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Research on the Performance of a Heavy-Duty Robotic Arm Featuring Pump-Valve Coordination and Independent Metering Control with Hydraulic-Pneumatic Energy Storage

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Abstract.

Hydraulic systems dominate heavy-duty robotic arm applications due to their high power density and inherent impact resistance. However, conventional architectures suffer from severe throttling losses at valve ports and considerable dissipation of gravitational potential energy, resulting in overall system efficiencies of less than 30 % - a key contributor to the high energy consumption of heavy-duty equipment. To overcome these limitations, this paper proposes a novel hydraulic system integrating a three-chamber hydraulic cylinder with hydraulic-pneumatic energy storage, incorporating pump-valve coordination and independent metering control for heavy-duty robotic arms. In the proposed system, the energy-storage chamber of the three-chamber hydraulic cylinder is directly connected to a hydraulic accumulator. A multi-stage pressure-adjustable valve is designed to adaptively regulate energy storage under varying working conditions, enabling efficient recovery and reuse of gravitational energy. Pre-charging the hydraulic accumulator to counterbalance the arm's self-weight improves dynamic response and significantly reduces flow demand. The two driving chambers of the three-chamber hydraulic cylinder adopt independent metering control, combined with a pump-valve coordinated control strategy dominated by velocity feedforward and regulated by position feedback. This approach minimizes throttling losses and mitigates the reverse nonlinear charging characteristics of hydraulic accumulators. This strategy also overcomes traditional constraints on actuator chamber area imposed by conventional valve configurations. To fully exploit the synergy between independent metering and hydraulic-pneumatic energy storage, a newly designed independent metering valve manifold is introduced, offering low pressure loss, rapid response, and high precision and reliability. A 38-ton hydraulic excavator boom system was selected as a representative case study. Firstly, energy flow analysis was conducted. Subsequently, a multidisciplinary

co-simulation model was developed. Then, system parameters and control strategies were optimized based on the machine's operational characteristics. Finally, a prototype was built to evaluate performance and energy efficiency. Results demonstrate that, compared with existing solutions under identical conditions, the proposed system reduces flow demand by approximately 38 %, peak power by around 48 %, and achieves a gravitational energy recovery efficiency of nearly 70 %, leading to overall energy savings of up to 40 %. Additionally, the system exhibits excellent tracking accuracy, rapid dynamic response, and stable operation with minimal pressure and velocity fluctuations.

Keywords. Heavy-duty robotic arm, pump-valve coordinated control, independent metering control, hydraulic-pneumatic energy storage, velocity-position compound control.

1. INTRODUCTION

Heavy-duty robotic arms are typically powered by centralized hydraulic systems with valve-controlled power distribution, which provide advantages such as high power density and strong impact resistance. However, relevant studies have shown that the overall energy efficiency of such systems is often below 30 % [1], becoming a critical bottleneck for the sustainable and energy-efficient development of heavy equipment. The main reasons are twofold: on the one hand, traditional four-edge valve spools exhibit mechanical coupling between the inlet and outlet ports, leading to simultaneous throttling and severe energy losses. Moreover, only one control variable can be regulated at a given time, resulting in low degrees of freedom and poor controllability. On the other hand, during the lowering process of heavy-duty robotic arms, large amounts of gravitational potential energy are dissipated as heat through throttling orifices, not only wasting energy but also requiring additional cooling devices, which increase system complexity and failure risk.

Independent metering control offers an effective means to decouple actuator chamber regulation, thereby improving both energy efficiency and control performance. Backé pioneered the concept by developing a hydraulic cylinder system controlled by four cartridge valves [2]. Subsequently, Jansson and Palmberg addressed the problem of energy dissipation in valve-controlled systems by employing four Valvistor valves with pressure compensation and flow regeneration to reduce losses [3]. Hu and Zhang further introduced a proportional valve in parallel at the pump outlet based on a four-spool configuration, enabling multiple neutral control functions [4]. Lyu, Chen and Yao proposed a pump-valve coordinated scheme, where the pump supplied the main flow and the valve ensured accuracy, reducing energy consumption by about 50 % [5]. Zhong et al. employed high-speed switching valves as the pilot stage of a dual-spool electro-hydraulic proportional valve, improving dynamic response by 21 % and control accuracy by 16 % [6].

In terms of control strategies, Meyer, Weiler and Murrenhoff developed a discrete logic control method for independent metering control systems, dynamically adjusting piston-rod side pressure to enhance stiffness and efficiency [7]. Lu and Yao proposed a multi-level adaptive robust control strategy utilizing five cartridge valves and an accumulator, resulting in 30–40 % energy savings [8]. Xu et al. combined pump-valve control strategies to optimize both flow and pressure regulation, significantly reducing energy consumption while improving performance [9]. Shi et al. introduced a mode-switching velocity–position compound control strategy based on pump-valve coordination and independent metering control, achieving smooth operation and high positioning accuracy under low energy consumption [10]. Li et al. integrated adaptive robust control with online parameter estimation to dynamically compensate for fluid compressibility and valve flow deviations, thereby improving control accuracy and stability [11].

Energy recovery from heavy-duty robotic arms primarily involves hydraulic, electrical, and mechanical approaches, which are also crucial for enhancing system efficiency. In hydraulic methods, Tong et al. proposed coupling high- and low-pressure accumulators with pump-motor torque, reducing energy consumption by 28–35 % [12]. Yang et al. developed a system using a three-chamber accumulator, increasing energy storage density by 43 % [13]. Tan et al. combined auxiliary and intensifying cylinders for energy recovery, achieving an efficiency of 58 % [14]. Beyond academic research, several manufacturers, including Liebherr (Germany), Sennebogen (Germany), Mantsinen (Sweden), Changlin Group (China), and Sunward Intelligent Equipment Group (China), have implemented mass compensation solutions based on energy-storage cylinders combined with accumulators. Reported applications indicate that such solutions can reduce the overall energy consumption of the machine by more than 30 % [15]. In electrical methods, Li, Wu and Cao controlled boom energy recovery based on excavator operation and battery state, improving recovery efficiency [16]. Lin et al. used proportional valves to control hydraulic motors, obtaining 35 % recovery efficiency with enhanced dynamic performance [17]. Do and Ahn employed hydraulic motors with planetary gearboxes, achieving 73 % regeneration efficiency and extending battery life by 16 % [18]. In mechanical methods, Latas and Stojek integrated a variable-inertia flywheel with a variable-displacement pump/motor in a novel hydromechanical accumulator, enabling multi-mode storage and improving energy density [19]. Li and Zhao combined flywheels, pump/motors, and regenerative valves, achieving 62 % recovery efficiency [20]. Cronk, Van and Strohmaier hybridized hydraulic accumulators with flywheels, reaching a conversion efficiency of 78 % and realizing dual-domain storage of hydraulic and kinetic energy [21].

Despite these significant advances, several challenges remain. independent metering control systems improve efficiency and control performance but involve complex multi-variable coordination, which limits their widespread adoption. Meanwhile, energy recovery techniques often involve multiple conversion stages, high system complexity, and trade-offs between efficiency and cost-effectiveness. Independent metering control and hydraulic-pneumatic energy storage offer complementary advantages in enhancing energy efficiency and control performance, yet their deep integration remains a challenge.

To address this gap, this study proposes a novel pump-valve coordinated and independent metering control system for a three-chamber hydraulic cylinder with hydraulic-pneumatic energy storage in heavy-duty robotic arms. In this system, the energy-storage chamber is directly connected to a hydraulic accumulator, together with a multi-level pressure-adjustable control valve. Through hydraulic-pneumatic balance, the system efficiently stores and utilizes gravitational potential energy under varying operating conditions. The two driving chambers of the cylinder adopt independent metering control principles, combined with a pump-valve coordinated strategy integrating velocity feedforward and position feedback, enabling smooth switching between operating modes to achieve high power density, high performance, and high energy efficiency. Based on theoretical analysis, a multidisciplinary co-simulation and experimental system was developed to investigate the operating characteristics and energy efficiency of the proposed heavy-duty robotic arm system.

2. System Principle

The principle of the proposed pump-valve coordinated and independent metering control system with hydraulic-pneumatic energy storage for heavy-duty robotic arms is illustrated in **Figure 2.1**. The system consists of an electrohydraulic power source, an independent metering valve manifold, a three-chamber hydraulic cylinder, a heavy-duty robotic arm, a hydraulic accumulator, and a multi-stage pressure-adjustable valve. The three-chamber hydraulic cylinder includes one energy-storage chamber and two driving chambers, with the two driving chambers designed to have equal effective areas.

The energy-storage chamber of the three-chamber cylinder is directly connected to the hydraulic accumulator via the multi-stage pressure-adjustable valve. Through hydraulic-pneumatic balancing, the self-weight of the robotic arm is compensated, allowing for the efficient storage and utilization of gravitational potential energy [14]. Depending on operating conditions, the energy-storage chamber can also be connected to the electrohydraulic power source or the tank via the adjustable valve to satisfy oil replenishment or pressure release requirements. The two driving chambers are connected to the independent metering valve manifold, enabling fully decoupled control [3]. Furthermore, the manifold is optimized to integrate flow regeneration, allowing direct interconnection between the two driving chambers of the cylinder.

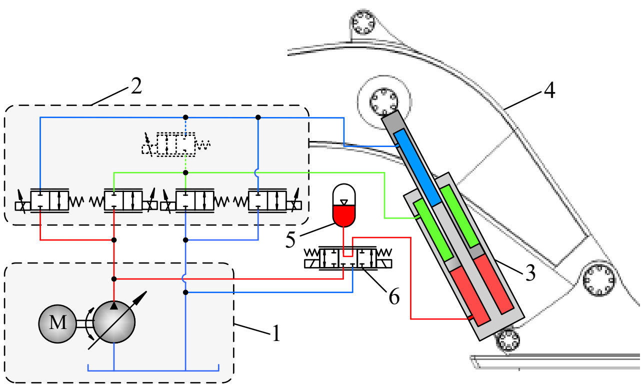

Figure 2.1. Principle of the pump-valve coordinated and independent metering control system with hydraulic-pneumatic energy storage for heavy-duty robotic arms. 1-Electrohydraulic power source,2-Independent metering valve manifold,3-Three-chamber hydraulic cylinder,4-Heavy-duty robotic arm,5-Hydraulic accumulator,6-Multi-stage pressure-adjustable valve.

According to load and operating conditions, the system can switch among different modes by adjusting motor speed, pump displacement, and valve openings [5]. This enables pump-valve coordinated control, independent metering control, energy recovery, and flow regeneration.

2.1. *Resistive Extension Mode*

As shown in **Figure 2.2**, the resistive extension mode operates in the first quadrant. In this mode, the inlet valve, outlet valve, and pressure-adjustable valve are fully open. The two driving chambers of the three-chamber cylinder are connected to the hydraulic pump and the tank, respectively, while the energy-storage chamber is connected to the accumulator. The cylinder is therefore driven jointly by the hydraulic pump and the accumulator to extend against the external load. The cylinder velocity is controlled through motor speed and pump displacement, with the system operating in pump control mode. This significantly reduces throttling losses while lowering overall flow demand.

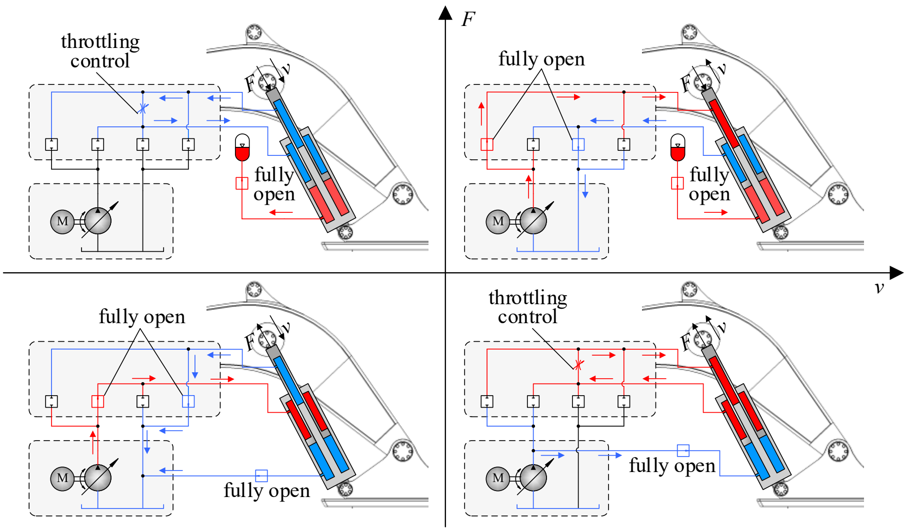

Figure 2.2. Operating modes of the pump-valve coordinated and independent metering control system with hydraulic-pneumatic energy storage for heavy-duty robotic arms.

2.2. *Overrunning Retraction Mode*

As shown in **Figure 2.2**, the overrunning retraction mode operates in the second quadrant. In this mode, the pressure-adjustable valve is fully open, and the two driving chambers of the cylinder are interconnected through the flow regeneration valve, while the energy-storage chamber is connected to the accumulator. In this condition, the gravitational potential energy of the robotic arm is directly recovered as hydraulic energy and stored in the accumulator. The cylinder velocity is regulated by throttling through the flow regeneration valve, which also mitigates the nonlinear back-pressure characteristic of the accumulator during charging. The system therefore operates in valve control mode with both energy recovery and flow regeneration.

2.3. *Resistive Retraction Mode*

As shown in **Figure 2.2**, the resistive retraction mode operates in the third quadrant. Similar to the resistive extension mode, the inlet valve, outlet valve, and pressure-adjustable valve are fully open. The two driving chambers are connected to the hydraulic pump and tank, respectively, while the energy-storage chamber is connected to the tank. In this case, the hydraulic pump drives the cylinder to retract against the load. The cylinder velocity is controlled by adjusting motor speed and pump displacement, and the system operates in pump control mode.

2.4. Overrunning Extension Mode

As shown in **Figure 2.2**, the overrunning extension mode operates in the fourth quadrant. Similar to the overrunning retraction mode, the pressure-adjustable valve is fully open. The two driving chambers are interconnected through the flow regeneration valve, while the energy-storage chamber is connected to the pump. In this case, the hydraulic pump replenishes oil into the energy-storage chamber to prevent cavitation and oscillations. The cylinder velocity is regulated through throttling by the flow regeneration valve, and the system operates in valve control mode.

3. SYSTEM ANALYSIS

A theoretical framework was developed for the proposed system, combining energy-flow analysis with mathematical modeling to support control strategy design.

3.1. Energy Flow Analysis

The energy flow of the pump-valve coordinated and valve-orifice independent control system with hydraulic-pneumatic energy storage for heavy-duty robotic arms is illustrated in **Figure 3.1**. Pump-valve coordinated control reduces throttling losses by switching between pump-control and valve-control modes. In addition, by coordinating motor speed with pump displacement, the pump supply matches actuator demand, minimizing overflow losses. Independent metering control enables independent regulation of pressure and flow in each chamber. This decouples the oil supply and return paths, eliminates simultaneous throttling, and enhances system controllability while reducing losses. Furthermore, return oil is either recovered by the hydraulic accumulator or directly regenerated to another actuator chamber, thereby realizing energy recovery and circulation [8]. Unlike conventional systems, where potential energy is dissipated as heat, the proposed system converts these losses into reusable energy, improving overall efficiency.

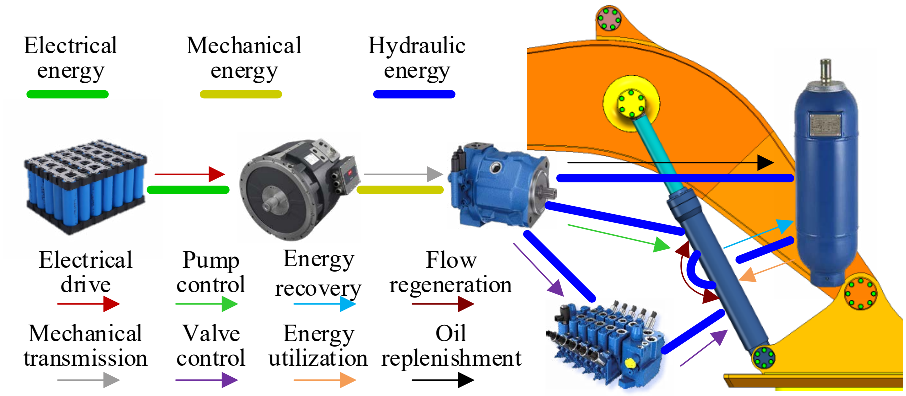

Figure 3.1. Energy flow of the pump-valve coordinated and independent metering control system with hydraulic-pneumatic energy storage for heavy-duty robotic arms.

3.2. System Modeling

Mathematical models are created for the main components and links. These models provide the basis for simulating system performance and evaluating energy efficiency.

The discharge power of the battery is:

$$P_b = \frac{T_e \omega_e}{\eta_e} \tag{3.1}$$

where P_b is the battery discharge power, T_e is the electromotor torque, ω_e is the electromotor speed, and η_e is the electromotor efficiency.

The torque balance of the electromotor and hydraulic pump is:

$$J_{ep}\dot{\omega}_e + B_{ep}\omega_e = T_e - T_p \tag{3.2}$$

where J_{ep} is the total rotational inertia of the electromotor and pump, B_{ep} is the total viscous damping coefficient, and T_p is the pump torque.

The pump torque is:

$$T_p = \frac{D_p p_p}{\eta_p} \tag{3.3}$$

where D_p is the pump displacement, p_p is the pump pressure, and η_p is the pump efficiency.

The pump flow rate is:

$$Q_p = D_p\omega_e - C_{lp}(p_p - p_t) \tag{3.4}$$

where Q_p is the pump flow, C_{lp} is the pump leakage coefficient, and p_t is the tank pressure.

The valve flow equation is:

$$Q_{v,j} = C_d w_{v,j} x_{v,j}\sqrt{\frac{2\Delta p_{v,j}}{\rho}} \cdot \mathrm{sgn}(\Delta p_{v,j}) \tag{3.5}$$

where $Q_{v,j}$ is the flow through the valve orifice, C_d is the flow coefficient, $w_{v,j}$ is the orifice area gradient, $x_{v,j}$ is the valve spool displacement, $\Delta p_{v,j}$ is the pressure drop across the valve, and ρ is the oil density.

The continuity equation of the three-chamber hydraulic cylinder is:

$$\dot{p}_j = \frac{\beta_e}{V_j}(Q_{v,j} - A_j\dot{x}_c - C_{lc}\Delta p_c) \tag{3.6}$$

where p_j is the chamber pressure, β_e is the effective bulk modulus, V_j is the chamber volume, A_j is the piston area, x_c is the piston displacement, C_{lc} is the cylinder leakage coefficient, and Δp_c is the chamber pressure differential.

The force balance of the three-chamber hydraulic cylinder is:

$$m_{eq}\ddot{x}_c + B_c\dot{x}_c + K_c x_c = A_1p_1 - A_2p_2 + A_3p_3 - F_L \tag{3.7}$$

where m_{eq} is the equivalent mass of piston rod and load, B_c is the viscous damping, K_c is the stiffness, A_1, A_2 are the driving chamber areas with pressures p_1, p_2, A_3 is the energy-storage chamber area with pressure p_3, and F_L is the external load.

The accumulator pressure dynamics are:

$$\dot{p}_3 = \frac{\beta_a}{V_a} Q_a \tag{3.8}$$

where β_a is the effective bulk modulus of the accumulator, V_a is the effective volume, and Q_a is the accumulator flow.

The energy stored in the accumulator is:

$$E_a = \frac{p_y V_y - p_x V_x}{\gamma - 1} \tag{3.9}$$

where E_a is the energy stored in the hydraulic accumulator, p_x, p_y are the pressures of the accumulator, V_x, V_y are the volumes of the accumulator, and γ is the adiabatic index.

4. CONTROL STRATEGY

To further improve system performance and efficiency, a pump-valve coordinated control strategy with velocity feedforward and position feedback regulation is adopted [9]. Velocity feedforward serves as the primary control loop, generating real-time commands for motor speed, pump displacement, and valve opening based on the desired velocity profile. This enables rapid response to target motions. Position feedback is introduced as a compensatory loop: the deviation between desired and actual position is used to correct the feedforward commands, thereby suppressing tracking errors caused by nonlinear factors such as leakage, friction, and fluid compressibility [11].

The motor speed feedforward signal u_{ef} is:

$$u_{ef} = \frac{v_e \cdot A}{D_p \omega_{emax}} \tag{4.1}$$

where A is the piston area of the driving chamber, and ω_{emax} is the maximum motor speed.

The pump displacement feedforward signal u_{pf} is:

$$u_{pf} = \frac{v_e \cdot A}{D_{pmax} \omega_e} \tag{4.2}$$

where D_{pmax} is the maximum pump displacement.

The valve opening feedforward signal u_{vf} is:

$$u_{vf} = \frac{v_e \cdot A}{Q_n} \sqrt{\frac{\Delta p_n}{\Delta p_{v,j}}} \tag{4.3}$$

where Q_n is the rated valve flow at pressure drop Δp_n.

The position feedback signal u_b is:

$$u_b = K_p \left(\int_{t_0}^{t_1} v_e \mathrm{d}t - x_c \right) + K_i \int_{t_0}^{t_1} \left(\int_{t_0}^{t_1} v_e \mathrm{d}t - x_c \right) \mathrm{d}t + K_d \frac{\mathrm{d}\left(\int_{t_0}^{t_1} v_e \mathrm{d}t - x_c \right)}{\mathrm{d}t} \tag{4.4}$$

where K_p, K_i, and K_d are proportional, integral, and derivative gains, respectively.

The overall control input is:

$$U = \left[u_{ef} + u_b, u_{pf} + u_b, u_{vf} + u_b \right] \tag{4.5}$$

This strategy leverages velocity feedforward for rapid response and position feedback for nonlinear compensation. Combined with pump-valve coordinated and energy recovery mechanisms, it enables high-precision control and energy-efficient operation of the heavy-duty robotic arm hydraulic system [21].

5. Simulation Study and Preliminary Experimental Validation

The boom system of a 38-ton hydraulic excavator was selected as a representative case for investigation. A multidisciplinary co-simulation model was developed in SimulationX, incorporating the mechanical, electrical, hydraulic, and control subsystems [10]. To further validate the operating characteristics and energy-saving performance, an experimental platform was constructed on a 38-ton excavator, as shown in **Figure 5.1**.

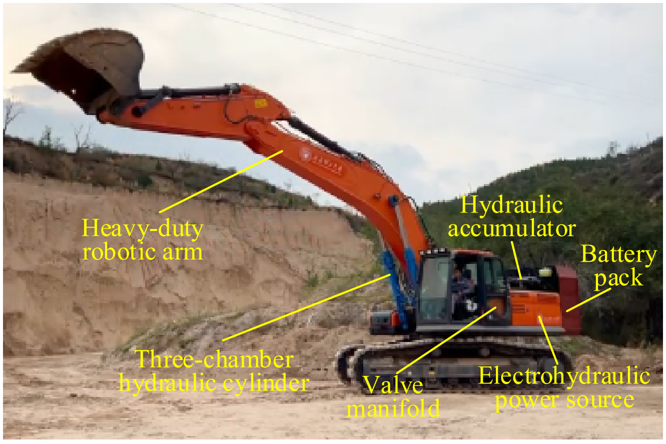

Figure 5.1. Experimental platform of the 38-ton hydraulic excavator.

The displacement and velocity curves of the boom cylinder are illustrated in **Figure 5.2**, where the maximum extension velocity was set to 200 mm/s and the maximum retraction velocity to 400 mm/s. The boom lifted from 2 to 7.5 s, remained stationary from 7.5 to 9 s, and descended from 9 to 12.5 s. As shown in **Figure 5.2**, both the original valve-controlled two-chamber cylinder system and the proposed pump–valve coordinated and independent metering controlled three-chamber cylinder system were able to track the desired displacement with overall smooth velocity profiles. During the initial lifting phase, the energy-storage chamber of the new system was directly connected to the hydraulic accumulator, thereby counterbalancing the boom's gravitational load and overcoming the inertial resistance. With the assistance of the accumulator, the proposed system exhibited faster dynamic response compared to the conventional system. However, the nonlinear charging/discharging characteristics of the accumulator introduced minor velocity fluctuations.

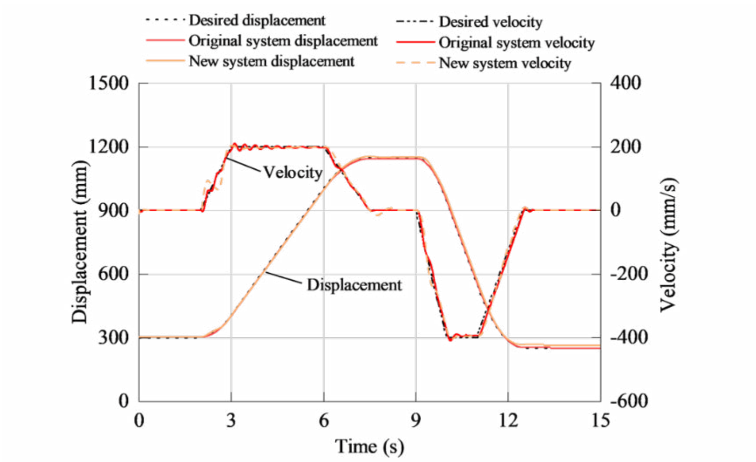

Figure 5.2. Displacement and velocity curves of the boom cylinder.

Figure 5.3 presents the pump output flow and accumulator pressure curves of both systems. For the conventional system, the required pump flow reached 424 L/min during boom lifting and 432 L/min during lowering. In contrast, the proposed system required only 173 L/min during lifting and 357 L/min during lowering. In the lifting phase, the accumulator discharged into the energy-storage chamber of the three-chamber cylinder, with its pressure gradually decreasing as stored energy was directly utilized. During lowering, the energy-storage chamber charged the accumulator, causing its pressure to increase as gravitational potential energy was converted into hydraulic energy and stored for subsequent reuse. Compared with the conventional two-chamber system, the smaller effective areas of the two driving chambers in the proposed three-chamber cylinder allowed a significant portion of the required flow to be supplied by the accumulator, thereby reducing the pump output flow by approximately 38 %.

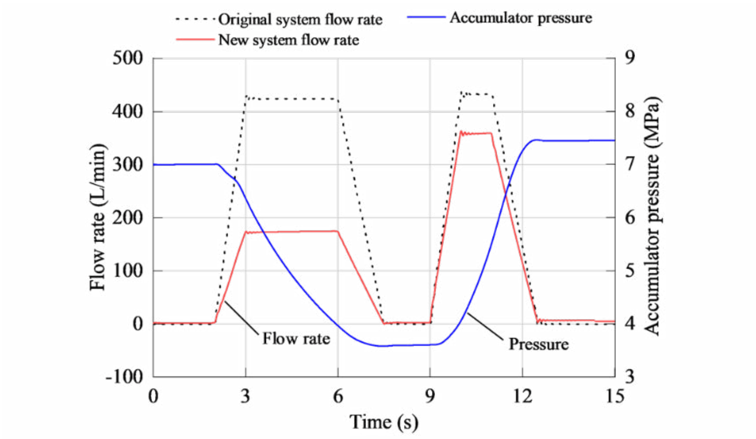

Figure 5.3. Pump output flow and accumulator pressure curves.

Figure 5.4 shows the system power and energy profiles. In the conventional system, the peak power reached 104 kW during lifting and 224 kW during lowering, with a total energy consumption of 821 kJ. In the proposed system, the corresponding peak powers were reduced to 54 kW and 175 kW, with a total energy consumption of 479 kJ. By integrating chamber-independent valve control and the three-chamber cylinder, the proposed system effectively reduced throttling losses and directly recovered gravitational potential energy. As a result, the peak power demand was reduced by approximately 48 %, the gravitational energy recovery rate reached about 70 %, and the overall energy savings were around 40 %.

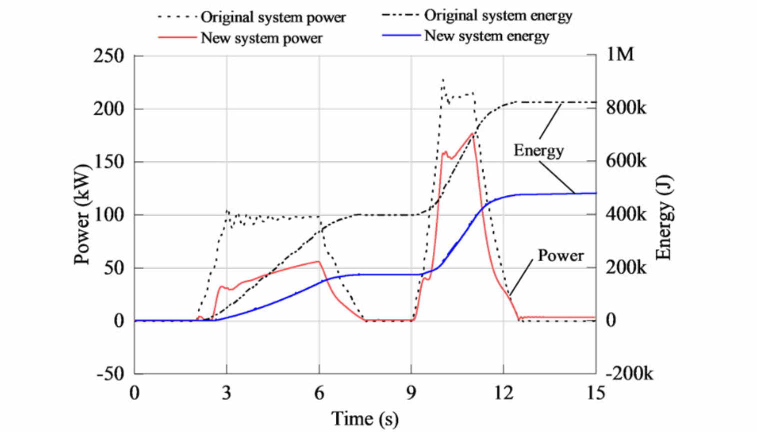

Figure 5.4. System power and energy curves.

6. Conclusions

A pump–valve coordinated and independent metering control three-chamber hydraulic cylinder system with hydraulic–pneumatic energy storage, together with a velocity feedforward–position feedback regulated pump–valve coordination strategy, has been proposed for heavy-duty robotic arms. Taking the boom system of a 38-ton hydraulic excavator as a representative case, the main conclusions are summarized as follows:

(1) The operating principle of the proposed system was analyzed. The system integrates pump–valve coordination and independent metering control with energy recovery and flow regeneration. It is capable of switching among different operating modes according to working conditions, thereby achieving high power density, superior performance, and improved energy efficiency.

(2) The energy flow of the system was examined, and a comprehensive mathematical model was established. A velocity feedforward–position feedback pump–valve coordination strategy was developed, enabling fast dynamic response through velocity feedforward and nonlinear error compensation through position feedback. Coupled with energy recovery, this strategy further enhances both control performance and system efficiency.

(3) Simulation and experimental validation demonstrated that, under identical working conditions compared to conventional systems, the proposed system reduced pump flow demand by approximately 38 %, peak power by 48 %, and achieved a gravitational energy recovery rate of about 70 %, resulting in overall energy savings of approximately 40 %. Moreover, the system exhibited excellent tracking accuracy and rapid dynamic response without significant pressure or velocity fluctuations.

This study provides a high-performance, high power density, and energy-efficient drive and transmission solution for heavy-duty equipment, offering significant potential for practical implementation and scalability in energy-saving, cost-reduction, and carbon-reduction applications.

7. ACKNOWLEDGMENTS

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8. NOMENCLATURE

A	piston area of the driving chamber	m^2
A_j	piston area	m^2
A_1, A_2	driving chamber areas	m^2
A_3	energy-storage chamber area	m^2
B_c	viscous damping	N·s/m
B_{ep}	total viscous damping coefficient	N·m/(rad/s)
C_d	flow coefficient	-
C_{lc}	cylinder leakage coefficient	m^3/(s·Pa)
C_{lp}	pump leakage coefficient	m^3/(s·Pa)
D_p	pump displacement	m^3/rad
D_{pmax}	maximum pump displacement	m^3/rad
E_a	energy stored in the hydraulic accumulator	J
F_L	external load	N
J_{ep}	total rotational inertia of the electromotor and pump	kg·m^2
K_c	stiffness	N/m
K_d	derivative gains	-
K_i	integral gains	-
K_p	proportional gains	-
m_{eq}	equivalent mass of piston rod and load	kg
P_b	battery discharge power	W
p_j	chamber pressure	Pa
p_p	pump pressure	Pa
p_t	tank pressure	Pa

p_x, p_y	pressures of the accumulator	Pa
p_1, p_2	driving chamber pressures	Pa
p_3	energy-storage chamber pressure	Pa
Q_a	accumulator flow	m^3/s
Q_n	rated valve flow	m^3/s
Q_p	pump flow	m^3/s
$Q_{v,j}$	flow through the valve orifice	m^3/s
T_e	electromotor torque	N·m
T_p	pump torque	N·m
u_b	position feedback signal	-
u_{ef}	motor speed feedforward signal	-
u_{pf}	pump displacement feedforward signal	-
u_{vf}	valve opening feedforward signal	-
V_a	effective volume	m^3
V_j	chamber volume	m^3
V_x, V_y	volumes of the accumulator	m^3
x_c	piston displacement	m
$x_{v,j}$	valve spool displacement	m
β_a	effective bulk modulus of the accumulator	Pa
β_e	effective bulk modulus	Pa
γ	adiabatic index	-
Δp_c	chamber pressure differential	Pa
Δp_n	pressure drop	Pa
$\Delta p_{v,j}$	pressure drop across the valve	Pa
η_e	electromotor efficiency	-
η_p	pump efficiency	-
ρ	oil density	kg/m^3
ω_e	electromotor speed	rad/s
ω_{emax}	maximum motor speed	rad/s
$w_{v,j}$	orifice area gradient	m^2/m

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