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Energy-saving technologies for construction machinery: a review of electro-hydraulic pump-valve coordinated system*

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Abstract: With the rapid development of the global economy, more and more attention has been paid to the energy conservation of construction machinery. The hydraulic system is the key component of construction machinery, and improving its energy utilization rate has become an important means to achieve energy conservation. In conventional valve-controlled or pump-controlled hydraulic systems of construction machinery, controllability and energy-saving performance typically cannot be considered at the same time. The pump-valve coordinated system combines the energy-saving characteristics of the pump-controlled system and the high-precision and high-frequency response of the valve-controlled system, which has the potential to become a primary research direction of electro-hydraulic systems. This review summarizes the recent research progress in energy-saving technologies based on pump-valve coordinated systems. Particularly, we discuss the structures of hydraulic systems in different categories of construction machinery, various control methods of the electro-hydraulic system, novel hydraulic hybrid energy regeneration systems, and key components. In addition, future directions and challenges of the pump-valve coordinated systems are described, such as independent metering system (IMS), common pressure rail (CPR), and hybrid power source (HPS).

Key words: Construction machinery; Energy saving; Pump-valve coordinated systems; Control algorithm; Hydraulic systems
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1 Introduction

Construction machinery that reduces the need for manual labor is crucial for various heavy-duty

industrial tasks. With the steady growth of the global economy, the average annual growth rate due to the demand for construction machinery exceeded 26%, and the sales volume reached a historical high of 1.13 million units in 2018 (Sleight, 2019). As global energy demand continues to grow, developing technologies to achieve energy conservation and emission reduction are of great importance to the industry of construction machinery. As shown in Table 1, major global brands of construction machinery including Caterpillar, Volvo, Komatsu, XCMG (Xuzhou Construction Machinery Group), and SANY (Sany Heavy Industry Co., Ltd.) are listed. As the world's largest construction machinery company, Caterpillar mainly manufactures excavators and loaders, with a market

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share of 12.60% in 2018. Komatsu and Hitachi are also major manufacturers that produce excavators and loaders, occupying 11.90% and 5.50% of market share, respectively. As a representative of European companies, Volvo primarily produces excavators and loaders, accounting for a 5.20% market share. XCMG, China's largest construction machinery manufacturer, focuses on cranes and loaders, with a market share of 4.80% (KHL, 2019). Different from construction machinery, the forklift market is made up of other heavy equipment manufacturers around the world, including Toyota Industries Corporation, KION Group AG, and Jungheinrich AG. Among them, Hangcha Group Co., Ltd. and Anhui Forklift Truck Group Co., Ltd. in China have shown the strongest sales growth in the past decade. Regarding the Chinese construction machinery market, for example, the top four categories of construction machinery by the accumulated number in China are forklifts (2650 thousand units), excavators (1686 thousand units), loaders (1614 thousand units), and cranes (655 thousand units), as shown in Fig. 1 (Lv, 2018). The situation in China is similar to the global market where excavators, loaders, cranes, and forklifts outnumber other categories, and are the main research focus of both industry and academia.

An important challenge for the construction machinery market is the large amount of energy consumption. For excavators and loaders, for example, the average fuel consumption of each heavy excavator is $0.0151 \text{ m}^3/\text{h}$, while the wheel loader reaches $0.0227 \text{ m}^3/\text{h}$. The total fuel consumption by construction machinery is significant worldwide, thus greatly aggravating the energy crisis and environmental problems (Mcclung-Logan, 2017; Tong ZM et al., 2019a). The hydraulic system has been widely used in construction machinery for its advantages of large power density and output force. As the execution system for construction machinery, the hydraulic system is designed to handle abrupt load and frequent stops. The conventional hydraulic system still suffers from obvious disadvantages, such as energy losses and poor controllability. In a typical valve-controlled system, the working efficiency of the construction machinery is usually below 30%, due to unavoidable throttling losses and pipeline damping losses (Zimmerman et al., 2007; Tong ZM et al., 2020). Therefore, concerns about the energy efficiency of

Table 1 Market share and sales of major construction machinery companies worldwide (KHL, 2019)

Company	Country	Annual sale (billion dollars)	Market share (%)
Caterpillar	USA	23.23	12.60
Komatsu	Japan	22.01	11.90
John Deere	USA	10.16	5.50
Hitachi	Japan	10.13	5.50
Volvo	Sweden	9.63	5.20
XCMG	China	8.90	4.80
SANY	China	8.43	4.60
Liebherr	Germany	8.10	4.40
Doosan	Korea	6.82	3.70
JCB	UK	5.50	3.00
Zoomlion	China	4.32	2.30
Liugong	China	2.77	1.50
Heli	China	1.37	0.74
Hangcha	China	1.25	0.67

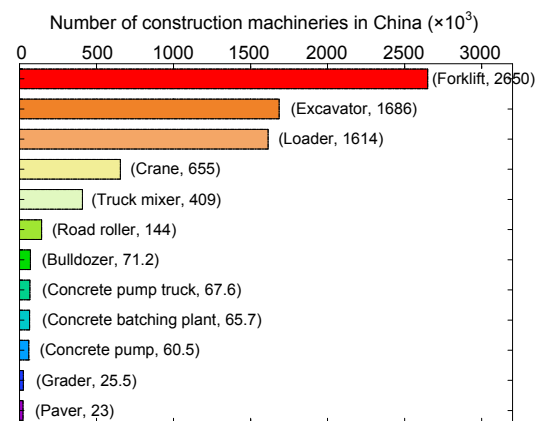


Fig. 1 Number of construction machineries in China by the end of 2017 (data source from China Construction Machinery Association) (Lv, 2018)

hydraulic systems have been raised due to numerous applications in various industries. Meanwhile, the nonlinearity and uncertainty in the hydraulic actuator's working process can cause a mismatch between the power source and actual working conditions. The efficiency of the power source is only about 75%, and there is still much room for improvement in the control performance of the hydraulic system. To improve the energy efficiency, the electro-hydraulic system has received special attention because of its advantageous controllability and flexibility over conventional systems. In an electro-hydraulic system, pumps and valves are directly driven by electrical circuits, thus

applying better control strategies (He et al., 2015). Based on this principle, existing literature has presented energy-saving methods in various fields. Quan et al. (2014) provided an overview of the research status of the direct pump control used in construction machinery. Lin et al. (2017) analyzed the different types and structures of the boom potential energy regeneration system (ERS). Wang et al. (2017) analyzed and compared the characteristics of the existing energy storage components for ERS. He and Jiang (2018) presented various types of hybrid electric system structures for different types of construction machinery. The results of these studies reflect the energy-saving advantages of electro-hydraulic systems, but these technologies still have difficulties in satisfying the demands of current construction machinery. For the differential cylinder, which is widely used as a construction machinery actuator, neither the pump control nor the valve control is ideal. The control accuracy and response speed of the pump control system are low, and the valve control system has low-efficiency problems. Additionally, existing energy recovery methods not only have low recovery efficiency but also worsen the control characteristics of the entire system due to the shortcomings of energy storage elements.

In order to have both a high-precision, high-frequency response of the valve control system and high efficiency of the pump control system, a new

type of pump-valve coordinated system has become a research hotspot of the hydraulic servo system (Xu et al., 2015b). Typical hydraulic systems of four types of construction machinery are shown in Fig. 2. The independent metering system (IMS) and load sensing (LS) technology are currently a popularly studied pump-valve coordinated control method (Figs. 2a and 2b). Control variables and degrees of freedom are increased to realize the composite control of the pump and valve, which can be applied to more complex equipment such as the excavator and loader. However, this method also makes it more difficult to control and requires more effective structural types and control strategies. The hydraulic systems of cranes and forklifts are relatively simple (Figs. 2c and 2d) but still have the problems of large throttling losses and overflow losses. More efficient energy recovery methods and control strategies need to be analyzed to promote energy-saving characteristics.

The aim of this review is to present and discuss the latest developments in energy-saving technologies for construction machinery based on pump-valve coordinated systems. First, we describe the typical structures of different hydraulic systems. Then, we present the status of electro-hydraulic systems for excavators, loaders, cranes, and forklifts. Next, we review the major control methods and hydraulic hybrid systems (HHSs). At last, future research directions and challenges are discussed.

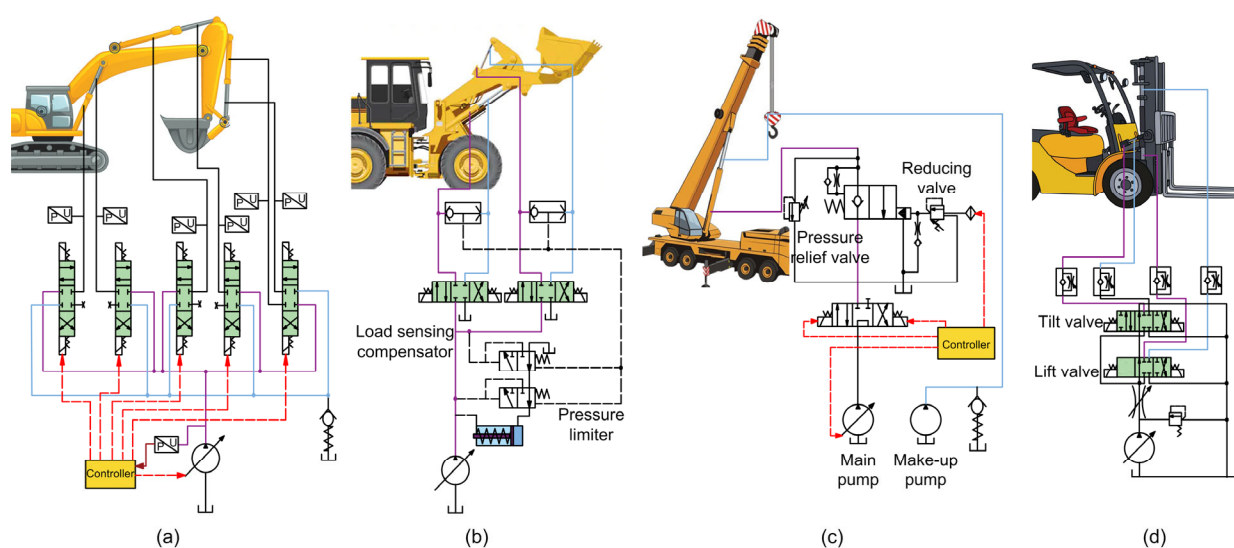


Fig. 2 Typical hydraulic schemes in common construction machinery: (a) independent metering control in excavators; (b) LS scheme in loaders; (c) make-up pump scheme in cranes; (d) coordinated control in forklifts

2 Hydraulic systems in the construction machinery

Traditional construction machinery mainly adopts the method of throttling and regulating the oil inlet path to control the movement of each actuator. This control method often causes a large amount of overflow energy loss due to the mismatch of the power of the hydraulic system. According to different performance characteristics, different types of on-demand flow supply control systems are selected. Typical schemes include negative flow control, positive flow control, LS control, and electro-hydraulic flow matching control.

Negative flow control systems are commonly applied in medium-sized machinery. A flow detection device is set on the bypass return oil circuit and produces a conditioning signal P_{st} to control the displacement of the pump and the bypass return flow to produce a negative linear relationship and thereby reduce bypass return energy loss. The basic working scheme is shown in Fig. 3a. The development of negative flow control technology is relatively mature, while the disadvantages are obvious. The energy loss of the bypass throttling inflow control still exists, and the flow characteristics of the valve port are greatly affected by the load, which directly affects system response. Regenerative energy utilization strategies were proposed to remedy these energy losses. The positive flow control system was then proposed for the application performance defect of the negative flow control system. The positive flow control provides the flow proportional to the given control signal, thus achieving the on-demand supply of traffic, as shown in Fig. 3b. The displacement of the pump and the opening of valves are controlled by the same operating signal, which helps to improve the response speed of the hydraulic system. Additional research was carried out based on the basic scheme, such as the pressure feedback-based damping method and the derivative positive flow control trajectory walking mechanism (Dong et al., 2018). Compared with negative control, bypass throttling losses can be reduced, but the energy losses of the multi-position valve cannot be eliminated.

The basic principle of electro-hydraulic LS is the principle of pressure feedback to achieve system flow supply and demand balance through pressure margin

closed-loop control, as shown in Fig. 3c. Adapting the supply pressure was seen as a convincing method for reducing the pressure loss of the valves. Du et al. (2017) proposed an optimized method based on load forecasting in which supply pressure was adapted to track the pressure required for any actuator branch. By adjusting the supply pressure, the pressure loss ought to be minimized, but the existence of a pressure feedback loop results in a small phase margin when the system uses a high gain, and a poor response when using a low gain. The contradiction between stability and fast response is difficult to perfect. For the first time, researchers from Zhejiang University and Hangcha established a hydraulic flow distribution model based on dynamic feedback by inventing the LS-hydraulic steering device, the LS-electric proportional multi-way valve, the forklift transmission, and the electromechanical-hydraulic integrated recovery for forklift braking energy and gravitational potential energy (Tong SG et al., 2018, 2019a, 2019b, 2020a).

To address the limitations of the LS, the control method of electro-hydraulic flow matching (EFM) is presented in Fig. 3d. EFM performs pump-valve coordinated control according to the real-time calculated flow to tackle the problems of slow response and low stability margin. The EFM control system adopts

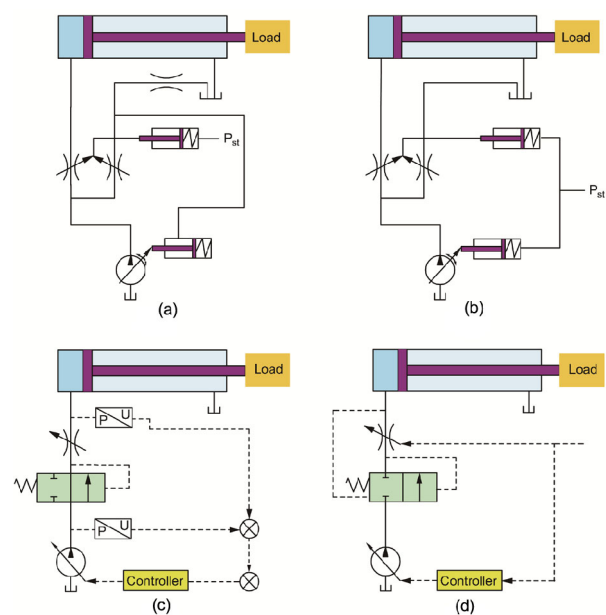


Fig. 3 Typical hydraulic systems used in construction machinery: (a) negative flow control; (b) positive flow control; (c) electro-hydraulic LS; (d) electro-hydraulic flow matching

the human-in-the-loop controller combined with the superior control algorithm, with the advantages of higher energy efficiency and fast system response compared to traditional LS systems. At the same time, its pressure margin is adaptive to load impedance. However, due to uncertain factors such as speed, temperature, and leakage of the hydraulic system, the feedforward calculation principle used in the EFM system has difficulty accurately and dynamically matching the flow of the pump valve, causing problems such as overcurrent or underflow matching. Efficiency performance is limited to the contradiction between valve opening and system oscillation. The use of a pressure compensator in the EFM system (Fig. 4) can compensate the pump or valve according to pressure feedback, thus improving energy characteristics and dynamic response characteristics. Cheng's group designed a series of compensators for EFM based on valve control (Cheng et al., 2017b), pump control (Cheng et al., 2017a), and pump-valve combined control (Cheng et al., 2018). The principle of the valve-based compensation controller was that resistive conditions corresponded to the maximum output signal of the valve, while overrunning conditions correlated to the input command. Pump-based compensator was then developed because of the suppressed damping capability and the nonlinearity of the valve-based compensator. Both of these methods have improved the performance of EFM to some extent, but the coupling operation of multiple actuators in actual systems often results in low damping properties. Cheng et al. (2018) proposed a pump-valve combined compensator based on the dynamic pressure feedback method. The hydraulic circuit with the largest flow demand was controlled by a pump-based compensator, and those with smaller flow demand were controlled by a valve-based compensator. This composite compensator improves dynamic performance, but parameter uncertainties require further study.

Another problem of the EFM is the flow mismatches between the major hydraulic components. For a more appropriate distribution strategy, a research tendency is hybrid control schemes. Xu et al. (2015a) proposed a displacement/pressure control scheme based on the integrated algorithm of pressure margin and Lyapunov function to correct flow mismatches. Ge et al. (2015) proposed a flow-pressure

combined controller to reduce pressure losses, enabling the operator to choose how much influence should respectively come from the pressure and flow parts. Shi et al. (2018) proposed a velocity-position combined strategy based on the pump-valve coordinated principle, as shown in Fig. 5. By monitoring the speed and displacement of the actuator, the mode is switched to achieve trajectory tracking.

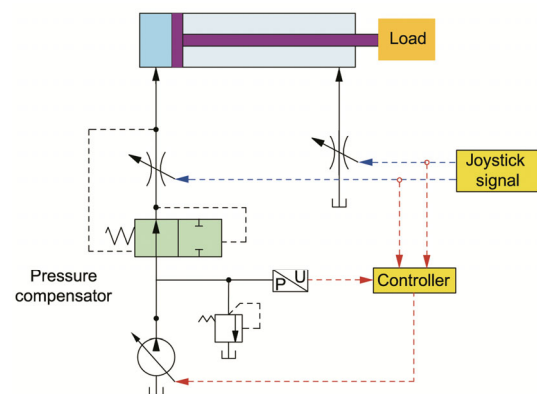


Fig. 4 Basic scheme of EFM with pressure compensator

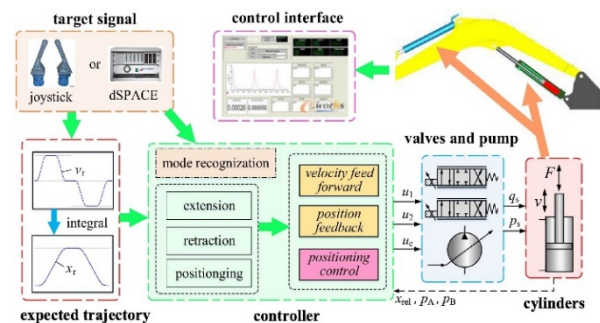


Fig. 5 Overall velocity-position combined control strategy based on the pump-valve coordinated principle. Reprinted from (Shi et al., 2018), Copyright 2018, with permission from Elsevier

Generally, hybrid control mainly uses switching parameters including pressure, flow, and actuator-displacement as control variables to achieve mode-switching. Nevertheless, the transition of mode switching is not smooth enough in the critical state, so that the hybrid control system may suffer from unexpected oscillation, especially in dynamically changing load conditions. Further research about the auto-tuning control algorithm has the potential to optimize the flow match performance.

3 Pump-valve coordinated control of construction machinery

3.1 Excavator

In mainstream hydraulic excavators, the work of the hydraulic system is driven by a power source, and the four actions of the moving boom, stick, bucket, and swing are achieved through valves. Multiple actuators are often driven by one power source and controlled by four-sided slide valves at the same time. In this structure, the inlet and outlet ports of the valve are throttled in conjunction, and a control action can only control the pressure or flow of a single cavity of the hydraulic actuator. Considering non-optimal working conditions, especially the reliability of work in extreme environments, it is necessary to establish sufficient pressure to balance the potential energy of the actuator in the oil return cavity, which will cause energy loss.

The IMS has attracted wide attention due to its excellent energy-saving function. The main idea of IMS is to decouple the inlet and outlet of the actuator through independent valves and finally ensure the energy efficiency and flexibility of configuration. Depending on the number of spools and types, there are several schemes for independent control of the load port, as shown in Fig. 6. The basic scheme of IMS is to use four 2/2 valves or two 3/3 valves to control the flow and pressure of the two chambers of

the actuator. In order to realize additional functions such as energy regeneration, one 3/3 valve with two 2/2 valves and five 2/2 valves get applied. Generally speaking, fewer valves ensure simpler structure of the system and easier control, but fewer functions. The increase in the number of spools can facilitate the regeneration of the flow and improve the control characteristics of the actuator, but it will also increase control difficulty. The research on IMS is primarily focused on system structure design, control characteristics, energy-saving technologies, and pump-valve coordinated control methods. Ge et al. (2017) adopted variable-speed motors to drive variable-displacement pumps, proposing a power matching method based on segmented speed and continuous displacement, with IMS for the load port, to meet the requirements of high dynamics and high energy efficiency. Yao et al. (2018) designed an open-loop control system for IMS. Lyu et al. (2019) developed a pump-valve coordinated IMS in which the pump provides a flow-driven valve to achieve trajectory tracking. Liu et al. (2017) adopted a strategy of consistent flow and pressure, with coordinated control of the dynamic and static coordinates of the pump and valve to improve the energy efficiency and stability of the boom system based on an independent metering circuit. However, in the IMS with a pump-valve co-control, the coordinated control method that matches the valve opening degree and the variable pump displacement is still

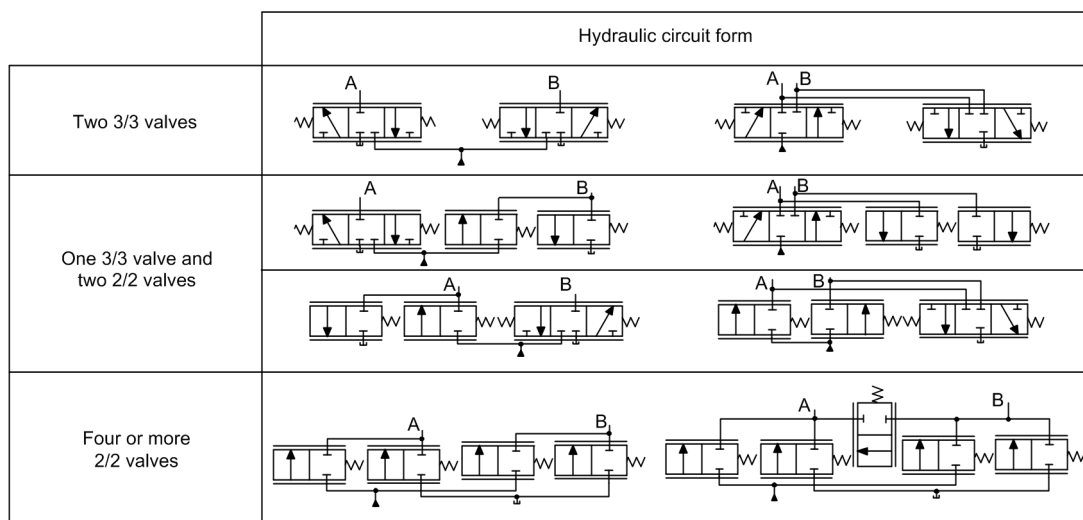


Fig. 6 Typical schemes in single-actuator IMS based on the number and type of spools
A and B are the ports of the two chambers

a key problem to be solved. With effective control strategies, working performance depends more on programming so that the system can be adapted to complex and changing working conditions.

3.2 Loader

A loader is a type of earth and stone construction machinery widely used for roads, railways, hydro-power, mines, and other construction projects. Loaders are mainly used for shovel loading or light digging of loose materials. At present, the hydraulic system of the mainstream loader principally includes a quantitative hydraulic system, a constant-variable hydraulic system, and a full variable hydraulic system. The quantitative hydraulic system, belonging to the overflow speed regulation system, is currently the most widely used hydraulic system in domestic loaders. The constant-variable hydraulic system is an improvement on the quantitative hydraulic system, which has an LS pump and an LS-closed neutral steering control valve. In the full-variable hydraulic system, the steering and working systems are all variable hydraulic systems. The variable system can adopt either a dual-variable pump or a large-displacement single-variable pump. The steering valve is under LS control, and the distribution valve is a closed neutral LS control valve. Compared with the former two systems, the full variable system is more energy-saving, environmentally friendly, and secure.

Therefore, structural optimization of the hydraulic system, especially the steering system, makes the system more energy-efficient, improving operating comfort and reliability, and in turn becoming one of the more popular research directions for loaders. Considering that the hydraulic steering system is widely used in small loaders and other construction machinery, how to predict its dynamic performance at the design stage has become an important issue. Gong et al. (2011) established a set of prediction methods and provided a simple dynamic simulation model of steering hydraulics (Fig. 7). Zhang et al. (2012) established a working device model of the loader hydraulic system. Using this model to analyze an energy-saving strategy, a new type of loader hydraulic system that reduced energy consumption and improved work efficiency was proposed. Yan (2012) analyzed the energy losses of the loader hydraulic system during

the work process of the moving arm, proposing an improvement based on the original hydraulic system to reduce the pressure and energy losses caused by the moving arm, while improving system reliability.

Depending on different kinds of energy consumption and working conditions, different analysis methods are applied to reduce energy losses. The steering pump in the hydraulic system of a loader has a large loss when the engine is operated at a high speed. The losses of the hydraulic system cause the temperature of the hydraulic oil to rise, which causes a series of adverse effects. Wang et al. (2013) used a power-split transmission system that not only optimized engine operation and regenerative brakes, but also improved the productivity, fuel efficiency, and maneuverability of loaders. Wang et al. (2013) also designed an energy management strategy based on dynamic programming to optimize the operation of power-split transmission and hydraulic systems.

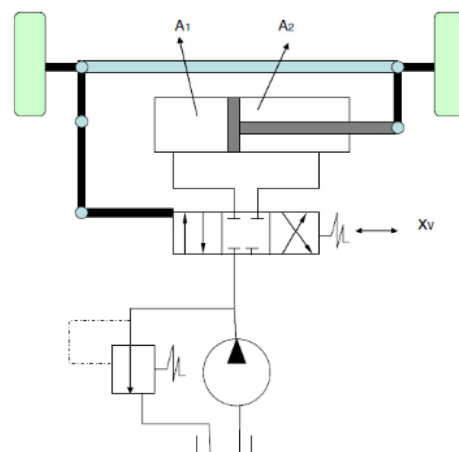


Fig. 7 Simplified hydraulic steering system of multifunctional loader (A_1 and A_2 are the oil volumes through two cylinder chambers, and X_v is the valve opening control signal). Reprinted from (Gong et al., 2011), Copyright 2011, with permission from Elsevier

3.3 Crane

Cranes can be divided into two types: bridge cranes and mobile cranes. Bridge cranes mount horizontally over workshops, warehouses, and storage yards to hoist equipment for lifting materials. Mobile cranes evolved from crawler cranes and overcame the shortcomings of the crawler plate of the crawler crane that can easily damage road surfaces. The hydraulic

system of a mobile crane is generally composed of loading and unloading two hydraulic systems. The loading hydraulic system generally consists of five main circuits: lifting, luffing, telescoping, turning, and controlling. The unloading hydraulic system is an outrigger circuit, which supports the entire machine and external load weight when the crane is working. Considering the working condition characteristics of the mobile crane, its hydraulic system has problems, such as pressure fluctuations and hydraulic shocks. In addition to solving these problems, other research topics include hydraulic system energy recovery, hybrid power, and optimization of the hydraulic system structure to increase operability and safety.

The research on the crane hydraulic system structure is usually based on modeling and simulation, supplemented by actual experiments (Hu et al., 2019). The mobile crane has the problems of high system pressure during stable slewing and excessive hydraulic impact at the beginning of slewing motion and braking. To address these two problems, Xie et al. (2011) developed a simulation model of the slewing hydraulic system and core hydraulic components using AMESim software. The required data are obtained from simulation and actual experiments, and the optimization scheme was provided and verified after ensuring the authenticity and reliability of the model. Li et al. (2012) established a simulation model of selector valves and LS pumps on AMESim for a specific hydraulic crawler crane. Based on the model simulation and dynamic analysis, a series of data was obtained, and a simulation analysis method that could sense changes of the pump along with load changes was proposed.

Other research studies are based on relatively novel methods recently proposed that are applied to the hydraulic system of cranes. Heikkilä and Linjama (2013) proposed a digital hydraulic power management system (DHPMS) with two independent outlets directly connected into the cylinder chambers. In this piston-type DHPMS, each piston has a separate on/off control valve for every single outlet, and inlet and flow are shared arbitrarily among the outlets, leading to highly efficient energy transfer (Fig. 8) (Heikkilä and Linjama, 2013). In order to improve the safety and production efficiency of the system, Koivumäki and Mattila (2015) proposed a Cartesian free-space motion control based on virtual decomposition con-

trol (VDC) for the nonlinearities of coupled mechanical linkage dynamics of the articulation systems and the inherently strong nonlinearities of the dynamics of hydraulic actuators on the redundant articulated hydraulic crane. The VDC method was developed specifically for the control of complex robotic systems. This allows the control problems of the entire system to be transferred into the control problem of a single subsystem, while strictly ensuring the stability of the entire hydraulic system. The experimental results show that the controller can well solve the highly nonlinear problems of articulated hydraulic systems.

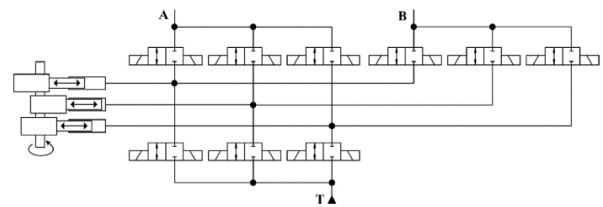


Fig. 8 Schematic presentation of a 3-piston DHPMS with two independent outlets. Reprinted from (Heikkilä and Linjama, 2013), Copyright 2013, with permission from Elsevier

3.4 Forklift

The main actuators of the forklift hydraulic system are tilting cylinders and lifting cylinders. During the working process, there are frequent starting, acceleration, braking, and lifting of forks. The frequently changing working process requires frequent oil-circuit switching of the hydraulic system, which worsens energy losses and results in low energy efficiency. In order to improve energy efficiency, scholars at home and abroad have studied the energy-saving technologies of forklift hydraulic systems. Typical examples are direct pump control technology, potential energy or brake energy recovery, and secondary regulation technology (Minav et al., 2015). Direct pump control cancels the valve control in the system, reducing throttling and overflow losses and resulting in significant energy-saving effects. However, pump control introduces additional uncertainties and nonlinearity into the system, resulting in increased control difficulty. The secondary regulation realizes energy recovery and reuse of recovered energy through the hydraulic accumulator and constant

pressure network. Its basic structure is shown in Fig. 9, which mainly includes the four basic functional units: secondary element (hydraulic transformer), load, hydraulic pump, and accumulator.

However, the efficiency of the hydraulic accumulator needs to be improved, and there is still room for the development of secondary regulation technology. Unlike the previous secondary regulation, the hydraulic transformer-based secondary systems have higher energy recovery efficiency. But hydraulic transformers have various problems such as noise, vibration, and coupled pressure (Shen et al., 2014). Additionally, the pressure adjustment range of the hydraulic regulator is relatively narrow, which limits its application in actual machinery. Shen et al. (2019) proposed a fuzzy sliding mode speed controller based on state estimation to solve the parameter coupling and inherent nonlinearity problems of the new hydraulic transformer-controlling cylinders. Huova et al. (2017) proposed a digital hydraulic method that includes hydraulic energy storage placed with the actuator, a method to efficiently convert energy from storage to mechanical work, and a small start-stop pump unit based on average power. Yang and Jiang (2014) designed a variable hydraulic transformer to control its load flow. However, a series of problems caused by the increased degree of rotational freedom between the port plate and the distribution structure offers new challenges.

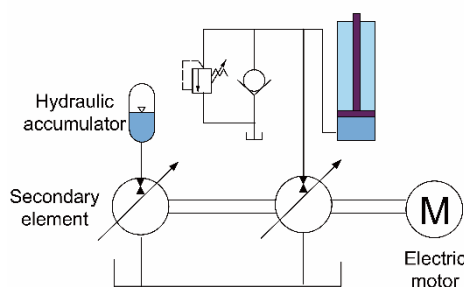


Fig. 9 Basic structure of the secondary regulation system in forklifts

4 Control methods for the electro-hydraulic system in construction machinery

The electro-hydraulic actuator (EHA) has widespread application in the field of construction

machinery for its energy-saving characteristics, load adaptability, and simple structure. However, control difficulty is actually problematic due to nonlinearities and uncertainties caused by dead-zone and friction characteristics (Tong SG et al., 2020b). Additionally, the changing work conditions and application of the variable-speed/displacement pump further exacerbate control difficulty. Potential control methods have been studied in past few years to promote the controllability of electro-hydraulic systems; typical control strategies are shown in Table 2.

4.1 Proportion integral differential algorithm control

Proportion integral differential algorithm (PID) is a typical linear control method used in electro-hydraulic systems, but it is difficult for the conventional PID method to solve the contradiction between fast response and stability of the system. In a system with variable parameters, the control performance of the PID cannot be guaranteed. Obvious oscillation often occurs on occasions where the actuator works with unstable velocity and dynamic fluctuation.

Appropriate parameter optimization and structural design according to the characteristics of the system are effective approaches for improving dynamic characteristics. The main control objects of PID include valve opening, variable pump displacement and speed, hydraulic cylinder speed, and displacement. Liu et al. (2013) used incomplete differential PID to control the spool displacement of the electro-hydraulic proportional valve to solve the problems of friction hysteresis, electromagnetic hysteresis, and slow system response. Yang et al. (2017) adopted the variable-speed integral PID method to control the speed of the variable-speed pump in the EHA system and improved the trajectory tracking control accuracy of the actuator by changing the integral speed. Integral separation PID is suitable for hydraulic systems with large hysteresis. Wang et al. (2019) used integral separation PID to control the displacement and speed of multi-stage hydraulic cylinders. When the error was greater than the set value, the PID method was applied to improve the corresponding ability of the system.

The other development direction of the PID controller is the combination with other control

methods. The theory of intelligent control and computer technology helps to form improved PID controllers such as fuzzy PID, adaptive PID, and optimization algorithm-based PID. The PID based on the optimization algorithm is dedicated to finding the optimal parameters. Ye et al. (2017) proposed a PID based on particle swarm optimization and genetic algorithm to find the optimal PID controller gain to improve the position control of a nonlinear hydraulic cylinder. Adaptive fuzzy PID does not require a precise mathematical model but promotes its robustness. Zuo et al. (2017) proposed a PID-based adaptive segmented switch controller, which realizes parameter self-adjustment according to error and change in error. Although the combination of lower energy consumption and precise position control of the PID method has universal significance for promoting control performance, PID control is insufficient for meeting the nonlinear and uncertain requirements of large multi-actuator systems.

4.2 Robust adaptive control

Robust adaptive control has advantages for solving the problems of uncertain parameters and unknown states and coupling with both factors of strongly nonlinear systems compared with pure robust or adaptive control. Lu and Yao (2014) designed a flow control strategy with adaptive robust control law to realize the precise motion tracking of the manipulator while minimizing hydraulic energy consumption. Wang CW et al. (2015) proposed nonlinear adaptive and deterministic robust control, taking motion disturbance, nonlinearity, and friction problems into account. The robust adaptive neural method used for nonlinear systems with unknown dead zones omitted the virtual control law of the intermediate step and constructed a practical robust adaptive law. Li XD et al. (2017) constructed an output-feedback adaptive robust controller, where adaptive control handled parameter uncertainty in the model, and

Table 2 Typical control strategies for electro-hydraulic actuators

Control method	Research trend	Sample of studies
PID control	Parameter optimization and structural design	1. Incomplete derivative PID (Liu et al., 2013); 2. Variable-speed integral algorithm (Yang et al., 2017); 3. Integral separation PID (Wang et al., 2019)
	PID control combined with other control methods	1. PID with optimization algorithm (Ye et al., 2017); 2. Adaptive PID (Zuo et al., 2017)
Adaptive control	Adaptive control integrating other control methods	1. Adaptive feedforward control (Li H et al., 2017); 2. Nonlinear adaptive control (Wu et al., 2017)
Robust control	Robust control method based on norm theory and μ -value synthesis	1. H_∞ control for unstructured uncertainty system (Guo et al., 2015); 2. μ -value synthesis for dead-zone (Kim et al., 2018)
	Adaptive robust control for changing the structure or parameters of the controller	1. Adaptive robust algorithm for unmodeled disturbances (Wang CW et al., 2015); 2. Unknown valve dead-zone (Deng et al., 2017)
Sliding mode (SM) control	Control strategies for controller flutter	1. Reaching law; 2. Filter method; 3. SM control based on boundary layer methods (Has et al., 2014; Xiao et al., 2015)
	SM control incorporated with other intelligent control algorithms	1. Terminal SM (Wang YY et al., 2015); 2. Discrete-time SM (Zhou et al., 2017); 3. Robust SM control based on optimization algorithm (Yao et al., 2014a)
Backstepping control	Backstepping control combined with uncertainty compensation	1. Barrier Lyapunov function (Tee et al., 2009); 2. State-observer-based robust control with backstepping (Yao et al., 2014b)

H_∞ is the infinite norm; μ is the structural singular value

robust control addressed residuals from parameter adaptation and unmodeled dynamics.

4.3 SM variable structure control

SM has good adaptability to external disturbances and uncertainties of model matching. Time-delay estimation terminal SM (TDE-SM), which can achieve the practical application in a simple model-free way, requires more attention. Wang YY et al. (2015) proposed a continuous nonsingular TDE-SM controller and related reaching law to ensure convergence and tracking precision under lumped uncertainties. Kim et al. (2019) proposed a discrete TDE-SM-based formulation to decrease computational effort and sensing signals. Zhou et al. (2017) employed an input-filter to tackle the influence of parametric uncertainty on the stability of TDE-SM.

Other SM methods include robust SM, fuzzy SM, and neural network SM. Zhang et al. (2014) integrated the SM, robust H_∞ control, and pole placement. Dao and Ahn (2015) designed a parameter-tuning SM controller based on the fuzzy grey prediction for EHA force control. The fuzzy system was used to approximate the minimum SM gain by taking system error as an input to ensure the system tracking speed.

4.4 Backstepping control method

The backstepping control method has become an effective electro-hydraulic system control method due to its ability to deal with non-matching uncertainties and unknown parameters. However, the performance of backstepping control decreases when parameter perturbation and unknown interference exist. One effective way to ease the problem is to combine the disturbance observer with the backstepping algorithm for strong interference compensation capability. Won and Kim (2015) proposed a backstepping control based on a high gain disturbance observer to estimate interference of friction, load force, and parameter uncertainty with position tracking error constraints. Guo et al. (2016) proposed an output position feedback control method based on an integrated extended-state-observer backstepping method. Although disturbance observers tackle the nonlinear and uncertain terms, extension of the work cycle occurs as well.

Special Lyapunov functions combined with backstepping are also an effective approach to compensate for nonlinearities and maintain stability after

determining the item derivation (Won et al., 2015). Yang et al. (2018) applied Lyapunov function-based differentiators to execute position tracking control. Additionally, the combination of backstepping control and obstacle Lyapunov function and its various variants (such as asymmetric obstacle Lyapunov function and symmetric Lyapunov function) is widely used in nonlinear systems.

5 Novel HHSs and components

5.1 Novel hybrid ERSs

Compared with conventional structure, HHS has certain advantages in energy recovery efficiency. In typical hybrid ERSs, recovered energy can be stored in different forms with the help of the HHS component. Lin et al. (2016) proposed an accumulator-motor-generator ERS and two control strategies for boom velocity control, as shown in Fig. 10. The boom potential energy is converted to electric and hydraulic energy with the application of generator and hydraulic accumulator, respectively. The combination of both enables short time energy recovery, even in the boom action.

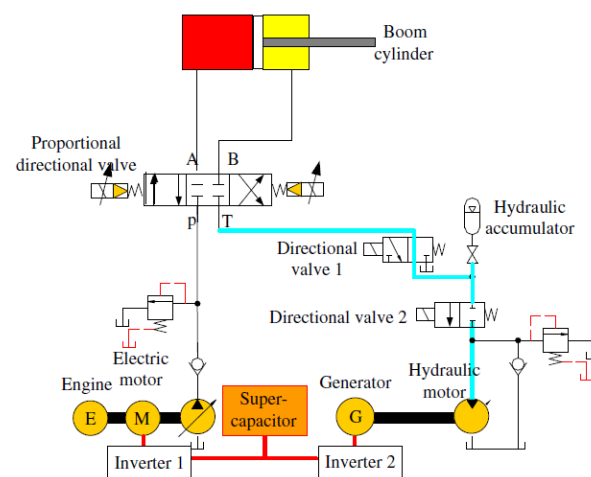


Fig. 10 Schematic of the accumulator-motor-generator ERS. Reprinted from (Lin et al., 2016), Copyright 2016, with permission from Elsevier

At the same time, as the hydraulic accumulator limits the operating point of the generator to an effective area, the recovery efficiency of the generator is improved. The class of hybrid system used

accumulators and electrical super-capacitors or generators as hybrid storage elements to recover potential energy. To recover as much energy as possible in a short time, Chen et al. (2019) polished Lin et al. (2016)'s system by adding valve control. However, this method worsened dynamic performance because of the uncontrollable performance of the accumulator.

In most construction machinery, gravitational energy and braking energy account for a significant amount of total potential energy. Given the fact that the difference between torque and flow needs a specifically tailored control strategy to coordinate, Xiao et al. (2014) designed a multiple-ERS to maximize the flow-coupling energy-saving potential. The proposed system included two pairs of variable pumps and hydraulic accumulators responsible for the energy recovery of the swing ERS and boom ERS, respectively. The main shortcoming of such a system is the coordination problem between hydraulic accumulator capacity and structural arrangement. Gong et al. (2019) next proposed a hybrid electrical regeneration system, including the regeneration motor and electrical motor to collect potential and kinetic energy, as shown in Fig. 11. A common problem of the hybrid system is that the existence of load-dependent pressure affects the system working performance during variable operation; currently, there are no general components available for these systems.

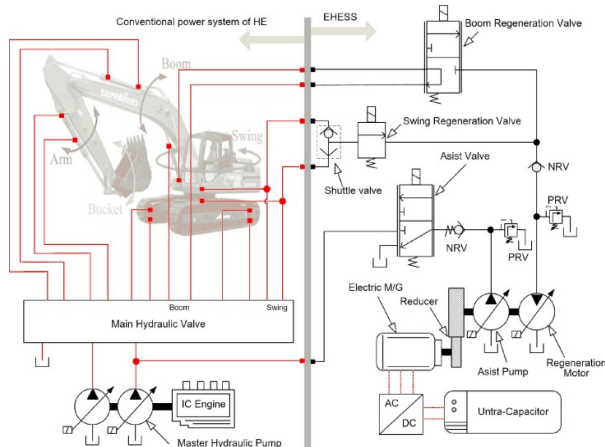


Fig. 11 Hybrid gravitational and braking energy regeneration (HE is the hydraulic excavator; EHES is the electro-hydraulic energy-saving system; NRV is the non-return valve; PRV is the pressure reducing valve; IC is the internal combustion; M/G means motor/generator). Reprinted from (Gong et al., 2019), Copyright 2018, with permission from Elsevier

5.2 Novel structure of energy-saving components

Although the hydraulic accumulator can avoid conversion loss during energy reuse, its structure and energy density are much lower than other energy storage components, which limits its scope of application in construction machinery. One solution is adding new structural components. A pressure-constant hydraulic accumulator using an area-varying piston is presented (van de Ven, 2013). The main principle is that the piston radius varied as a function of piston displacement and then transformed into the function of an axial contact between the piston and the diaphragm (Fig. 12). Latas and Stojek (2018) proposed a hydrokinetic accumulator consisting of a flywheel with a variable moment of inertia to enhance the storage density of the accumulator (Fig. 13). However, the mathematical model needs to be polished by taking energy losses into account during the entire hydraulic circuit.

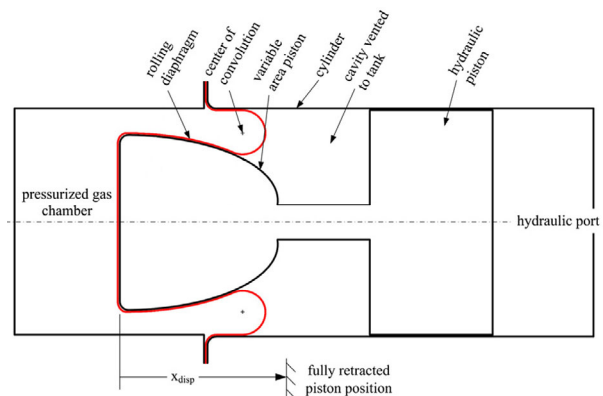


Fig. 12 A pressure-constant hydraulic accumulator using an area-varying piston. Reprinted from (van de Ven, 2013), Copyright 2013, with permission from Elsevier

In addition to compound accumulators, other components also received structural improvement for increased energy saving, such as the three-chamber cylinder (TCC) (Zhao et al., 2017). The basic structure of TCC is shown in Fig. 14. One chamber of TCC is directly linked to a hydraulic accumulator and others linked to the driving circuit. There is almost no energy conversion loss in the primary loop since recovered energy is stored in the form of hydraulic energy in TCC-ERSs. The increase in accumulator volume resulted in poor control performance but promoted stability, while the cross-sectional area of the TCC performed oppositely, requiring a compromise

between the volume of the accumulator and the cross-sectional area.

Hydraulic-pneumatic energy storage (HPES) also offers great advantages in energy conversion and energy transmission (Cheng et al., 2019; Tong ZM et al., 2019b). Hao et al. (2018) proposed two ERSs suitable for heavy-duty lifting machinery based on HPES to solve these problems. In single-cylinder configuration,

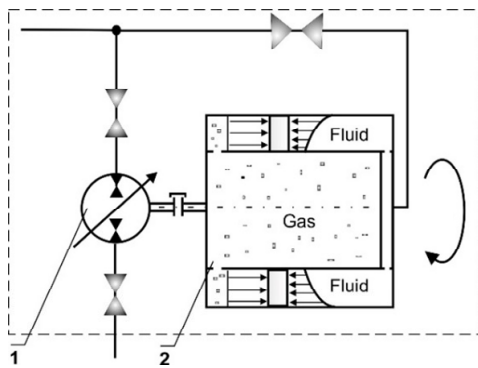


Fig. 13 Schematic presentation of the hydrokinetic accumulator (1: variable-displacement pump/motor; 2: flywheel of variable moment of inertia). Reprinted from (Latas and Stojek, 2018), Copyright 2018, with permission from Elsevier

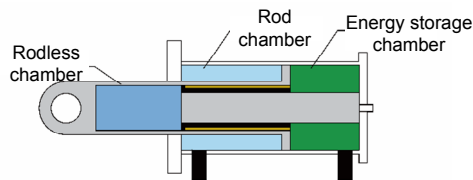


Fig. 14 Basic structure of TCC

the HPES was integrated to form a TCC, while an HPES was added to the double-cylinder to drive the system directly, as shown in Fig. 15. The cylinder or chamber was connected to an accumulator and thus the potential hydraulic energy could be reutilized directly, especially with the assistance of the pre-charge pressure of the accumulator.

The use of asymmetric structure is also an effective way to improve dynamic performance. Considering the complexity of changing the structure of the system, Ge et al. (2018) proposed a novel hydraulic asymmetric pump to reutilize gravitational energy directly and compensate for the asymmetric flow caused by differential cylinders. The asymmetric pump has three ports, two of which connect to the actuator cylinder, with the left one connected to an accumulator (Fig. 16). However, the scalability and cost-effectiveness of the converter at different power levels require further study.

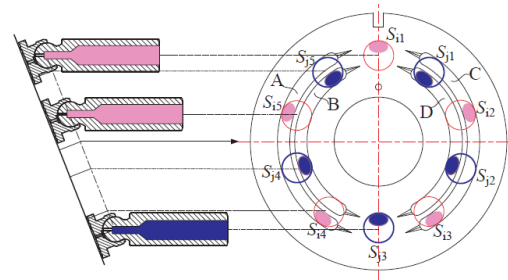


Fig. 16 Working principle of the asymmetric pump. Reprinted from (Ge et al., 2018), Copyright 2018, with permission from Elsevier

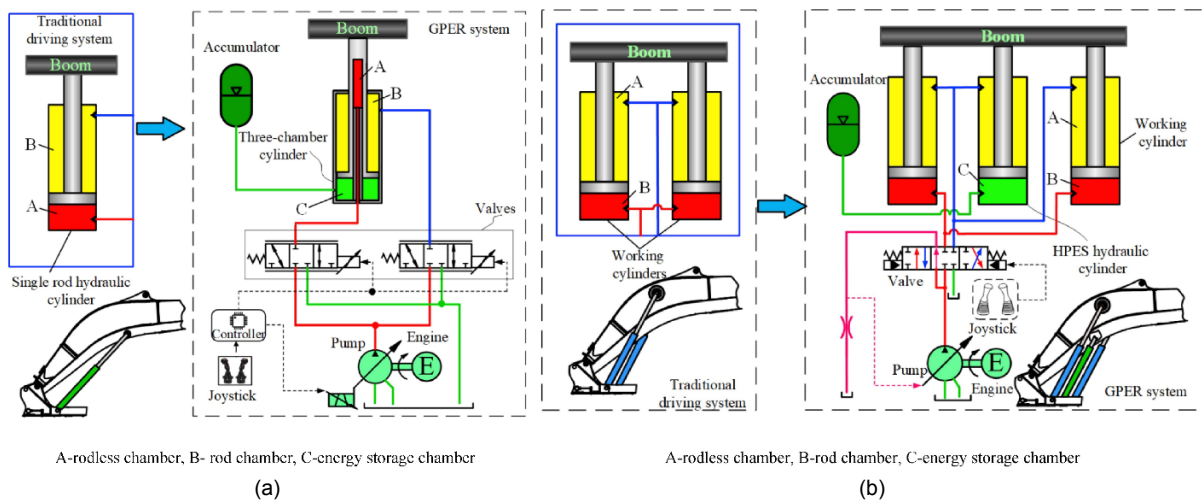


Fig. 15 Principle of ERS based on HPES: (a) a single TCC system; (b) double-cylinder with HPES. GPER is the gravitational potential energy recovery. Reprinted from (Hao et al., 2018), Copyright 2018, with permission from Elsevier

6 Future research directions and challenges

6.1 IMS with electro-hydraulic flow matching scheme

Some scholars have applied the meter-in and meter-out valves in the EFM system to achieve a reasonable distribution of flow by increasing the control degree of freedom. Huang et al. (2018) integrated the pump-valve coordinated control with the meter-in and meter-out method to match the flow rate with the actuator speed. Shi et al. (2018) proposed a primary velocity/tracking mode-switching control strategy based on a pump-valve coordinated control principle for a single actuator. The mode-switching strategy worked for controllability, while the meter-in and meter-out valves devoted to execute flow control and energy regeneration, thus realizing high precision and low consumption simultaneously. However, the increase in the degree of freedom led to an increase in control variables and therefore affected the control strategy. Casoli et al. (2016) proposed a programming hybridization methodology that allowed comparison of different system layouts, choosing the best control strategy and ultimately determining a more efficient hybrid system layout. Ding et al. (2019) designed a similar multi-mode switching system and related composite controller. Different from Shi et al. (2018)'s method, Ding et al. (2019)'s model was suitable for multi-actuator systems and extended control degrees. Decoupling allowed control of multiple variables, enabling independent flow and pressure control modes for the actuators.

6.2 Common pressure rail

The common pressure rail (CPR) is a technique that can be substituted in a multi-actuator system for its high efficiency and high reliability. The CPR is based on a constant pressure network and adjusts the displacement of the hydraulic pump/motor in the hydraulic transmission system to adapt to load changes, as shown in Fig. 17. Through the hydraulic transformer, not only can energy recovery be achieved under all four quadrants, but the actuator can also obtain energy from the constant pressure network. Therefore, a new structural hydraulic transformer that can effectively drive the linear load without throttle loss requires CPR (Shen et al., 2014). Immonen et al. (2016) designed an integrated electro-hydraulic en-

ergy converter that converts electrical energy into hydraulic energy, thus lessening energy loss in pipelines and valves.

However, the hydraulic transformer has various problems such as noise, vibration, and coupled pressure. Additionally, the pressure regulating range of the hydraulic transformer is relatively narrow, which limits its application in practical machinery. Current hydraulic transformers like the three-port structure, digital transformer, and variable transformer have the ability to tackle the aforementioned problems to some extent. However, a series of problems resulting from the added rotational freedom between the port plate and distribution structure has become a new challenge.

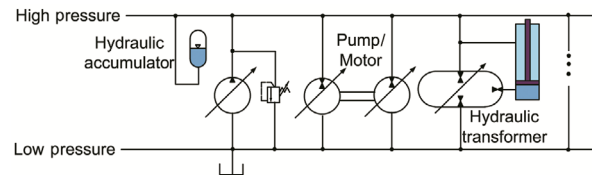


Fig. 17 Basic scheme of CPR

6.3 Hybrid power sources

At present, the internal combustion engine (ICE)-driven heavy construction machinery fails to meet discharge demands, while a pure electric power source cannot support long-time power output. As a compromise, hybrid power source (HPS) has the ability to meet the requirements of emissions and power output at the same time, thus becoming a current major research trend. The overall structure of HPS is comprised of series structure, parallel structure, and series-parallel structure. A series-parallel structure uses a mechanical connection between the ICE and transmission system by adding a generator and power transmission line. The power of an ICE and motor in a series-parallel structure can be relatively small but is easy to control with high efficiency. Additionally, there are potential energy recovery and braking energy recovery used in HPS systems (Wang EH et al., 2015). The major challenge of HPS is the optimization of control management, an important part of energy conservation research. Due to the complexity of HPS, existing mature control methods are not fully applicable to HPS.

7 Conclusions

The hydraulic system is a key component in construction machinery, the efficiency of which largely depends on throttling losses, overflow energy losses, and damping losses. Energy-saving technologies for various hydraulic systems have therefore become a research focus of many global companies and universities. This review discusses the structure of hydraulic systems in different types of construction machinery, various control methods of electro-hydraulic systems, novel hydraulic hybrid ERSs, and key components. In addition, future directions and challenges such as IMS and CPR on the pump-valve coordinated system are described. Commonly used methods, such as negative/positive flow control, LS, and flow matching are discussed regarding energy saving, stability, and controllability. The advantages and disadvantages of typical control methods are summarized and analyzed. Conventional methods like PID control, sliding mode control, and robust control offer a wide range of applications but are unable to meet the control requirements of modern hydraulic systems. Combining other control algorithms to design a hybrid control strategy is a new direction for improving the accuracy and robustness of the system. Apart from efficiency promoting measures, hybrid energy regeneration methods and novel hydraulic components are also discussed. Such systems collect different types of energy or store energy in different forms, improving the energy utilization rate. However, the working compatibility of the regeneration system and new components of the original system remain unresolved. In spite of improved working performance, this incomplete development restricts further application in practical hydraulic systems. Effective techniques, such as independent metering control and CPR, are likely to draw more attention from researchers in the future.

Power matching between the power system and the hydraulic system is a crucial technology for realizing energy savings. Although the widely used LS systems can achieve local power matching, the dynamic matching mechanism between power source-to-hydraulic pump and hydraulic pump-to-load currently has not been solved, and there is still room for improvement in energy utilization rates. Therefore, the research focus of energy-saving technologies in

the future is no longer the structural optimization of individual hydraulic components but global power matching for different operating conditions and intelligent control algorithms for electro-hydraulic systems. With the development of digital technology, the dynamic coordinated control among power sources, variable pumps, and valves becomes feasible through electronic sensing, transmission, and control. In addition, energy recovery technology shows great opportunity for many applications. Future studies are encouraged to concentrate on the performance optimization of secondary components, energy storage components, and coordinated control strategies of energy reuse systems and hydraulic systems.

Contributors

Zhe-ming TONG and Shuang-shuang WU designed the research and wrote the first draft of the manuscript. Shui-guang TONG and Yu-wei ZHONG conducted the literature review. Yu-qing YUE and Yuan-song LI processed the data. Shui-guang TONG and Zheng-yu XU revised the final version and provided the funding support.

Conflict of interest

Zhe-ming TONG, Shuang-shuang WU, Shui-guang TONG, Yu-qing YUE, Yuan-song LI, Zheng-yu XU, and Yu-wei ZHONG declare that they have no conflict of interest.

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中文概要

题目: 基于泵阀协控电液系统的工程机械节能技术综述

概要: 随着全球经济的飞速发展和工程机械全球保有量的持续上升, 工程机械的节能问题变得越来越突出。液压系统是工程机械的关键子系统, 因此提高其能源利用率是当前实现工程机械节能的重要手段之一。而在传统的阀控或泵控液压系统中, 由于受阀件和液压泵的固有特性制约, 系统可控性和节能性通常无法得到兼顾。泵阀协控系统 将泵控系统的节能特性与阀控系统的高精度和高频率响应相结合, 使其成为当前电液系统的一个研究热点。本文总结了泵阀协控电液系统节能技术的最新研究进展, 并重点分析了不同类型工程机械的液压系统结构、电动液压系统的控制方法、新型液压混合能量再生系统以及关键部件。同时, 从负载口独立控制技术、共压导轨技术 (CPR) 和混合动力源系统三个方面探讨了泵阀协控系统的未来发展方向和面临的挑战。

关键词: 工程机械; 节能; 泵阀协控系统; 控制算法; 液压系统