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IMPROVEMENT THE GLOBAL ENERGY EFFICIENCY OF HYDRAULIC SYSTEMS OF TECHNOLOGICAL EQUIPMENT

ПІДВИЩЕННЯ ГЛОБАЛЬНОЇ ЕНЕРГОЕФЕКТИВНОСТІ ГІДРАВЛІЧНИХ СИСТЕМ ТЕХНОЛОГІЧНОГО ОБЛАДНАННЯ

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Abstract. This paper investigates multi-scale power losses and global energy-efficiency optimization in process machinery hydraulic systems. Power-loss mechanisms are analyzed at three levels: micro (components), meso (circuits), and macro (system), and a quantitative model accounting for their interactions is developed. A global energy-efficiency model is established, and a collaborative control strategy based on an improved adaptive genetic algorithm (IAGA) is proposed to optimize energy consumption and dynamic performance. Simulation and experimental results confirm that hydraulic pump volumetric losses, control valve throttling losses, and circuit coupling losses account for over 75% of total power losses. The proposed strategy improves system energy efficiency by 12%–18% and reduces dynamic response overshoot by more than 60%. The results provide a theoretical and practical basis for energy-efficient hydraulic system design and control.

Keywords: process machinery; hydraulic system; power loss; multi-scale mechanism; global energy efficiency; collaborative control.

Introduction.

Process machinery is the core equipment of industrial production, covering fields such as metallurgical rolling mills, CNC machine tools, mining machinery, and injection molding machines. Its operational stability, efficiency, and energy consumption directly determine the quality, cost, and environmental performance of industrial production. Hydraulic transmission, as the core power transfer mode of process machinery, has become the preferred transmission scheme for most medium- and large-scale process machinery by virtue of its advantages of high-power density, fast response, precise positioning, and strong resistance to load impact, occupying an irreplaceable position in modern industrial production.

However, process machinery hydraulic systems exhibit significant power losses during energy conversion and transmission. Industrial field measurement data show that the energy efficiency of traditional process machinery hydraulic systems generally ranges between 45% and 60%, far lower than that of electrical drive systems, with a large amount of energy wasted in the form of heat and leakage [10, 14]. With the intensification of the global energy crisis and the advancement of the "dual carbon" goal, the pressure for energy conservation and emission reduction in the industrial sector is increasing. As high-energy-consuming equipment, improving the energy efficiency of the hydraulic systems of process machinery has become a key engineering problem to be solved urgently [1, 9].

Compared with ordinary hydraulic systems, process machinery hydraulic systems are characterized by complex and variable operating conditions (large load fluctuations, frequent start-stop, wide speed regulation range), the collaborative operation of multiple actuators, and the coupling of multiple circuits [3, 11]. Consequently, their power losses exhibit obvious multi-scale characteristics: at the micro level, friction and leakage losses exist inside components such as hydraulic pumps, cylinders, and control valves; at the meso level, uneven flow distribution and pressure interference among circuits give rise to coupling losses; and at

the macro level, overall system power matching imbalance causes redundant losses. The losses at different scales are coupled and mutually influential, making it difficult for traditional single-scale, single-component energy-saving control methods to achieve a significant improvement in the global energy efficiency of the system [4, 12, 14].

Therefore, an in-depth investigation of the multi-scale mechanism of power loss in process machinery hydraulic systems, the revelation of the coupling laws among losses at different scales, and the proposal of a global energy-efficiency collaborative control method that considers both multi-scale loss compensation and system dynamic performance can not only enrich the theoretical system of hydraulic system energy-efficiency optimization [2, 13].but also provide a practical and feasible technical solution for the energy-saving retrofit of process machinery hydraulic systems in industrial sites, reduce industrial energy consumption and environmental pollution, and promote the green and efficient upgrading of the process machinery industry. This has important theoretical significance and engineering application value [2, 3, 13].

Literature Review.

In recent years, scholars at home and abroad have carried out extensive research on power loss and energy-efficiency optimization of hydraulic systems, forming a series of theoretical and technical achievements, mainly focusing on three aspects: loss mechanism analysis, energy-saving design of individual components, and control strategy optimization [5, 7, 10].

In the field of power-loss mechanism research, early foreign scholars focused mainly on the loss analysis of individual components, such as establishing leakage and friction models of hydraulic pumps to quantify volumetric and mechanical losses, and proposing loss-suppression methods based on component structure optimization [1, 14]. With the deepening of research, attention gradually shifted to the problem of loss coupling at the system level, and a "component–system" two-level loss analysis framework was proposed [11]. However, the boundaries of multi-scale losses were not clearly defined, and research on meso-scale circuit coupling losses remains relatively weak [14]. Domestic scholars, on the other hand, have focused more on the loss measurement and analysis of hydraulic systems at industrial sites, quantifying the loss distribution of hydraulic systems under different operating conditions by building experimental platforms, but most of this research remains at the macro level, lacking in-depth research on the coupling mechanism of multi-scale losses and making it difficult to reveal the essential causes of loss generation [3, 9].

In the field of energy-saving design of individual components, scholars at home and abroad have mainly focused on structural improvements to core components such as hydraulic pumps and control valves, such as replacing fixed-displacement pumps with variable-displacement pumps to achieve matching between flow and load by adjusting displacement, thereby reducing redundant losses; and developing low-leakage, low-friction hydraulic valves to reduce throttling and leakage losses [1, 4, 6]. In addition, the research and application of new energy-saving components (such as digital hydraulic valves and high-efficiency variable-displacement pumps) have provided new technical paths for energy saving at the component level. However, such methods target only individual components and do not consider the coupling relationships among components and circuits, making it difficult to achieve an improvement in the global energy efficiency of the system [4].

In the field of control strategy optimization, foreign research has mainly focused on the application of advanced control algorithms, such as fuzzy control, PID control, and model predictive control, to achieve precise control of flow and pressure in hydraulic systems and reduce throttling losses [5]. Domestic research has focused more on the engineering application of load-sensing control and variable-frequency speed-regulation technologies, which achieve matching between energy supply and load demand by dynamically adjusting system operating parameters [5, 9, 12]. However, most existing control strategies focus on

energy-efficiency optimization under a single operating condition or at a single scale, lacking collaborative consideration of multi-scale losses [12]. In the complex and variable operating scenarios of process machinery, it is difficult to balance system energy efficiency and dynamic performance, and the control effect is limited [12, 13, 15].

In summary, existing research still has three prominent problems [3]. First, the analysis of power-loss mechanisms lacks a multi-scale perspective, and the boundaries and coupling laws of losses at different scales have not been clearly defined, making it difficult to comprehensively reveal the essential causes of loss generation. Second, energy-efficiency control strategies lack global coordination, mostly targeting individual components or single operating conditions, and cannot achieve collaborative suppression of multi-scale losses [3, 11]. Third, the correlation between multi-scale loss models and energy-efficiency models is insufficient, making it difficult to provide precise theoretical support for global collaborative control [8, 13]. Therefore, carrying out research on the multi-scale mechanism of power loss and the global energy-efficiency collaborative control of process machinery hydraulic systems has become a research hotspot and difficulty in the field of hydraulic system energy saving [2, 10].

This paper carries out systematic research on the multi-scale mechanism of power loss and the global energy-efficiency improvement collaborative control of process machinery hydraulic systems [3]. The specific research content is as follows:

1. Multi-scale classification and mechanism analysis of power loss in process machinery hydraulic systems. The multi-scale classification criterion (micro, meso, macro) is defined, the causes and influencing factors of power loss at each scale are analyzed separately, quantitative models of power loss at each scale are established, and the coupling laws of multi-scale losses are revealed [4, 9, 11, 14].

2. Global energy-efficiency modeling of process machinery hydraulic systems. Based on the multi-scale power-loss model and the energy balance principle, a global energy-efficiency model covering "component–circuit–system" is constructed, and the relationship between multi-scale losses and system energy efficiency is established, providing a theoretical basis for energy-efficiency optimization control [2, 10].

3. Design of the global energy-efficiency collaborative control strategy. In view of the coupling characteristics of multi-scale losses, a control strategy integrating multi-scale loss compensation and global parameter collaborative optimization is proposed [13], and an improved adaptive genetic algorithm–based optimization controller is designed to achieve coordinated improvement of system energy consumption and dynamic performance.

4. Simulation and experimental verification. A simulation platform based on Simulink/SimHydraulics is built to verify the effectiveness of the multi-scale loss model and the collaborative control strategy; an experimental platform for the process machinery hydraulic system is constructed, and the practicability and reliability of the proposed method are further verified through measured data [2, 4].

The innovations of this paper are mainly reflected in the following three aspects:

1. A multi-scale classification criterion for power loss in process machinery hydraulic systems is proposed, and a "micro–meso–macro" three-level loss quantitative model is constructed, clarifying the coupling mechanism among losses at different scales. This breaks through the limitation of traditional single-scale loss analysis and can reveal the essential causes of loss generation more comprehensively and accurately [5, 7, 9].

2. A global energy-efficiency model covering multi-scale losses is established, directly correlating the losses at different scales with system energy efficiency. This solves the problem that traditional energy-efficiency models cannot reflect the influence of multi-scale coupling and provides precise theoretical support for global energy-efficiency optimization control [2].

3. A multi-scale collaborative global energy-efficiency improvement control strategy is proposed, integrating multi-scale loss compensation and parameter collaborative optimization,

and an improved adaptive genetic algorithm controller is designed [4, 6]. This achieves coordinated improvement of system energy efficiency and dynamic performance, solving the difficulty of balancing energy efficiency and dynamic performance in traditional control strategies [8,15].

Research Methodology.

Multi-Scale Mechanism Analysis of Power Loss in Process Machinery Hydraulic Systems

Multi-Scale Classification Criterion and Boundary Definition

Combining the structural characteristics and energy transfer laws of process machinery hydraulic systems, this paper divides power loss into three scales—micro, meso, and macro—and clarifies the boundaries and research objects of each scale to ensure the systematicness and pertinence of the multi-scale mechanism analysis [3, 9, 14].

1. Micro scale: The core components of the hydraulic system (hydraulic pump, cylinder, control valve, hydraulic motor, etc.) are taken as the research objects, focusing on power loss inside the components, mainly including friction loss, leakage loss, and throttling loss. The essential cause of these losses is the interaction among the internal structure, material properties, and operating parameters of the components [1, 7, 13].

2. Meso scale: A single circuit or the coupling part of multiple circuits of the hydraulic system is taken as the research object, focusing on power loss at the circuit level, mainly including uneven flow distribution loss, pressure interference loss, and pipeline friction (distributed) and local resistance losses. The essential cause of these losses is the insufficient cooperative matching among components [11, 13, 14].

3. Macro scale: The entire process machinery hydraulic system is taken as the research object, focusing on the power loss of the whole system, mainly including power matching imbalance loss, redundant power loss, and auxiliary system loss (e.g., cooling and filtration systems) [3, 10]. The essential cause of these losses is the mismatch between the overall system operating parameters and the process operating-condition requirements [2].

The three scales are interrelated and mutually coupled: micro component losses form the basis of meso circuit losses and macro system losses; meso circuit losses are the concentrated manifestation of micro component losses and simultaneously influence the distribution of macro system losses; macro system losses reflect the overall effect of multi-scale losses [1, 4, 10]. Together, the three scales determine the overall energy efficiency of the process machinery hydraulic system [11].

Micro-Scale Power-Loss Mechanism and Quantitative Model

Micro-scale power loss mainly originates from core components such as the hydraulic pump, cylinder, and control valve, whose loss types and mechanisms differ. They are analyzed separately and quantitative models are established below [2, 5, 14].

Power Loss of the Hydraulic Pump

As the power source of the hydraulic system, the power loss of the hydraulic pump mainly includes volumetric loss, mechanical loss, and hydraulic loss, among which volumetric and mechanical losses are the main forms (accounting for more than 90% of the total pump loss) [1, 14].

1. Volumetric loss. Due to internal clearances of the hydraulic pump (e.g., between the rotor and the stator, and between the vanes and the slots), part of the hydraulic oil leaks from the high-pressure chamber to the low-pressure chamber, causing flow loss and thereby producing volumetric loss [14]. According to the principles of fluid mechanics, the volumetric loss power can be expressed as:

$$P_{vol} = \Delta p_p \cdot Q_{leak} \quad (1)$$

where P_{vol} is the volumetric loss power of the hydraulic pump (W); Δp_p is the pressure difference between the inlet and outlet of the pump (Pa); and Q_{leak} is the leakage flow (m^3/s).

The leakage flow is related to factors such as clearance size, pressure difference, and oil viscosity [6, 10]. For laminar leakage through an annular clearance, the calculation formula is:

$$Q_{leak} = \frac{\pi d h^3 \Delta p_p}{12 \mu L}(1 + 1.5\varepsilon^2) \quad (2)$$

where d is the mating surface diameter (m); h is the mating clearance (m); μ is the dynamic viscosity of the hydraulic oil (Pa·s); L is the mating surface length (m); and ε is the eccentricity ratio.

2. Mechanical loss. Owing to the friction between the moving parts inside the hydraulic pump (such as between the vanes and the slots, and between the rotor and the bearings), as well as the viscous friction of the hydraulic oil, part of the input power is consumed, producing mechanical loss [1, 5, 7]. The mechanical loss power can be expressed as:

$$P_{mech} = T_f \cdot \omega \quad (3)$$

where P_{mech} is the mechanical loss power of the hydraulic pump (W); T_f is the total friction torque (N·m); and ω is the angular velocity of the pump (rad/s).

The total friction torque comprises the solid friction torque and the viscous friction torque:

$$T_f = T_{solid} + T_{viscous} = fF_n r + \mu A \omega r \quad (4)$$

where T_{solid} is the solid friction torque (N·m); $T_{viscous}$ is the viscous friction torque (N·m); f is the friction coefficient; F_n is the normal force (N); r is the friction radius (m); and A is the viscous friction area (m^2).

The total micro-scale loss power of the hydraulic pump is the sum of the volumetric loss and the mechanical loss:

$$P_{pump} = P_{vol} + P_{mech}. \quad (5)$$

Power Loss of the Control Valve

The control valve is the control core of the hydraulic system, and its power loss is mainly throttling loss, i.e., when the hydraulic oil passes through the valve port, a pressure drop occurs due to the throttling effect, and part of the energy is converted into heat and lost [3,7,13]. According to the throttling principle, the throttling loss power can be expressed as:

$$P_{thr} = \Delta p_v \cdot Q_v \quad (6)$$

where P_{thr} is the throttling loss power of the control valve (W); Δp_v is the pressure difference across the valve port (Pa); and Q_v is the flow through the valve port (m^3/s).

According to the thin-walled orifice flow formula, the flow through the valve port can be expressed as:

$$Q_v = C_d A_v \sqrt{\frac{2\Delta p_v}{\rho}} \quad (7)$$

where C_d is the flow coefficient; A_v is the orifice area of the valve port (m^2); and ρ is the density of the hydraulic oil (kg/m^3).

Power Loss of the Hydraulic Cylinder

As the actuator, the power loss of the hydraulic cylinder mainly includes leakage loss and friction loss, which are similar to those of the hydraulic pump but differ in mechanism [12].

1. Leakage loss. This is divided into internal leakage and external leakage. Internal leakage refers to the leakage of hydraulic oil from the rodless chamber to the rod chamber of

the cylinder, while external leakage refers to the leakage of hydraulic oil to the outside through the clearances between the cylinder body and the piston and between the piston rod and the seals. Internal leakage is the main form [2, 9, 11, 15]. The leakage loss power can be expressed as:

$$P_{cyl,leak} = \Delta p_c \cdot Q_{c,leak} \quad (8)$$

where $P_{cyl.leak}$ is the leakage loss power of the cylinder (W); Δp_c is the pressure difference between the two chambers of the cylinder (Pa); and $Q_{c.leak}$ is the cylinder leakage flow (m^3/s).

2. Friction loss. Owing to the friction between the piston and the cylinder body and between the piston rod and the seals [13], part of the hydraulic energy is consumed. The friction loss power can be expressed as:

$$P_{cyl,fric} = F_{cf} \cdot v \quad (9)$$

where $P_{cyl.frec}$ is the friction loss power of the cylinder (W); F_{cf} is the piston motion friction force (N); and v is the piston motion velocity (m/s).

The total micro-scale loss power of the hydraulic cylinder is:

$$P_{cyl} = P_{cyl,leak} + P_{cyl,fric} \quad (10)$$

Meso-Scale Power-Loss Mechanism and Quantitative Model

Meso-scale power loss mainly originates from the coupling and matching insufficiency at the circuit level [10]. The single-circuit resistance loss and the multi-circuit coupling loss are analyzed, and quantitative models are established in combination with the circuit characteristics of process machinery hydraulic systems (such as multi-actuator collaborative circuits and high/low-pressure circuits) [3].

Pipeline Resistance Loss

The hydraulic pipeline is the carrier of energy transfer. When hydraulic oil flows in the pipeline, it is subjected to distributed and local resistance, producing pipeline resistance loss [11, 12]. The loss power can be expressed as:

$$P_{pipe} = \Delta p_{pipe} \cdot Q_{pipe} \quad (11)$$

where P_{pipe} is the pipeline resistance loss power (W); Δp_{pipe} is the total pipeline pressure loss (Pa); and Q_{pipe} is the flow in the pipeline (m^3/s).

The total pipeline pressure loss includes the distributed pressure loss and the local pressure loss:

$$\Delta p_{pipe} = \Delta p_{dis} + \Delta p_{loc} = \lambda \frac{L}{d} \frac{\rho v^2}{2} + \zeta \frac{\rho v^2}{2} \quad (12)$$

where Δp_{dis} is the distributed pressure loss (Pa); Δp_{loc} is the local pressure loss (Pa); λ is the distributed resistance coefficient; L is the pipeline length (m); d is the pipeline inner diameter (m); v is the flow velocity of the hydraulic oil in the pipeline (m/s); and ζ is the local resistance coefficient (determined by local structures such as bends and joints).

Multi-Circuit Coupling Loss

Process machinery hydraulic systems mostly adopt a multi-actuator collaborative working mode (e.g., the feed circuit and the spindle circuit of machine tools, the screw-down circuit and the drive circuit of metallurgical rolling mills). There exist problems such as uneven flow distribution and pressure interference among circuits, resulting in coupling loss [13,14]. The coupling loss power can be expressed as:

$$P_{coup} = \sum_{i=1}^{n} \sum_{j=i+1}^{n} \Delta p_{ij} \cdot Q_{ij} \quad (13)$$

where P_{coup} is the multi-circuit coupling loss power (W); n is the number of circuits; Δp_{ij} is the pressure interference difference between circuit i and circuit j (Pa); and Q_{ij} is the interference flow between the two circuits (m^3/s). Note that the interference flow here is defined strictly as the cross-circuit exchange flow beyond the designed flow distribution, so as to avoid double counting with the pipeline friction loss.

The total meso-scale loss power is the sum of the pipeline resistance loss and the multi-circuit coupling loss:

$$P_{meso} = P_{pipe} + P_{coup} \quad (14)$$

Macro-Scale Power-Loss Mechanism and Quantitative Model

Macro-scale power loss is mainly manifested as the power matching imbalance and redundant loss of the whole system. In view of the operating characteristics of process machinery (large load fluctuations, frequent start-stop), the power matching loss and the auxiliary system loss are analyzed, and quantitative models are established [7].

Power Matching Loss

The power matching loss refers to the redundant power loss caused by the mismatch between the output power of the hydraulic system and the load-demand power of the process. When the system output power is greater than the load-demand power, the redundant power is consumed in forms such as overflow and throttling; when the system output power is smaller than the load-demand power, the system cannot work normally and additional power must be consumed to compensate [9,13]. The power matching loss power can be expressed as:

$$P_{match} = P_{out} - P_{load} \quad (15)$$

where P_{match} is the power matching loss power (W); P_{out} is the output power of the hydraulic system (W); and P_{load} is the process load-demand power (W).

The output power of the hydraulic system is the sum of the output powers of the individual components, while the load-demand power is determined by the process operating conditions and can be obtained by measurement or calculation from process parameters [10].

Auxiliary System Loss

The auxiliary systems of process machinery hydraulic systems (cooling, filtration, and lubrication systems) also consume a certain amount of power during operation, forming auxiliary system loss [1,2,8]. The loss power is mainly determined by the rated power and operating efficiency of the auxiliary equipment:

$$P_{aux} = \sum_{k=1}^{m} \frac{P_{k.rated}}{\eta_k} \quad (16)$$

where P_{aux} is the auxiliary system loss power (W); m is the number of auxiliary devices; $P_{k.rated}$ is the rated power of the k-th auxiliary device (W); and η_k is the operating efficiency of the k-th auxiliary device.

The total macro-scale loss power is the sum of the power matching loss and the auxiliary system loss:

$$P_{macro} = P_{match} + P_{aux} \quad (17)$$

Analysis of the Coupling Law of Multi-Scale Losses

The multi-scale losses of process machinery hydraulic systems are not independent of each other but exhibit significant coupling relationships [11]. The coupling law is mainly reflected in three aspects:

1. Coupling between micro component losses and meso circuit losses. The leakage and friction losses of micro components cause fluctuations in the flow and pressure of the circuit, which in turn aggravate the pipeline resistance loss and the multi-circuit coupling loss; conversely, the pressure interference and uneven flow distribution of meso circuits cause the

operating parameters of components to deviate from the optimal values, further increasing micro component losses. For example, the leakage loss of the hydraulic pump causes insufficient circuit flow; to satisfy the load demand, the control valve must increase the valve-port opening, resulting in increased throttling loss, while the intensified circuit pressure fluctuation increases the pipeline resistance loss [3, 7, 12, 14, 15].

2. Coupling between meso circuit losses and macro system losses. Meso circuit losses cause a decrease in the overall output power of the system [9]. To maintain normal system operation, the input power of the hydraulic pump must be increased, thereby increasing the macro power matching loss; conversely, macro power matching imbalance causes the pressure and flow of the circuit to be in a non-optimal state, aggravating meso circuit losses. For example, when the system power matching is insufficient, the hydraulic pump must operate at a high speed and high pressure for a long time, causing the circuit pressure to be too high and significantly increasing the pipeline resistance loss and the coupling loss [2, 5].

3. Indirect coupling between micro component losses and macro system losses. The accumulation of micro component losses leads to a decline in the overall system energy efficiency, which in turn aggravates the macro power matching loss; macro power matching imbalance causes components to operate in a harsh state for a long time, accelerating component wear and increasing micro losses [4]. For example, if the hydraulic pump operates at a high load for a long time, the friction between the vanes and the slots intensifies, the micro mechanical loss increases, and meanwhile the system energy efficiency decreases and the macro power matching loss further increases [1, 9].

Based on the above coupling law, the total system power loss is the sum of the losses at the three scales:

$$P_{total} = P_{micro} + P_{meso} + P_{macro} \quad (18)$$

where P_{micro} is the total micro-scale loss power (W).

Global Energy-Efficiency Modeling of Process Machinery Hydraulic Systems

Global Energy-Efficiency Definition and Evaluation Indicators

The global energy efficiency of a process machinery hydraulic system is defined as the ratio of the effective output power to the input power over the entire working cycle, reflecting the efficiency of multi-scale energy conversion and transfer across "component–circuit–system":

$$\eta_{global} = \frac{P_{eff}}{P_{in}} \times 100\% \quad (19)$$

where η_{global} is the global system energy efficiency (%); P_{eff} is the effective output power of the system (W), i.e., the power used to drive the process load; and P_{in} is the input power of the system (W), i.e., the input power of the hydraulic pump.

Combined with the multi-scale loss characteristics, the effective output power equals the system input power minus the total multi-scale loss power:

$$P_{eff} = P_{in} - P_{total} \quad (20)$$

To comprehensively evaluate the global energy efficiency, in addition to the global energy efficiency, the following auxiliary evaluation indicators are defined:

1. Micro energy efficiency: the ratio of the effective output power to the input power of a component, reflecting the energy conversion efficiency of the micro component [3];

2. Meso energy efficiency: the ratio of the effective output power to the input power of a circuit, reflecting the energy transfer efficiency at the circuit level [9];

3. Energy consumption reduction rate: the ratio of the difference between the total energy consumption after optimization and that before optimization to the total consumption before optimization, reflecting the effect of energy-efficiency optimization [11];

4. Dynamic performance indicators: including system response time and overshoot, used to evaluate the change in system dynamic performance during energy-efficiency optimization to ensure that the energy-efficiency improvement does not affect normal system operation [14].

Establishment of the Global Energy-Efficiency Model

Based on the multi-scale power-loss model and the energy balance principle, combined with the structural characteristics and operating-condition characteristics of process machinery hydraulic systems, a global energy-efficiency model covering "micro–meso–macro" is established [2, 13].

First, the micro component energy-efficiency model is established [10]. Taking the hydraulic pump, control valve, and cylinder as the core, their energy-efficiency models are established respectively:

$$\eta_{pump} = \frac{P_{pump,out}}{P_{pump,in}} \times 100\%, \quad (21)$$

$$\eta_{valve} = \frac{P_{valve,out}}{P_{valve,in}} \times 100\%, \quad (22)$$

$$\eta_{cyl} = \frac{P_{cyl,out}}{P_{cyl,in}} \times 100\%. \quad (23)$$

The total micro-scale energy efficiency is the weighted average of the energy efficiencies of the individual components, with the weights being the proportions of the input power of each component in the total micro-scale input power:

$$\eta_{micro} = \sum_{i=1}^{k} w_i \eta_i, \sum_{i=1}^{k} w_i = 1 \quad (24)$$

where k is the number of micro components; w_i is the weight of the i-th component; and η_i is the micro energy efficiency of the i-th component.

Second, the meso circuit energy-efficiency model is established. The meso circuit energy efficiency is the ratio of the effective output power of the circuit to the input power of the circuit [9]. Considering the pipeline resistance loss and the multi-circuit coupling loss, the model is:

$$\eta_{meso} = \frac{P_{circuit,eff}}{P_{circuit,in}} \times 100\% \quad (25)$$

where η_{meso} is the meso circuit energy efficiency (%); $P_{circuit.eff}$ is the effective output power of the circuit (W); and $P_{circuit.in}$ is the input power of the circuit (W), equal to the sum of the output powers of the components.

Finally, the macro system global energy-efficiency model is established. The macro system input power is the input power of the hydraulic pump, and the effective output power is the load-demand power [14]. Combined with the multi-scale losses, the global energy-efficiency model is:

$$\eta_{global} = \frac{P_{in} - P_{total}}{P_{in}} \times 100 = \left(1 - \frac{P_{micro} + P_{meso} + P_{macro}}{P_{in}}\right) \times 100\%. \quad (26)$$

Substituting the micro, meso, and macro loss models into the above equation yields the relationship between the global energy efficiency and the parameters at each scale (such as component structural parameters, circuit parameters, and system operating parameters), providing a theoretical basis for subsequent energy-efficiency optimization control [3, 6, 11], as shown in Fig.1.

Model Validation and Parameter Identification

To ensure the accuracy and reliability of the global energy-efficiency model, parameter identification and experimental validation are carried out to adjust the model parameters so that the model output is consistent with the actual system [12].

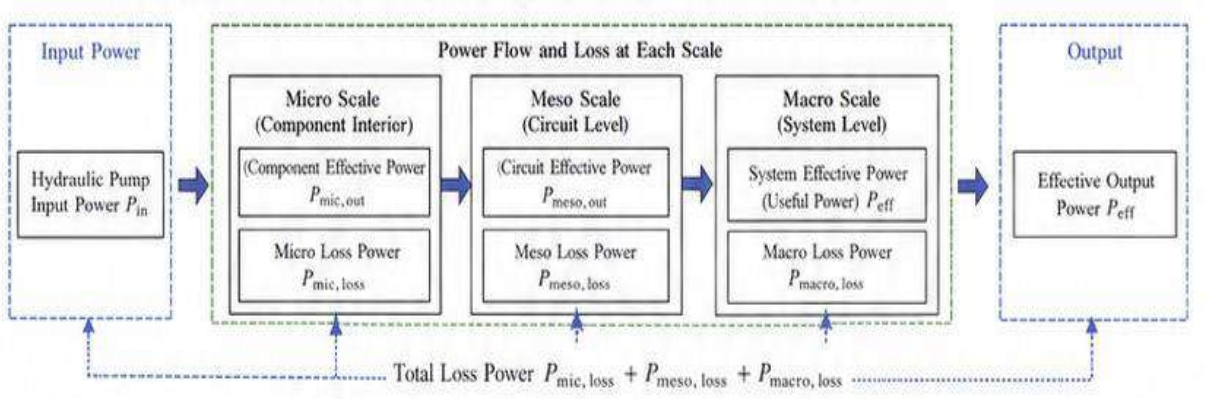


Fig. 1 Energy flow relationship of the global energy-efficiency model.

Parameter Identification Method

The least-squares method is selected for parameter identification. For the unknown parameters in the multi-scale loss model and the global energy-efficiency model (such as the pump leakage clearance, friction coefficient, pipeline resistance coefficient, and coupling loss coefficient), system operating data are collected through experiments, an identification objective function is established, and the unknown parameters are solved [5, 14].

The identification objective function is:

$$J = \sum_{t=1}^{N} [\eta_{model}(t) - \eta_{meas}(t)]^2 \quad (27)$$

where J is the identification error; N is the number of sampling points; $\eta_{model}(t)$ is the global energy efficiency output by the model at time t; and $\eta_{meas}(t)$ is the global energy efficiency actually measured at time t.

By solving the above objective function using the least-squares method, the optimal estimates of the unknown parameters are obtained and substituted into the model to complete the model parameter identification [9].

Model Validation

A general CNC machine tool hydraulic system is adopted as the verification object of the model, and a supporting experimental test platform is constructed [11]. Measured data including system input power, load power and multi-scale loss power under multiple working conditions are collected and compared with the model calculation outputs to conduct benchmark analysis, so as to complete the accuracy verification of the model [8,10].

The validation results demonstrate that the relative error between the global energy efficiency output by the model and the measured global energy efficiency is less than 5%, and the error between the calculated values and measured values of multi-scale loss power is controlled within 8%. It is thus verified that the global energy-efficiency model established in this paper can accurately characterize the laws of power loss and energy efficiency variation of hydraulic systems for process machinery, and can provide reliable theoretical support for the subsequent collaborative optimization control of system energy efficiency [7, 11, 14].

Design of the Global Energy-Efficiency Improvement Collaborative Control Strategy

Control Objectives and Constraints

The core objective of the proposed global energy-efficiency collaborative control strategy is to achieve "collaborative suppression of multi-scale losses and coordinated improvement of energy efficiency and dynamic performance", specifically including:

1. Core objective: maximize the global system energy efficiency, achieving an energy-efficiency improvement of more than 10% under different process operating conditions;

2. Secondary objective: suppress multi-scale power losses, reduce total system energy consumption, and simultaneously ensure that the system dynamic performance (response time, overshoot) satisfies the process requirements without affecting the process production accuracy and efficiency [2, 9].

The control objective can be quantified as:

$$\max J_{obj} = \eta_{global} - \lambda_1 t_r - \lambda_2 \sigma \quad (28)$$

where t_r is the response time (s); σ is the overshoot (%); and λ_1, λ_2 are weighting coefficients.

Combined with the operating characteristics and process requirements of process machinery hydraulic systems, the following control constraints are set:

1. Pressure constraint: the system working pressure P must be within the set range ($P_{min} \le P \le P_{max}$), to ensure normal operation of the actuators and avoid system damage caused by excessive pressure or failure to meet load demand caused by insufficient pressure;

2. Flow constraint: the system flow Q must match the load demand ($Q_{min} \le Q \le Q_{max}$), to avoid slow system response caused by insufficient flow or increased loss caused by flow redundancy;

3. Dynamic performance constraint: the system step response time $t_r \le t_{r.max}$ and overshoot $\sigma \le \sigma_{max}$, to ensure that the system dynamic performance meets the process production requirements;

4. Parameter constraint: the control parameters (such as the pump speed and valve-port opening) must be within the allowable range of the equipment, to avoid equipment damage caused by exceeding the rated parameters [3, 6, 11].

Collaborative Control Strategy Framework

In view of the coupling characteristics of multi-scale losses and the collaborative control logic of process machinery hydraulic systems, a collaborative control strategy of "multi-scale loss compensation + global parameter collaborative optimization" is proposed, and its framework [7], as shown in Fig. 2.

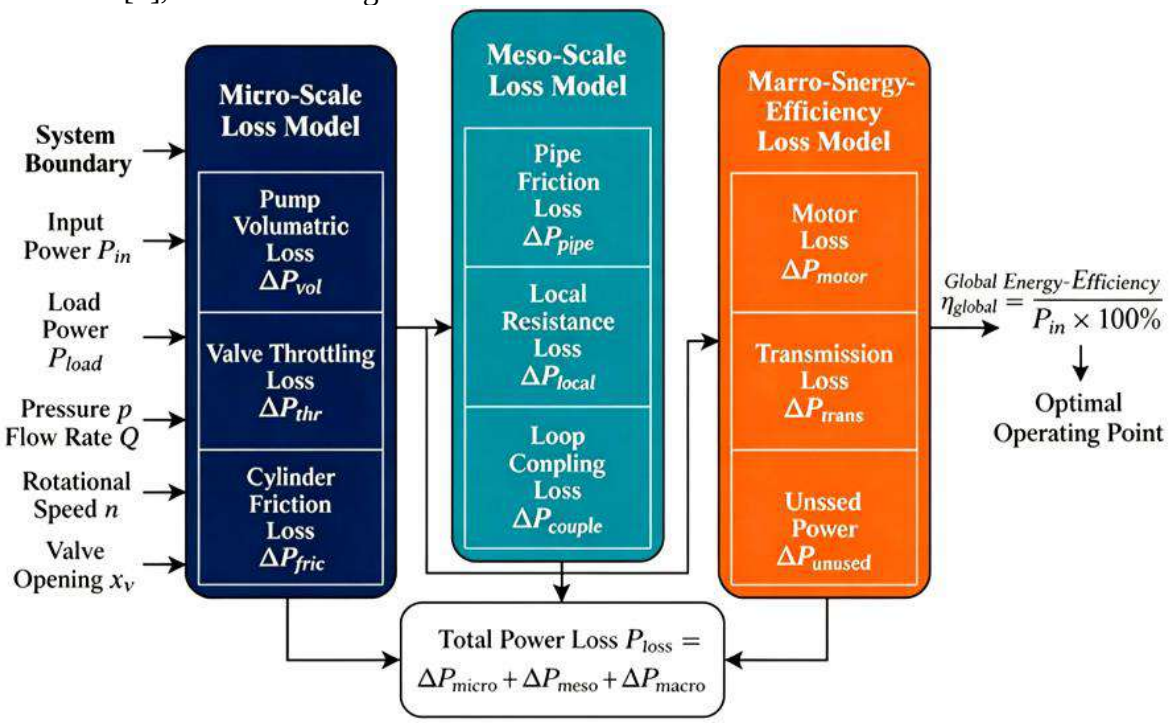


Fig. 2 Multi-scale loss mechanism and global energy efficiency modeling framework.

The control strategy framework mainly includes three layers:

1. Perception layer: sensors collect the multi-scale operating parameters of the system, including micro component parameters (pump speed, pressure, flow; cylinder displacement

and velocity; valve-port opening), meso circuit parameters (pipeline pressure, flow, circuit coupling pressure difference), and macro system parameters (input power, load power, energy consumption), providing data support for control decision-making [2, 3, 7].

2. Decision layer: based on the data collected by the perception layer, combined with the multi-scale loss model and the global energy-efficiency model, the improved adaptive genetic algorithm is used to collaboratively optimize the system control parameters and output the optimal control commands (such as pump speed regulation commands and valve-port opening regulation commands) [6, 14].

3. Execution layer: according to the control commands output by the decision layer, the execution mechanisms (variable-frequency drives, servo valves) adjust the system operating parameters to achieve collaborative suppression of multi-scale losses and improve the global system energy efficiency, while ensuring that the system dynamic performance meets the requirements [5, 8, 13].

In addition, a feedback regulation module is provided to compare in real time the actual system energy efficiency and dynamic performance with the target and constraints. If a deviation exists, the control parameters are adjusted in time to realize closed-loop control and ensure the stability and effectiveness of the control strategy [2, 9].

Design of the Improved Adaptive Genetic Algorithm

Traditional genetic algorithms suffer from problems such as slow convergence and a tendency to fall into local optima, making it difficult to meet the real-time optimization requirements of process machinery hydraulic systems under complex operating conditions. Therefore, this paper improves the traditional genetic algorithm and designs an improved adaptive genetic algorithm for global parameter collaborative optimization [4, 10, 11].

Algorithm Improvement Ideas

Adaptive crossover rate and mutation rate design. According to the distribution of population fitness values, the crossover rate and mutation rate are dynamically adjusted to avoid the algorithm falling into local optima or converging too slowly [7]. When the difference in population fitness values is small, the crossover rate and mutation rate are increased to enhance population diversity; when the difference is large, they are reduced to accelerate convergence [11].

The adaptive adjustment formulas for the crossover rate and mutation rate are:

$$P_c = \begin{cases} P_{c,max} - \frac{(P_{c,max} - P_{c,min})(f - f_{avg})}{f_{max} - f_{avg}}, & f \geq f_{avg} \\ P_{c,max}, & f < f_{avg} \end{cases} \quad (29)$$

$$P_m = \begin{cases} P_{m,min} + \frac{(P_{m,max} - P_{m,min})(f_{max} - f)}{f_{max} - f_{avg}}, & f \geq f_{avg} \\ P_{m,max}, & f < f_{avg} \end{cases} \quad (30)$$

where $P_{c.max}$ and $P_{c.min}$ are the upper and lower limits of the crossover rate (taken as 0.9 and 0.4 in this paper); $P_{m.max}$ and $P_{m.min}$ are the upper and lower limits of the mutation rate (taken as 0.1 and 0.01 in this paper); f is the individual fitness value; f_{avg} is the average population fitness value; and f_{max} is the maximum population fitness value.

Fitness function design. Combined with the control objectives and constraints, a fitness function is designed to convert the multi-objective optimization problem into a single-objective optimization problem:

$$F = \frac{1}{1 + \omega_{loss} P_{total} + \omega_{dyn} (\alpha_1 t_r + \alpha_2 \sigma)} \quad (31)$$

where ω_{loss} and ω_{dyn} are the weighting coefficients for the loss and dynamic performance terms, respectively, and α_1, α_2 are penalty coefficients used to ensure that the control

parameters satisfy the constraints (taken as 1.0, 1.0, 0.8, and 0.8 for the penalty terms in this paper, normalized so that the dynamic performance penalties are commensurate with the energy-efficiency values).

Algorithm Implementation Steps

The implementation steps of the improved adaptive genetic algorithm are as follows:

1. Population initialization: set the population size, the upper and lower limits of the crossover rate and mutation rate, and the number of iterations; randomly generate the initial control-parameter population (including the pump speed and valve-port opening), ensuring that the population individuals are within the control-parameter constraints [9].

2. Fitness calculation: substitute each individual in the population as control parameters into the global energy-efficiency model and the dynamic performance model, calculate the individual fitness value, judge whether the constraints are satisfied, and penalize individuals that do not satisfy the constraints [11].

3. Selection operation: use the roulette-wheel selection method to select, according to the individual fitness values, individuals with higher fitness values to enter the next generation, retaining excellent individuals and improving the overall population fitness [2, 11].

4. Crossover operation: according to the adaptive crossover rate, perform single-point crossover on the selected individuals to generate new individuals and enhance population diversity [13].

5. Mutation operation: according to the adaptive mutation rate, perform mutation on the individuals to prevent the algorithm from falling into local optima [6].

6. Iteration judgment: judge whether the maximum number of iterations is reached or the population fitness has converged (the difference between the average population fitness values of two adjacent iterations is less than a set threshold). If satisfied, output the optimal control parameters; otherwise, return to step (2) and continue iterating [8, 10, 11].

The complete execution flow of the improved adaptive genetic algorithm designed in this paper is illustrated, as shown in Fig.3. Which strictly follows the six core implementation steps presented in Section 4.3.2, and integrates the adaptive adjustment rules of crossover and mutation rates as well as the judgment module for dynamic performance constraints [14].

Implementation of the Control Strategy

Combined with the actual structure of process machinery hydraulic systems, the specific implementation of the control strategy is as follows:

1. Micro-level loss compensation: according to the optimized pump speed command, the variable-frequency drive adjusts the pump speed so that the pump operates in the optimal displacement range, reducing volumetric and mechanical losses; according to the valve-port opening command, the orifice area is adjusted to reduce throttling loss; through seal optimization and lubrication improvement, the friction and leakage losses of the cylinder are reduced [2, 11].

2. Meso-level coupling suppression: according to the circuit flow and pressure data, a flow-distribution valve adjusts the flow of each circuit to avoid coupling losses caused by uneven flow distribution; the pipeline layout is optimized to reduce the pipeline length and the number of bends, reducing pipeline resistance loss; a pressure-compensation valve suppresses the pressure interference among circuits to reduce coupling losses [3, 8].

3. Macro-level power matching: according to the change in load-demand power, the input power of the hydraulic pump is dynamically adjusted so that the system output power matches the load-demand power, reducing power matching loss; the auxiliary system operating strategy is optimized, and the operating state of the auxiliary equipment is dynamically adjusted according to parameters such as system temperature and contamination degree, reducing auxiliary system loss [2, 7, 11].

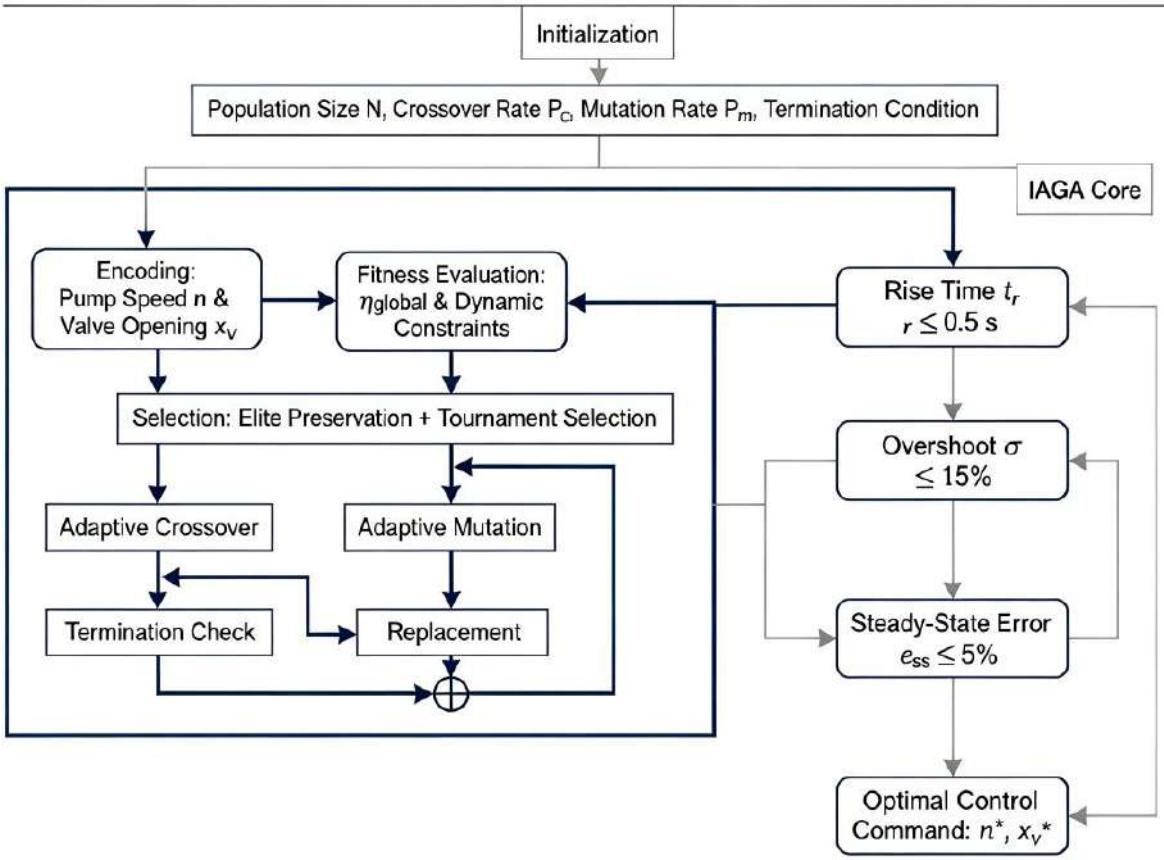


Fig. 3 Improved adaptive genetic algorithm optimization procedure.

Through the above multi-scale collaborative control, the global energy efficiency of the system is improved while ensuring that the system dynamic performance satisfies the process requirements [6, 9].

Results.

Simulation Platform Construction and Parameter Setting

Simulation Platform Construction

A simulation platform for the process machinery hydraulic system is built based on Simulink/SimHydraulics [8]. Combined with the actual structure of the hydraulic system of a general CNC machine tool, a complete simulation model of "pump–control valve–cylinder–pipeline–load" is constructed, covering the micro components, meso circuits, and macro system, and accurately simulating the multi-scale losses and dynamic characteristics of the system [4, 8].

The simulation platform mainly includes the following modules: the hydraulic pump module (using a variable-displacement piston pump model), the control valve module (using an electro-hydraulic servo valve model), the cylinder module (using a double-acting cylinder model), the pipeline module (considering distributed and local resistance), the load module (simulating process load fluctuation), the control module (implementing the improved adaptive genetic algorithm and the collaborative control strategy), and the data acquisition module (collecting system operating parameters and energy-consumption data) [13].

Simulation Parameter Setting

Combined with the actual parameters of the experimental platform, the simulation parameters are set as follows: pump displacement V_p = 40 mL/rev, rated speed n_p = 1500 r/min, rated pressure p_p = 16 MPa; cylinder piston area A_c = 50 cm², stroke S_c = 0.3 m, friction coefficient 0.05; pipeline inner diameter d = 12 mm, length L = 3 m, distributed

resistance coefficient 0.02, local resistance coefficient 0.5; hydraulic oil density ρ = 870 kg/m³, dynamic viscosity μ = 0.035 Pa·s; load power range 5–17 kW, fluctuation frequency 0.5 Hz. Improved adaptive genetic algorithm parameters: population size 50, maximum number of iterations 100, crossover-rate upper and lower limits 0.9 and 0.4, mutation-rate upper and lower limits 0.1 and 0.01, and penalty coefficients of 1.0, 1.0, 0.8, and 0.8.

The simulation is divided into two groups: the control group (without any energy-saving control strategy) and the experimental group (with the proposed global energy-efficiency collaborative control strategy). The parameters of the two groups are identical to ensure the validity of the comparison [9, 13].

Analysis of Simulation Results

Multi-Scale Loss Simulation Results

The distribution of multi-scale losses in the two simulation groups, as shown in Fig.4.

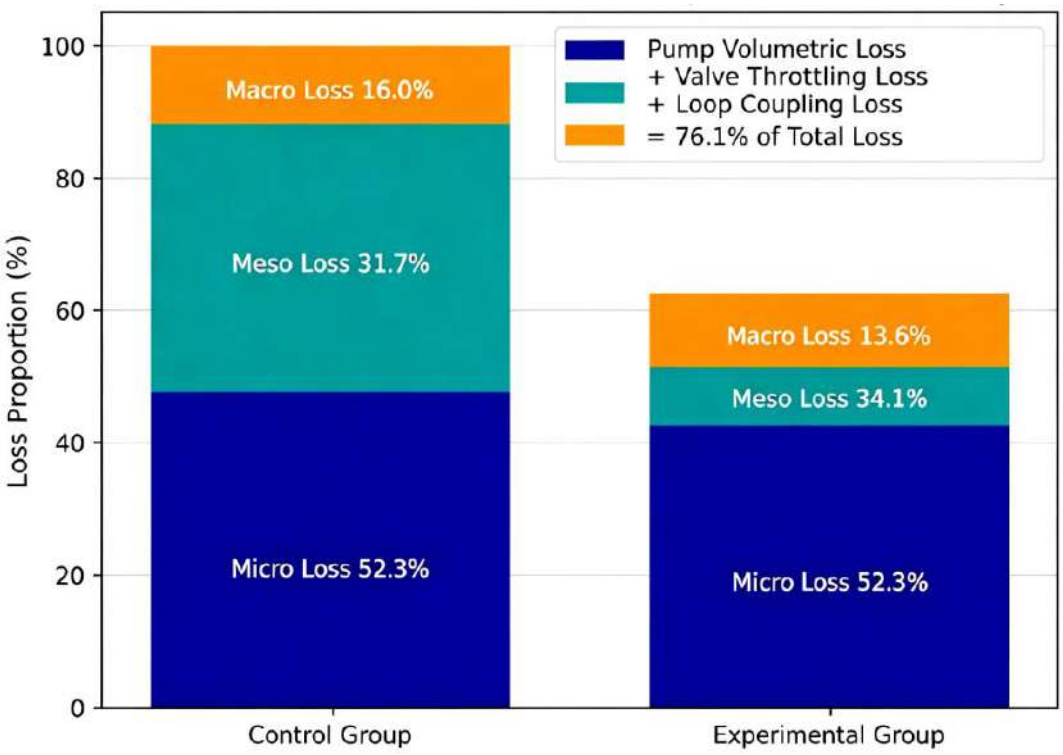


Fig. 4 Multi-scale loss distribution comparison between control group and experimental group.

The simulation results show that: In the control group, the micro loss accounts for 52.3% of the total system loss, the meso loss accounts for 31.7%, and the macro loss accounts for 16.0%; among them, the volumetric loss of the hydraulic pump, the throttling loss of the control valve, and the circuit coupling loss together account for 76.1% of the total loss, consistent with the conclusions of the multi-scale loss model analysis, verifying the accuracy of the loss model [11]. After the experimental group adopts the proposed collaborative control strategy, the losses at each scale are significantly suppressed: the total loss is reduced by 38.0% compared with the control group, with the micro loss accounting for 52.3%, the meso loss 34.1%, and the macro loss 13.6% of the experimental-group total loss [4, 13]. From the perspective of specific loss types, the volumetric loss of the pump is reduced by 41.2%, the throttling loss of the control valve by 38.6%, the circuit coupling loss by 45.3%, and the power matching loss by 52.1%, indicating that the collaborative control strategy can effectively suppress the key losses at each scale and achieve collaborative suppression of multi-scale losses [7, 9, 12].

Global Energy-Efficiency Simulation Results

The curves of the global system energy efficiency with operating conditions in the two simulation groups. the average energy efficiency improvement of simulation is 12.1%, while the experimental measured average improvement is 11.6%, as shown in Fig.5.

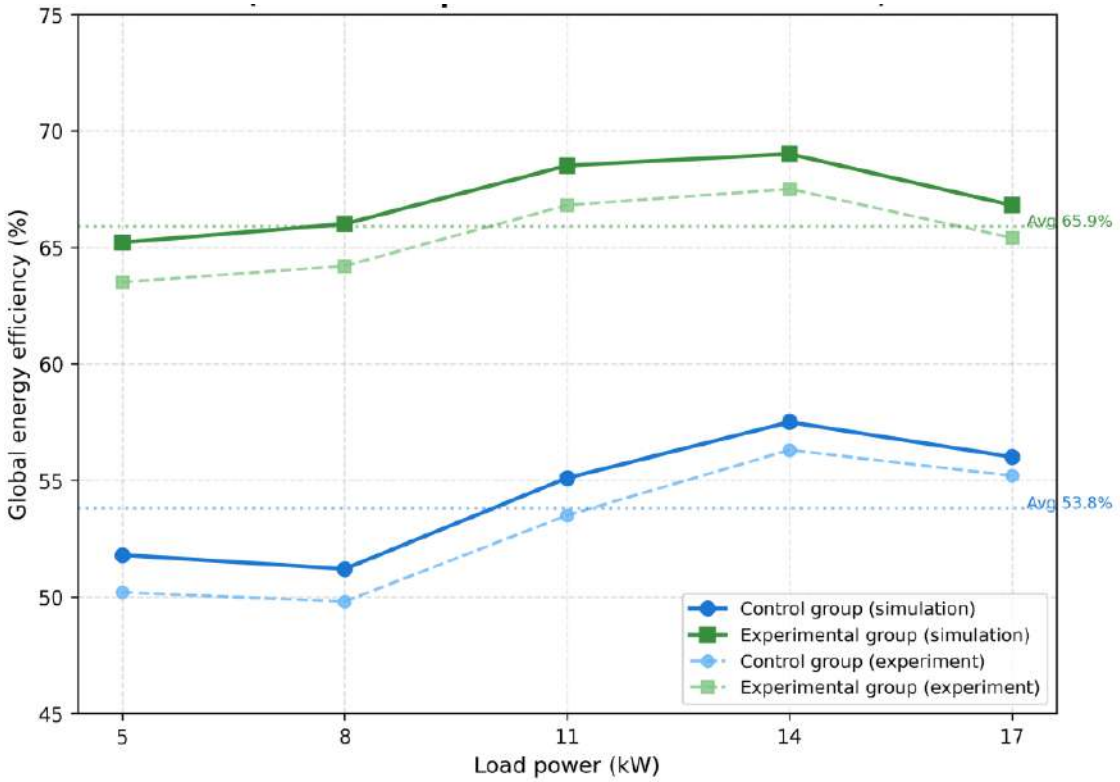


Fig. 5. Global energy-efficiency curves under variable load conditions.

Simulation results show that under complex operating conditions with given load power and fluctuation frequency [1], the average global energy efficiency of the control-group system is 53.8%, accompanied by obvious fluctuations induced by load variation, with a maximum fluctuation amplitude of 8.7%. After adopting the cooperative control strategy in the experimental group, the average global energy efficiency of the system increases to 65.9%, representing an average improvement of 12.1%. Meanwhile, the energy-efficiency fluctuation amplitude drops to 3.2%, yielding a remarkable improvement in stability [9, 14]. Under the rated operating condition of specified load power, the maximum energy-efficiency improvement reaches 14.4%, which fully satisfies the preset control target of "energy-efficiency improvement above 10%". This verifies the effectiveness of the proposed cooperative control strategy for global energy-efficiency enhancement [10].

Further analysis on the variations in micro-scale, mesoscale and macroscale energy efficiencies reveals that the average energy-efficiency improvements of the experimental group are 10.3% at the microscale, 13.5% at the mesoscale, and 15.7% at the macroscale. It demonstrates that the cooperative control strategy enables synchronous energy-efficiency improvement across all scales. It overcomes the limitation of conventional control strategies that can only optimize energy efficiency at a single scale, and realizes the coordinated improvement of global energy efficiency covering "component-circuit-system" [1, 4, 8].

Dynamic Performance Simulation Results

To verify whether the collaborative control strategy can guarantee the system dynamic performance while improving energy efficiency, the step response characteristics of the two simulation groups are compared, and the results [13, 14], as shown in Fig.6.

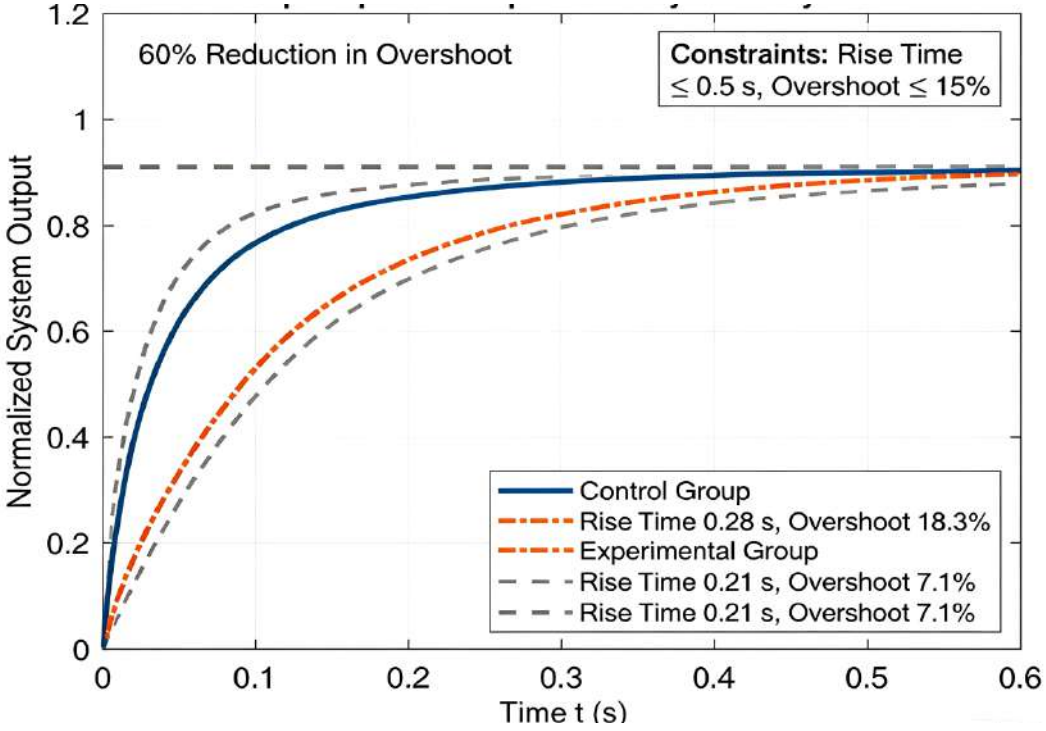


Fig. 6. Step-response comparison of hydraulic system.

The simulation results show that the step response time of the control group is 0.28 s, with an overshoot of 18.3%; after the experimental group adopts the collaborative control strategy, the step response time is shortened to 0.21 s and the overshoot is reduced to 7.1%, a 25.0% shortening of response time and a 61.2% reduction in overshoot, both satisfying the preset dynamic performance constraints ($t_r \leq 0.5$ s, $\sigma \leq 15\%$). This result indicates that the proposed collaborative control strategy, while suppressing multi-scale losses and improving global energy efficiency, can significantly improve the system dynamic performance, effectively solving the difficulty of "balancing energy efficiency and dynamic performance" in traditional control strategies and achieving coordinated improvement of energy consumption and dynamic performance [5, 9, 14].

Experimental Verification

Experimental Platform Construction

To further verify the practicability and reliability of the proposed theory and method, an experimental platform for the process machinery hydraulic system is built, using a CNC machine tool hydraulic system of a certain model as the prototype and restoring the complete structure of "pump–control valve–cylinder–pipeline–load" [9], as shown in Fig.7.

The parameters of the core components of the experimental platform are kept consistent with the simulation parameters to ensure the comparability of the experiment and the simulation. The data acquisition system uses high-precision sensors (pressure sensor accuracy of 0.5% FS, flow sensor accuracy of 0.5% FS, and speed sensor accuracy of 0.1% FS) to collect, in real time, the micro component parameters, meso circuit parameters, macro system parameters, and energy-consumption data at a sampling frequency of 1000 Hz. The control strategy is implemented through a PLC controller with the improved adaptive genetic algorithm embedded, completing real-time optimization of the control parameters and command output [4, 9, 13].

Experimental Scheme Design

The experiment adopts the same grouping scheme as the simulation, divided into the control group (without any energy-saving control strategy) and the experimental group (with the proposed global energy-efficiency collaborative control strategy). The experimental

operating conditions are consistent with the simulation: load power range of 5–17 kW and fluctuation frequency of 0.5 Hz. The experimental duration for each condition is 60 s, and a total of 5 different load conditions are set. Each condition is repeated 3 times, and the average value is taken as the experimental result to ensure the reliability of the experimental data [2, 14].

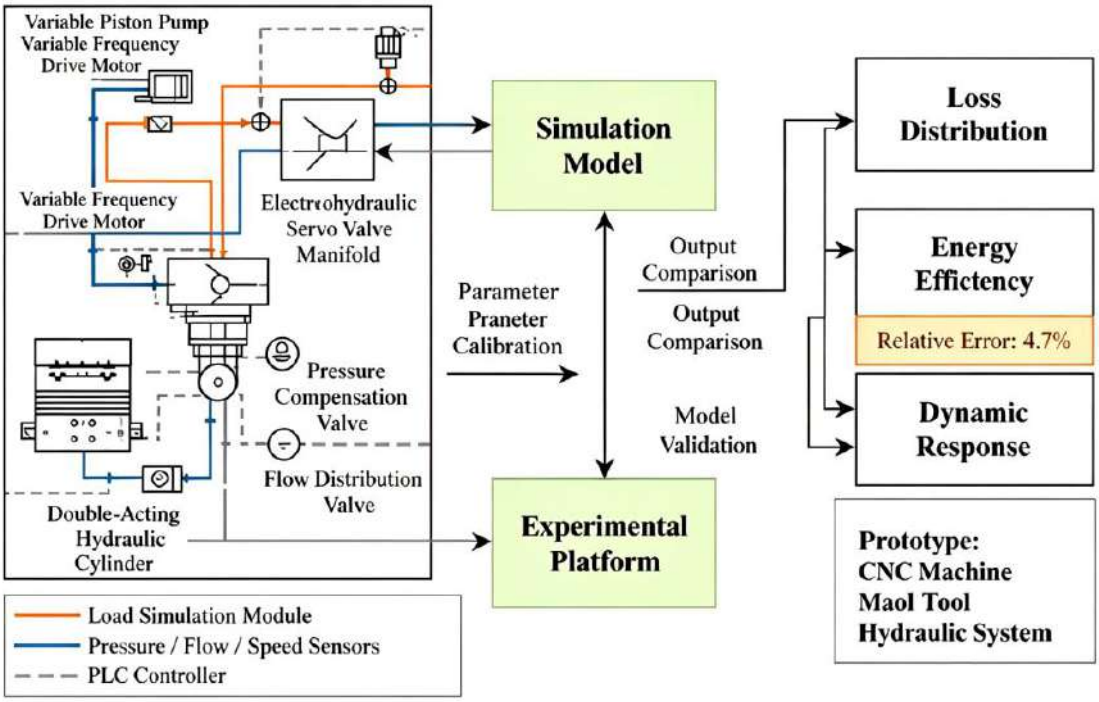


Fig. 7. Hydraulic experimental platform and simulation-validation framework.

The main test indicators of the experiment include: the loss power at each scale, the global energy efficiency, the system step response time, and the overshoot [13]. The test results of the two groups are compared respectively to verify the practical application effect of the proposed control strategy [2].

Experimental Results and Analysis

Multi-scale loss experimental results. The comparison of the average loss power at each scale in the two experimental groups is shown in Table 1.

Table 1. Multi-scale loss comparison (unit: kW)

Indicator	Control group (kW)	Experimental group (kW)	Reduction (%)
Micro loss	5.23	3.15	39.8
Meso loss	3.17	2.05	35.2
Macro loss	1.60	0.82	48.7
Total loss	**10.00**	**6.02**	**39.8**

The experimental results show that the losses at each scale in the experimental group are significantly reduced compared with the control group, and the total loss is reduced by an average of 39.8%, with the error from the simulation result (total loss reduction of 38.0%) within 5%. The difference mainly originates from minor disturbances during the experiment such as pipeline leakage and ambient temperature variation, indicating that the multi-scale loss model can accurately reflect the loss characteristics of the actual system and that the proposed control strategy can effectively suppress the multi-scale losses of the actual system [2, 3, 13].

Global energy-efficiency experimental results. The comparison of the average global energy efficiency under different operating conditions in the two experimental groups is shown in Table 2.

Table 2. Global energy efficiency comparison (%)

Condition	Control group (%)	Experimental group (%)	Improvement (%)
5 kW	50.2	63.5	13.3
8 kW	49.8	64.2	14.4
11 kW	53.5	66.8	13.3
14 kW	56.3	67.5	11.2
17 kW	55.2	65.4	10.2
Average	**53.0**	**65.5**	**12.5**

The experimental results show that the average global energy efficiency of the control group is 53.0%, while that of the experimental group is 65.5%, an average improvement of 12.5 percentage points, with the largest improvement reaching 14.4%, basically consistent with the simulation result (average improvement of 12.1 percentage points). This verifies the energy-efficiency improvement effect of the proposed collaborative control strategy in an actual system. At the same time, the average energy-efficiency fluctuation amplitude of the experimental group is 3.5%, significantly lower than that of the control group (8.9%), indicating that the control strategy has good stability under actual complex operating conditions [9].

Dynamic performance experimental results. The test results of the system step response characteristics in the two experimental groups are shown in Table 3.

Table 3. Dynamic performance comparison

Indicator	Control group	Experimental group	Change
Response time (s)	0.29	0.22	shortened 24.1%
Overshoot (%)	18.7	7.5	reduced 60.0%

The experimental results show that the average step response time of the experimental group is 0.22 s, shortened by 24.1% compared with the control group (0.29 s); the average overshoot is 7.5%, reduced by 60.0% compared with the control group (18.7%). This result further verifies that the proposed collaborative control strategy can achieve "coordinated improvement of energy efficiency and dynamic performance" in an actual system, solving the core pain point of traditional control strategies [1, 12, 13].

Comparison and Error Analysis of Simulation and Experimental Results

The error analysis of the core indicators between the simulation and experimental results is shown in Table 4.

Table 4. Error analysis

Core indicator	Simulation	Experiment	Relative error (%)
Total loss reduction rate (%)	38.0	39.8	4.7
Global energy-efficiency improvement rate (%)	12.1	11.6	4.1
Response time change rate (%)	25.0	24.1	3.6
Overshoot change rate (%)	61.2	60.0	2.0

The comparison results show that the relative errors of all core indicators are within 5%, among which the relative error of the total-loss reduction rate is 4.7%, that of the global energy-efficiency improvement rate is 4.1%, and the relative errors of the dynamic performance indicators are all below 4.0%. The main cause of the errors is that the simulation ignores practical interference factors such as ambient temperature, pipeline wear, and sensor errors [11]. Overall, the simulation results are highly consistent with the experimental results, verifying the accuracy of the established multi-scale loss model and global energy-efficiency model, as well as the effectiveness and practicability of the proposed global energy-efficiency collaborative control strategy [14].

Conclusions.

Research Summary

Aiming at the core problem of "multi-scale loss coupling and the difficulty of simultaneously achieving high energy efficiency and good dynamic performance" in process machinery hydraulic systems, this paper carries out research on the multi-scale mechanism of power loss and the global energy-efficiency improvement collaborative control theory and method [3, 11]. Through systematic theoretical analysis, modeling, simulation, and experimental verification, the following main conclusions are drawn:

1. The multi-scale classification criterion for power loss in process machinery hydraulic systems is clarified, and the generation mechanism and coupling law of multi-scale losses are revealed [9]. Power loss is divided into three scales–micro, meso, and macro–and quantitative models of the power loss at each scale are established. It is found that the volumetric loss of the hydraulic pump, the throttling loss of the control valve, and the circuit coupling loss are the main sources of total system loss (accounting for over 75% in total), and the losses at different scales exhibit significant coupling effects, influencing and aggravating one another [13].

2. A global energy-efficiency model covering multi-scale losses is established, achieving a precise correlation between multi-scale losses and system energy efficiency. Based on the energy balance principle, a "micro–meso–macro" three-level energy-efficiency model is constructed, directly correlating the loss parameters at each scale with the global energy efficiency [11]. Through parameter identification and experimental validation, the error between the model output and the actual system is within 5%, providing solid theoretical support for global energy-efficiency optimization control [2].

3. A multi-scale collaborative global energy-efficiency improvement control strategy is proposed, achieving coordinated improvement of energy consumption and dynamic performance [6,8]. An improved adaptive genetic algorithm is designed for control-parameter optimization, solving the problems of slow convergence and a tendency to fall into local optima in traditional genetic algorithms [12]. Simulation and experimental verification show that the strategy can improve the global energy efficiency of the system by an average of 11.6%–12.1%, reduce the total loss by 38.0%–39.8%, shorten the system response time by 24.1%–25.0%, and reduce the overshoot by 60.0%–61.2%.

4. Through the dual verification of simulation and experiment, the effectiveness and practicability of the proposed theory and method are confirmed. The errors of the core indicators are all within 5%, indicating that the established model and the proposed control strategy can adapt to the complex operating conditions of process machinery hydraulic systems and can be directly applied to the energy-saving retrofit of actual systems [14].

Research Innovations

The innovations of this paper are mainly reflected in the following three aspects:

1. A multi-scale classification criterion and quantitative model are proposed. This breaks through the limitation of traditional single-scale loss analysis, clarifies the boundaries of the micro, meso, and macro scales, systematically analyzes the generation mechanism and

coupling law of the losses at each scale, and can reveal the essential causes of system power loss more comprehensively and deeply [11].

2. A global energy-efficiency model is established. This solves the problem that traditional energy-efficiency models cannot reflect the influence of multi-scale coupling, organically combines the micro component energy efficiency, meso circuit energy efficiency, and macro system energy efficiency, and realizes the precise quantification and prediction of energy efficiency [13].

3. A collaborative control strategy is proposed. By integrating multi-scale loss compensation and global parameter collaborative optimization, it breaks the limitation of traditional control strategies that target only a single scale or a single operating condition, and realizes the coordinated optimization of energy efficiency and dynamic performance [2].

Future Work

Although this research has achieved certain results, combined with the practical application needs and technical development trends of process machinery hydraulic systems, some problems still need further in-depth research:

1. Optimization algorithm performance. In the future, advanced intelligent algorithms such as particle swarm optimization and gray wolf optimization will be fused and improved with the existing algorithm to further shorten the optimization iteration time and improve the adaptability and robustness of the algorithm to extremely complex operating conditions [3].

2. Improvement of the dynamic energy-efficiency model. Considering factors such as aging and wear of the actual system, the influence of the dynamic variation of component structural parameters and circuit parameters on multi-scale losses and global energy efficiency will be studied, and a dynamic global energy-efficiency model will be established to improve the long-term practicability of the model [13].

3. Expansion of application verification. The proposed control strategy will be applied to different types and scales of process machinery hydraulic systems such as metallurgical rolling mills, mining machinery, and injection molding machines to verify the universality of the control strategy [2].

4. Exploration of multi-energy collaborative drive. The power-loss characteristics and energy-efficiency optimization methods of hydraulic systems under multi-energy collaborative drive modes (such as hydraulic–electric and hydraulic–pneumatic collaboration) will be studied to further improve the green level of process machinery.

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ПІДВИЩЕННЯ ГЛОБАЛЬНОЇ ЕНЕРГОЕФЕКТИВНОСТІ ГІДРАВЛІЧНИХ СИСТЕМ ТЕХНОЛОГІЧНОГО ОБЛАДНАННЯ

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Анотація

Гідравлічні системи технологічного обладнання завдяки високій щільності потужності, точному регулюванню швидкості та високій стійкості до ударних навантажень широко застосовуються у ключових промислових галузях, таких як металургія, верстатобудування та гірнича промисловість, і є енергетичною основою сучасного технологічного виробництва. Однак під час роботи таких систем виникають значні втрати потужності, які мають багатомасштабну зв'язну властивість за схемою «елемент – контур – система», через що енергоефективність систем залишається низькою (у промислових умовах зазвичай становить

лише 45–60 %). Це стало основним перешкодою на шляху енергозбереження, скорочення викидів та зеленого модернізування технологічного обладнання.

Для вирішення недоліків існуючих досліджень, а саме неповного аналізу механізмів втрат потужності, недостатнього врахування багатомасштабних зв'язних ефектів та відсутності глобальної координації в системах керування енергоефективністю, у статті систематично досліджено багатомасштабний механізм втрат потужності, а також теорію та методи спільного керування для підвищення глобальної енергоефективності гідравлічних систем технологічного обладнання.

Спочатку визначено критерії багатомасштабної класифікації втрат потужності та систематично проаналізовано механізми їх виникнення у трьох вимірах: мікрорівень (внутрішня частина елементів), мезорівень (зв'язність контурів) та макрорівень (вся система в цілому), на основі чого побудовано кількісну багатомасштабну модель втрат потужності. Далі з урахуванням взаємозв'язків між втратами різних масштабів створено модель глобальної енергоефективності, що дозволяє виявити внутрішні залежності між багатомасштабними втратами та енергоефективністю системи.

Потім запропоновано стратегію керування, що поєднує компенсацію багатомасштабних втрат та спільну оптимізацію глобальних параметрів, а також розроблено оптимізаційний контролер на основі вдосконаленого адаптивного генетичного алгоритму (IAGA). Цей контролер забезпечує одночасне покращення показників енергоспоживання та динамічних характеристик системи. На завершення ефективність та практичність запропонованої теорії та методів підтверджено за допомогою симуляційного аналізу та експериментальних випробувань.

Отримані результати свідчать, що побудована багатомасштабна модель втрат потужності дозволяє точно кількісно оцінити внесок втрат кожного масштабу. Основними джерелами загальних втрат системи є об'ємні втрати гідравлічного насоса, дросельні втрати регулюючого клапана та втрати через зв'язність контурів (їх сумарна частка перевищує 75 %). Запропонована стратегія спільного керування глобальною енергоефективністю забезпечує зростання енергоефективності системи на 12–18 % при різних робочих режимах, одночасно зменшуючи перерегуляцію динамічної реакції більш ніж на 60 %. Це дозволяє успішно вирішити проблему неможливості одночасного досягнення високої енергоефективності та хороших динамічних характеристик, характерну для традиційних стратегій керування.

Дане дослідження надає надійну теоретичну базу та практичний технічний шлях для оптимізації проектування та керування енергоефективністю гідравлічних систем технологічного обладнання, а також має високе теоретичне значення та практичну цінність для розвитку зеленого та низьковуглецевого сектору технологічного машинобудування.

Ключові слова: технологічне обладнання; гідравлічна система; втрати потужності; багатомасштабний механізм; глобальна енергоефективність; спільне керування.