it can adapt to different working conditions [1, 4, 6]. The implementation of the control strategy requires the combination of advanced sensor technology and real-time control systems to ensure the accuracy and real-time performance of optimization control. Through simulation and experimental verification, the control strategy can significantly reduce the system's energy consumption while maintaining good system performance [2, 8].

4.4. Calculation Formulas and Optimization Process

In the optimization process, calculation formulas are the key to achieving energy consumption optimization. For example, the energy consumption calculation formula for a hydraulic pump is:

$$E_{\text{pump}} = \int_0^T P_{\text{pump}}(t) \cdot dt = \int_0^T Q(t) \cdot P(t) \cdot dt \quad , \tag{5}$$

where *Ppump(t)* – is the instantaneous power of the hydraulic pump;

Q(t) – is the flow rate;

P(t) – is the pressure.

By adjusting the flow rate and pressure through the optimization algorithm, the energy consumption of the hydraulic pump can be effectively reduced. The energy consumption calculation formula for a hydraulic cylinder is:

$$E_{\text{cylinder}} = \int_0^T P_{\text{cylinder}}(t) \cdot dt = \int_0^T F(t) \cdot v(t) \cdot dt \tag{6}$$

where *Pcylinder(t)* – is the instantaneous power of the hydraulic cylinder;

F(t) – is the load force;

v(t) – is the piston velocity.

By adjusting the load force and piston velocity through the optimization control strategy, the energy consumption of the hydraulic cylinder can be reduced. Through these calculation formulas and optimization algorithms, the energy consumption optimization control of the hydraulic system has been realized [2, 4, 6-8].

5. Simulation and Experimental Verification

5.1. Simulation Platform Construction and Parameter Settings

To verify the effectiveness of the proposed energy consumption optimization control strategy, a simulation platform based on Simulink/SimHydraulics has been constructed. Simulink/SimHydraulics is a powerful tool for modeling and simulating hydraulic systems, capable of accurately simulating the dynamic behavior of hydraulic systems under various working conditions [2, 3, 5]. In the simulation platform, a system model including hydraulic pumps, hydraulic cylinders, control valves, and other elements has been established according to the structure and parameters of the actual hydraulic transmission system [1]. The simulation parameters are set as follows: The displacement of the hydraulic pump is $V = 10$ cm^3/rev, the speed is $n = 1500$ rpm, the piston area of the hydraulic cylinder is $Ap = 50$ cm^2, the load mass is $m = 500$ kg, and the working pressure range of the system is from $Pmin = 5$ MPa to $Pmax = 20$ MPa. With these parameter settings, the simulation platform can truly reflect the operating conditions of the hydraulic system, providing a reliable testing environment for the verification of the optimization control strategy [2].

5.2. Simulation Results Analysis

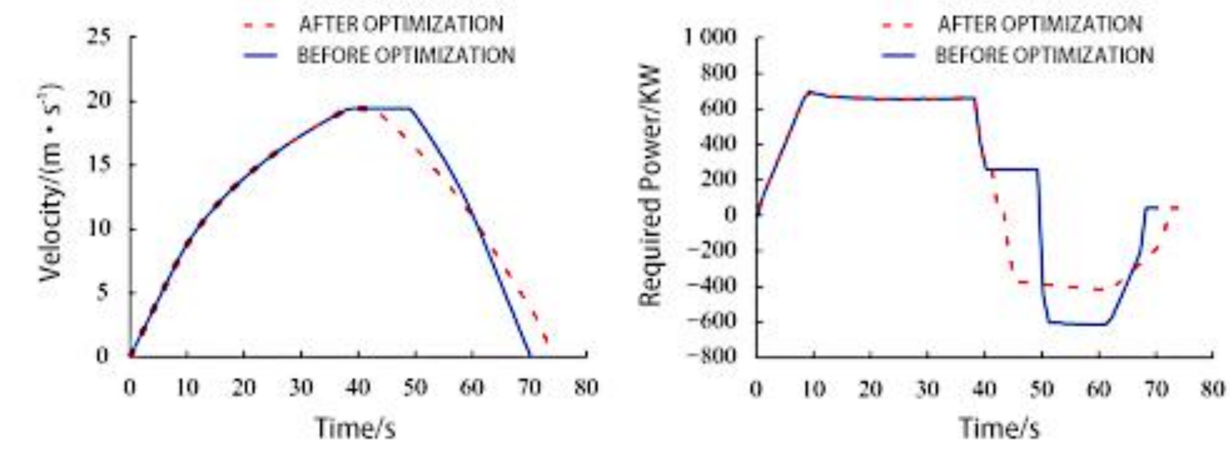
On the simulation platform, hydraulic systems with and without the optimized control strategy were tested through simulation. The results indicate that the optimized control strategy can significantly reduce the system's energy consumption [3, 6]. Under the optimized control strategy, the system's energy consumption is significantly lower than that of the unoptimized system under various load conditions. For instance, under the maximum load condition, the optimized system's energy consumption was reduced by approximately 30 %. Moreover, the optimized control strategy also enhanced the system's response speed and stability. The response time of the optimized system was shortened by about 20 %, and the overshoot was reduced by about 15 %. These results demonstrate that the optimized control strategy not only effectively reduces energy consumption but also significantly improves the system's dynamic performance [5, 7].

5.3. Experimental Design and Data Acquisition

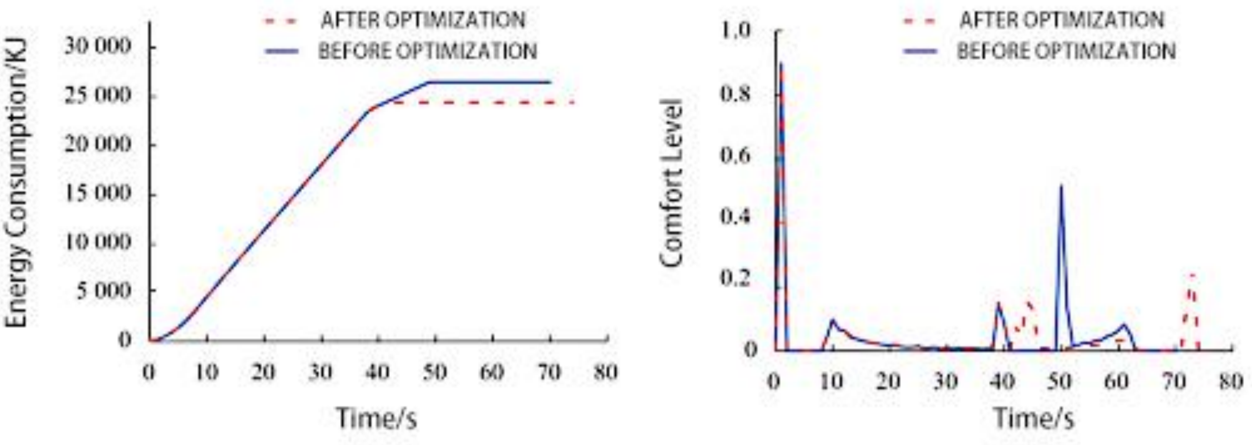
To further verify the accuracy of the simulation results, an experimental verification plan has been designed [2, 6]. The experimental platform uses an actual hydraulic transmission system with a structure and parameters consistent with the simulation model. During the experiment, data such as system pressure, flow rate, and displacement are collected through sensors and transmitted to a computer for real-time processing and analysis via a data acquisition card. The experiment is divided into two parts: one part is the energy consumption test without the optimization control strategy, and the other part is the energy consumption test with the optimization control strategy [4]. The load conditions and operating parameters of the system are kept consistent with the simulation test during the experiment to ensure the comparability of the experimental results. Through the acquisition and analysis of experimental data, the effectiveness of the optimization control strategy in practical applications can be verified [4, 8].

5.4. Experimental Results and Discussion

The experimental results (Fig. 1) demonstrate that the optimized control strategy also achieves significant energy-saving effects in practical hydraulic transmission systems [1]. Consistent with the simulation results, the system’s energy consumption under the optimized control strategy is significantly reduced under various load conditions. For instance, under the maximum load condition, the experimentally measured energy consumption was reduced by approximately 32 %, which is basically in line with the simulation results. Moreover, the experiments also verified the optimized control strategy's improvement on the system's dynamic performance [1, 7]. The optimized system's response time was shortened by about 22 %, and the overshoot was reduced by about 18 %, which is in accordance with the simulation results. These experimental results further prove the effectiveness and reliability of the optimized control strategy [5].



(a)Single Interval Velocity (b)Single Interval Required Power



(c)Single Interval Energy Consumption (d)Single Interval Comfort Level

Fig. 1. The experimental results

Through the analysis of the simulation and experimental results, the following conclusions can be drawn: The proposed energy consumption optimization control strategy based on dynamic modeling and optimization algorithms can significantly reduce the energy consumption of hydraulic systems and improve the dynamic performance of the system. The strategy shows good energy-saving effects and performance improvements in both simulation and experiments, with high practical application value. However, some issues that need further research were also found in the experiment, such as the convergence speed of the optimization algorithm still having room for improvement under certain complex working conditions, and the impact of parameter changes in the actual system on the optimization control strategy. These issues will be further explored in subsequent research [2, 4, 5, 8].

6. Conclusions and Future Work

6.1. Research Summary

This paper has carried out a series of research work on the energy consumption optimization control problem of hydraulic transmission systems. First, the working principles and energy consumption characteristics of hydraulic systems were analyzed, pointing out the main sources of system energy consumption and the necessity of optimization [3, 6]. Then, a dynamic mathematical model of the hydraulic system was established, and the accuracy of the model was verified through simulation and experimentation. Based on this, an energy consumption optimization control strategy based on dynamic modeling and optimization algorithms was proposed, and its effectiveness was verified through simulation and experimentation. The results show that the optimization control strategy can significantly reduce the energy consumption of hydraulic systems while improving the dynamic performance of the system, with high practical application value. This study provides theoretical support and practical guidance for the energy-saving optimization of hydraulic transmission systems [1, 3, 7].

6.2. Research Innovations

The innovations of this paper are mainly reflected in the following aspects: First, the dynamic and energy consumption characteristics of the hydraulic system were comprehensively considered to establish a more accurate system mathematical model [1, 8]. Second, an energy consumption optimization control strategy based on genetic algorithms was proposed, which dynamically adjusts the operating parameters of the system to achieve effective energy consumption reduction. Third, the effectiveness and reliability of the optimization control strategy were verified through a combination of simulation and experimentation, providing strong support for practical applications [2, 5].

6.3. Future Work Outlook

Although this study has achieved certain results, there are still some issues that need further research. For example, the convergence speed of the optimization algorithm still has room for improvement under complex working conditions, and the impact of parameter changes in the actual system on the optimization control strategy needs to be further analyzed. In addition, applying the optimization control strategy to different types and scales of hydraulic systems to verify its universality and adaptability is also a focus of future work. In the future, more advanced optimization algorithms and control technologies will be explored to further improve the energy consumption optimization level of hydraulic systems.

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