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Review

Review of Flow-Matching Technology for Hydraulic Systems

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Abstract: The flow-matching problem of hydraulic systems is an important factor affecting the working performance and energy saving of hydraulic systems. According to the different flow-matching mechanisms, the flow-matching technology of hydraulic systems can be divided into three categories: positive flow-control technology, negative flow-control technology, and load-sensitive control technology. In this paper, the working mechanism of flow-matching technology and the cause of energy loss are analyzed, and the research results of flow matching are introduced from two aspects of energy saving and consumption reduction and system performance improvement. In the direction of energy saving and consumption reduction, the purposes of energy saving and consumption reduction are achieved by means of multi-way valve commutation, independent inlet and outlet control, parallel replacement of shuttle valve by a cylinder piston rod controlled by pilot pressure, change of hydraulic resistance of a pressure compensating valve, improvement of the power regulation range of a hydraulic pump, and potential energy recovery. In the direction of system performance, by means of flow-forecasting system pressure change, applying flow unsaturation real-time control idea, and combining electronic control technology with load-sensitive technology, the pressure drop during transmission process and the transmission signal lag are reduced, the speed regulation interval is enlarged, fine-tuning characteristics are improved, and the response speed is increased. The research results indicate that improving the structure and the control strategy of hydraulic systems and improving the flow-matching degree of a system to achieve global matching will be a future development trend.

Keywords: flow matching; load sensitivity; positive flow control; negative flow control; energy saving; consumption reduction

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1. Introduction

In today's world characterized by increasingly scarce energy, energy conservation and emission reduction have penetrated into all walks of life. As high energy-consuming machinery and equipment, engineering machinery is particularly important in energy conservation and emission reduction [1–3]. The hydraulic system is widely used in construction machinery due to its advantages of a large output torque and wide range of stepless speed regulation. However, the hydraulic system works with certain energy loss [4,5]. Realizing the adaptation of load demand and system flow through flow-matching technology, reducing energy loss caused by redundant flow or pressure in the hydraulic system, and improving the energy utilization rate of the hydraulic system are urgent engineering technical problems [6–10].

Flow matching occurs when the load demand is equal to the power output of the power source, and the output flow of the hydraulic pump is just enough to keep the load working [11–15]. This technology solves the coordination problem between output power and the load characteristic curve of hydraulic system to the greatest extent, and reduces the loss of flow and pressure, improving the energy utilization ratio of a hydraulic system [16–20]. At present, common flow-matching technologies are positive flow-control technology, negative flow-control technology, and load-sensitive control technology. Positive flow-control technology maintains the consistency of pump displacement and operating pressure through the pilot pressure control valve spool stroke proportional to the flow rate of the pump output, resulting in better system energy saving [21,22]. However, positive flow-control requires the secondary pilot pressure to be retrieved from the shuttle valve block to achieve the displacement control of the pump, so the control oil circuit is complicated and influences the response speed of the system to a certain extent [23,24]. Negative flow-control technology transforms primary flow control into closed-loop control based on flow detection of the bypass oil circuit and feedback control of pump displacement, which reduces air-flow and throttling losses and improves system energy saving [25,26]. However, the maneuverability and system stability of negative flow-control technology are greatly affected by load and flow, meaning the operation performance is slightly worse [27–29]. Load-sensitive control technology controls the displacement of the pump according to the pressure and flow required by the load, making it almost only provide the flow required by the load to the circuit, realizing the adaptation of load pressure to system flow and greatly improving the energy-saving of the system [30–35]. The flow-matching degree of a hydraulic system is an important factor affecting the energy-saving level of the system, and is related to the energy-saving development of hydraulic machinery.

In conclusion, in view of the shortcomings of flow-matching technology in its energy-saving effects and work performance, it is of great theoretical significance and practical engineering application value to carry out flow-matching technology research. From the angle of flow matching, this paper analyses the energy-saving strategies and performance improvement methods of the hydraulic system, focuses on the advantages and development difficulties of three main flow-matching technologies of the hydraulic system, and puts forward a possible future research direction for flow-matching technology of hydraulic systems.

2. Positive Flow-Control Technology and Negative Flow-Control Technology

The constant power control system of construction machinery usually uses dual oil pumps for oil supply, which leads to the excessive volume and weight of the hydraulic system, limiting the application of the hydraulic system in construction machinery [36,37]. In order to solve this problem, a single-pump multi-loop hydraulic control system represented by positive flow and negative flow-control systems has emerged.

2.1. Working Principle

The structure of the positive flow-control system is shown in Figure 1a,b. The positive flow-control system is characterized by pilot control, which controls the change-over valve and regulates the displacement of the hydraulic pump through pilot pressure, thus avoiding the problems of complex intermediate links and long response time. The positive flow-control system is equipped with a shuttle valve in the pilot control circuit. The shuttle valve selects each pilot pressure signal, uses the highest pilot pressure as the pump displacement regulating signal, and regulates the output displacement of the main pump [38,39]. When the system is connected without a load, the pilot pressure is zero, and the hydraulic pump only outputs a small amount of standby flow to maintain the flow of the hydraulic system, which can effectively eliminate the air flow loss [40]. The flow of the hydraulic pump and the operating speed of the actuator are proportional to the control pressure, which can effectively reduce the bypass throttling loss. Therefore, the positive flow system has a good energy-saving effect and can easily control the hydraulic pump [41].

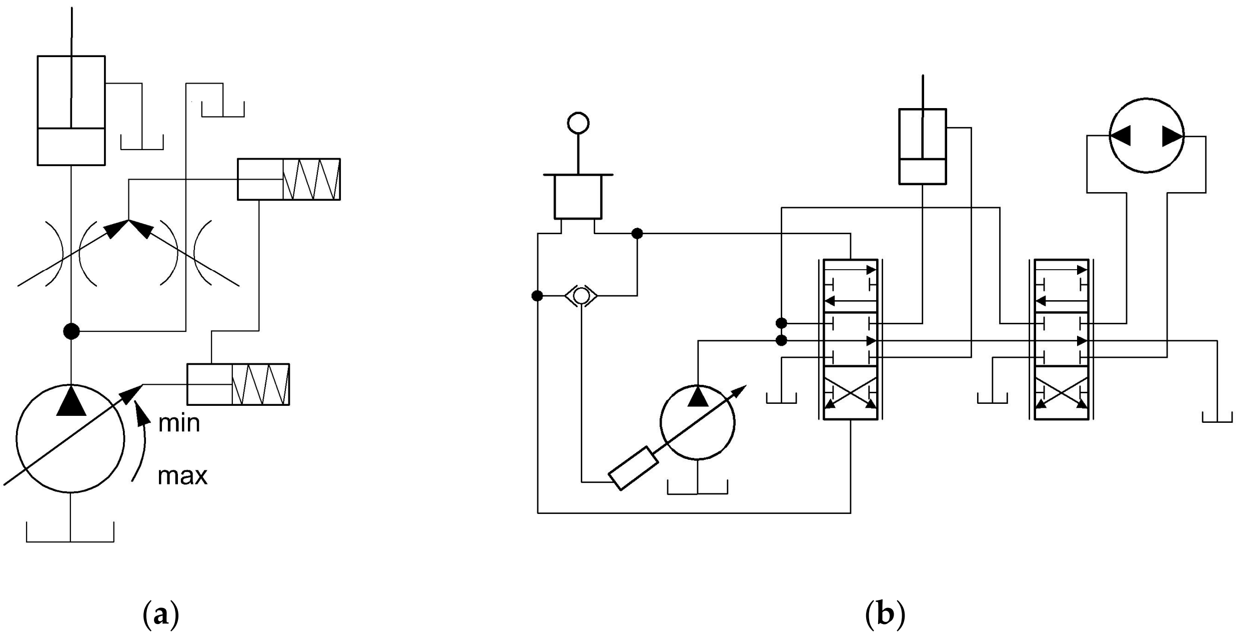
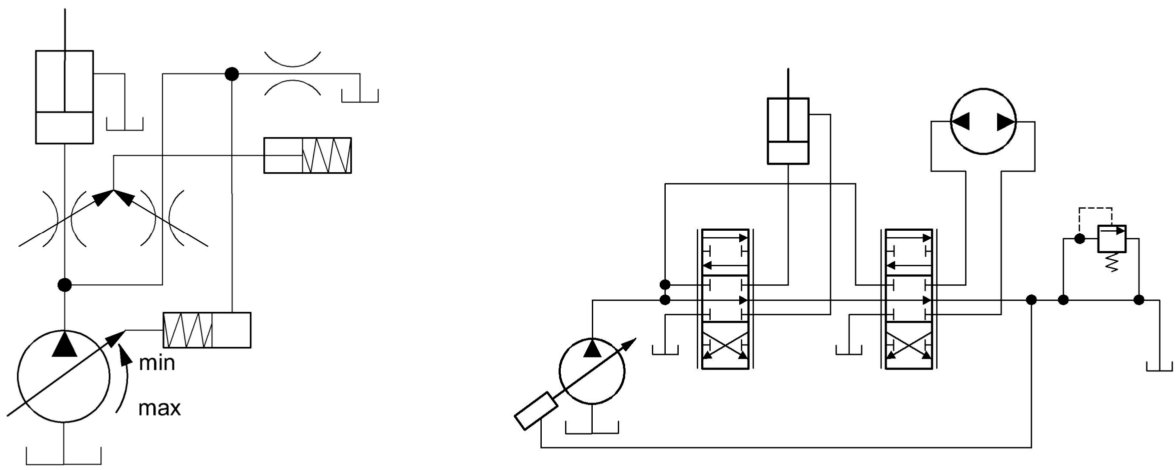


Figure 1. Positive flow-control system. (**a**) Structure diagram of positive flow-control system. (**b**) Schematic diagram of positive flow-control system.

The structure of the negative flow control system is shown in Figure 2a,b. The displacement of the main pump of the negative flow control system is inversely proportional to the pressure controlled Each valve link in the multi-way valve adopts an open center structure. A throttle port is set behind each reversing valve and in front of the oil return tank. The displacement of the pump is adjusted by adjusting the pressure of the hydraulic oil flowing through the throttle port. When the multi-way valve acts, the hydraulic flow from the hydraulic pump is divided into two parts; one share of the hydraulic oil enters the actuating element for work after passing the multi-way valve, and the other portion of the hydraulic oil flows into the hydraulic oil tank through the middle returning-oil passage of the multi way valve. When the main valve cores of all directional valves in the hydraulic system are in the middle position, the hydraulic oil output from the main pump directly flows into the oil tank through the middle return circuit. At this time, the inlet pressure of the throttle port increases, that is, the pressure of the control oil circuit increases, which reduces the displacement of the main pump and effectively reduces the air flow loss of the system. When the pilot handle acts, the spool of the reversing valve will shift. At this time, the valve port area of the reversing valve to the actuating element increases, and the valve port area to the return oil circuit decreases. During the whole flow process, the pressure of the orifice, that is, the pressure of the negative flow control oil circuit, decreases gradually, the displacement of the hydraulic pump increases gradually, and the working speed of the actuating element increases gradually. In the negative flow control system, the pilot control pressure determines the opening of the throttle port of the reversing valve spool, thus controlling the oil volume of the hydraulic system's return-oil circuit. The oil volume determines the pressure of the return-oil circuit, and the displacement of the main pump is adjusted by the pressure.



(**a**) (**b**)

Figure 2. Negative flow-control system. (**a**) Structure diagram of negative flow-control system. (**b**) Schematic diagram of negative flow-control system.

The negative flow-control turns the primary flow-control into a closed-loop control which greatly reduces the air flow loss and throttling loss, realizes the matching of the output flow of the hydraulic pump according to the demand, avoids the overflow loss and system heating of the traditional hydraulic system, and greatly reduces the power loss. The negative flow-control system has the advantages of a stable starting process, no impact, and good speed regulation performance. The disadvantage is that the response time is long, and the system stability is greatly affected by the load and system flow. When the pressure is high, the system's controllability becomes poor, and the speed control stability is affected.

The difference between the positive flow-control system and the negative flow-control system is that the pressure acquisition points of the control signals are different. The positive flow-control system uses the main control valve core to control the pressure, while the negative flow-control system uses the pressure signal in the front of the oil-return throttle valve. However, both positive flow and negative flow-control systems control the displacement of the main pump by collecting control pressure signals, so as to match the output flow of the pump with the flow required by the load. Many scholars have different forms of optimization strategies for positive and negative flow systems, but they basically focus on two aspects: firstly, changing the system structure, reducing the system energy loss, and maximizing the pump output power; and secondly, optimizing the control strategy of the system, improving the response speed of the system, and improving the performance of the speed regulation performance of the system.

2.2. Development Status

2.2.1. Energy-Saving Effect Optimization

Pressure loss is one of the main energy losses of the hydraulic system, which affects not only the matching of pump valves, but also the reliability of the hydraulic system [42]. Pressure loss is mainly divided into local pressure loss and pressure loss along the way. The pressure loss formula is shown in formulas (1), (2), and (3) [43]. According to the formula analysis, it can be seen that the pressure loss is concentrated on the structure of the flow changes caused by the hoses, hard pipes, valve ports, pipe joints, elbows, and diameters of hydraulic pipes. Pressure loss can cause system heating, aging of pipes, and unnecessary energy loss [44,45]. Song et al. [46] analyzed the pressure loss of the hydraulic system, established a joint electromechanical hydraulic simulation model, focused on the analysis of the pressure loss of the hydraulic system of the excavator under typical working conditions, and explored the specific values of the pressure loss of the excavator under different actions and the distribution of the pressure loss, which laid a foundation for the research on the energy loss and performance improvement of the excavator with positive flow control. Wang et al. [47] combined the pipeline structure of the hydraulic system and the structure and layout of the multi-way valve flow passage, changed the internal confluence of the multi-way valve to that of the external pipeline of the multi-way valve, and appropriately increased the pipe inner-diameter parameters. After optimization, the pressure loss of the valve core was reduced by 24%, the pressure loss of the pipeline was reduced by 43%, and the pressure loss from the pump to the hydraulic cylinder was reduced by 30%, which greatly reduced the pressure loss of the hydraulic system and improved the energy utilization rate of the excavator.

$$\Delta P_1 = \xi \frac{\rho V_1^2}{2} \tag{1}$$

$$\Delta P_2 = \lambda \frac{L}{d} \frac{\rho V_2^2}{2} \tag{2}$$

$$\Delta P = \Delta P_1 + \Delta P_2 = \xi \frac{\rho V_1^2}{2} + \lambda \frac{L}{d} \frac{\rho V_2^2}{2} \tag{3}$$

The positive flow-control system controls the displacement of the variable displacement pump by selecting the highest oil pressure in the pilot pressure through the shuttle valve, instead of comprehensively and accurately controlling the displacement of the variable displacement pump according to the pilot control oil pressure of each actuator, resulting in low system power utilization and large energy loss [48]. Zhang et al. [49] proposed a new structure to control the displacement of variable displacement pumps: the composite pilot pressure positive flow control system. The system principle is shown in Figure 3. The displacement of variable displacement pumps is controlled by paralleling the five-cylinder piston rods controlled by pilot pressure. The displacement of variable displacement pumps is comprehensively controlled according to the flow required by the boom cylinder, stick cylinder, bucket cylinder, travel motor, and swing motor. This system does not need to compare the pilot pressure through the shuttle valve, and the system structure is simple. The flow required under the same working conditions is reduced by 26.2%, with good flow matching accuracy and power utilization.

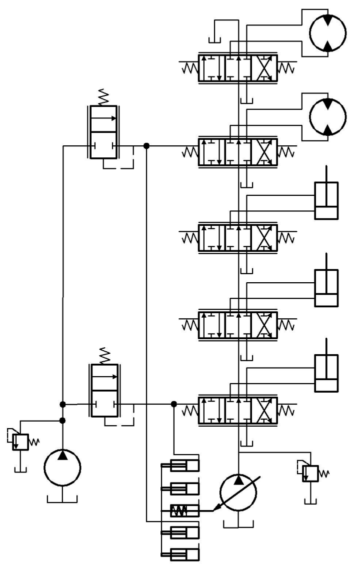


Figure 3. Synthetic pilot pressure positive flow-control system.

Chen et al. [50] analyzed the energy loss path of the hydraulic system based on the basic principles and characteristics of the negative-flow hydraulic system. On the basis of the hydraulic system control theory and the principal characteristics of hydraulic components, he used AMEsim and ADAMS to jointly simulate and solve the dynamic response characteristics of the hydraulic system and system energy consumption under various operations, obtained the system energy consumption distribution diagram, and quantified the energy-saving effect of the negative flow-control system. The output power of the hydraulic system is limited by the maximum output power of the hydraulic pump. When the set upper limit of the hydraulic pump power is reached, the operating speed of the actuating element will not be faster with the operation, which means that when the engine works at the speed corresponding to the maximum torque point, the hydraulic pump cannot effectively absorb the output power, which seriously wastes the engine power [51]. At the same time, the working range of the hydraulic pump deviates too much from the minimum energy consumption area, which makes the energy consumption larger. Che et al. [52] has developed the limit load control system of the negative-flow hydraulic system. The system principle is shown in Figure 4, so that the power of the hydraulic pump can be adjusted or expanded with the change of working conditions, so that the hydraulic pump can absorb the power of the engine as much as possible with the change of load. The negative feedback loop of the hydraulic system is cancelled, a pressure sensor is added at the negative-flow feedback port of the multi way valve, and an electric proportional pressure-reducing valve is added at each of the two negative-control pressure ports of the main pump. At the same time, the torque of the main pump is slightly greater than the maximum torque of the engine by reasonably adjusting the pre tightening force of the spring in the displacement adjustment mechanism to avoid the system entering the constant power adjustment area. Compared with the traditional negative flow-control system, the power regulation range of the main pump of the extreme load control system is wider, the power reserve is eliminated, and 100% power utilization can be achieved in the full speed range of the engine. The load flow of dual pump displacement can be adjusted independently, and the speed can be adjusted flexibly for the purpose of load demand flow, and the intelligent variable pressure cutoff is realized, so that the system pressure is controlled near the set cutoff pressure value, reducing the oil leakage loss of the overflow valve.

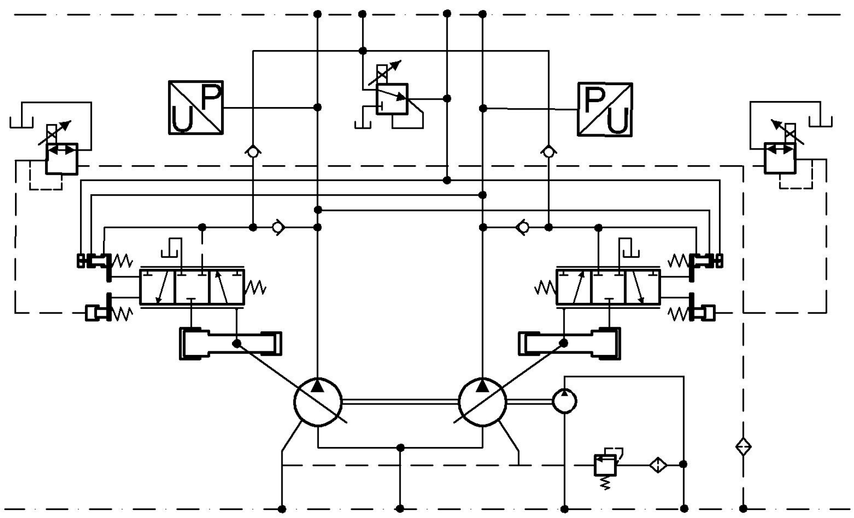


Figure 4. Negative flow-limit load control system.

The negative flow control system can reduce or even basically eliminate the power loss, but it still cannot fundamentally solve the drastic change of the load, and also cannot solve the problem of the engine fuel efficiency reduction caused by the drastic change of the engine working state. Fu et al. [53] designed a new boom potential energy-recovery hydraulic system based on the motion track of the boom, stick, and bucket of the excavator. Potential energy recovery during the falling process was realized, motor speed and energy conversion mechanism efficiency were improved, and the potential energy recovery of boom was 22.6% and the efficiency of the energy conversion mechanism was increased from 85% to 91%. Yang et al. [54] introduced a parallel hybrid power system and oil electric potential energy recovery device on the basis of traditional negative flow-control. When the load power changes, the motor absorbs or supplements the difference between the engine output power and the load power, so that the engine output power is stable. At the same time, the energy consumption of the system decreases by 12.9%, which improves the energy utilization ratio. Ying et al. [55] installed a variable hydraulic motor in the oil-return pipeline. The speed and torque of the generator are adjusted by controlling the position of the hydraulic motor. Proportional flow control valves are installed in the system to reduce flow through the hydraulic motor under heavy load and high-speed conditions. This results in an energy regeneration efficiency of about 50%, reducing the power required to drive the generator.

Cai et al. [56] analyzed the power control principle of the engine and the constant power variable pump based on the negative flow control system, and proposed the goal and method of power control. By controlling the variable displacement pump, the power consumed by the actuator is kept within the maximum power of the engine, and the impact fluctuation caused by the change of the working resistance of the actuator is kept within the response capacity of the engine, so as to ensure that the absorbed power of the variable displacement pump is less than or equal to the output power of the engine, and then the absorbed power of the variable displacement pump is maximized so that the absorbed power of the variable displacement pump is close to the output power of the optimal working point of the engine.

2.2.2. Performance Optimization

Speed regulation is one of the criteria to measure the working performance of hydraulic systems. Hydraulic systems mostly use throttle speed regulation modes of fixed speed and variable displacement at fixed speed. Fixed-speed and fixed-displacement modes cannot match the flow of hydraulic pump and load, so the overflow loss is serious. Variable displacement at a fixed speed matches the flow of the hydraulic pump with load by changing the displacement of the variable pump, but variable pump has a small speed range, low power utilization, and no obvious effect on energy saving. Zhang et al. [57], in order to maximize the speed regulation interval of a hydraulic system, reduced the throttle loss at the main spool work port and bypassed loss at the bypass port, and thus a real-time control idea with a double-folded line sectional speed curve and instantaneous flow unsaturation was put forward. The double-folded line segment speed curve was formed by correcting the slope of the governing characteristic curve according to the operator's "feel", as shown in Figure 5a,b. [a, b] is the speed regulation dead zone, which is caused by the closed length of the valve port when the main valve core is in the middle position. The handle swing in this zone is at the empty stroke; [b, d] refers to the whole speed regulation range. The speed regulation section [b, d] can be divided into two sections, of which [b, c] is a fine adjustment section, in which the mechanism works softly and is suitable for completion; [c, d] is a fast interval, which is suitable for fast action. The double-folded line characteristic curve enlarges the governing interval of the positive-flow system and makes the slope in the interval smaller and the fine-tuning characteristic better.

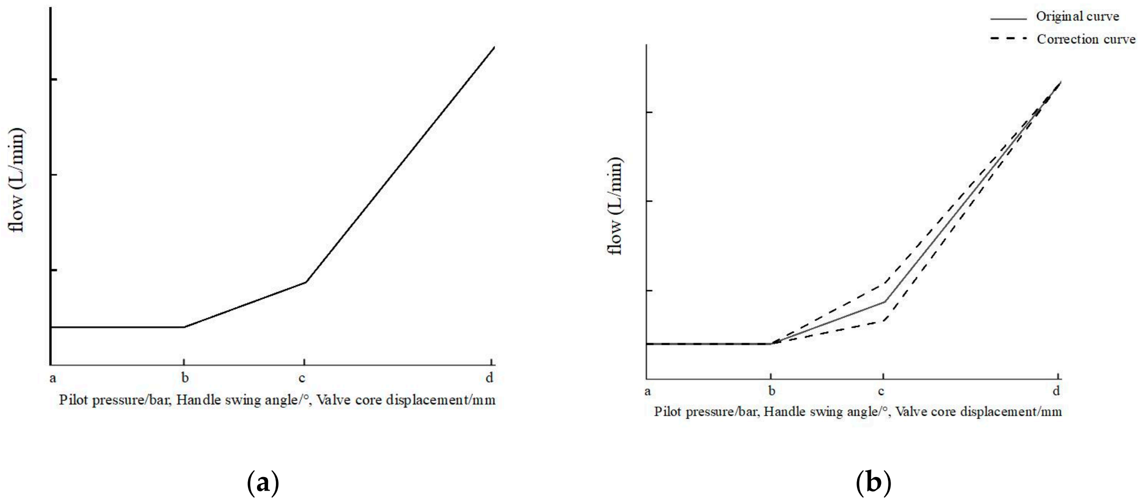


Figure 5. Speed regulation characteristic curve. (**a**) Speed regulation characteristic curve. (**b**) Double-break line type speed regulation characteristic curve.

Response speed is another measure of the performance of a hydraulic system. The speed regulation performance of the hydraulic system is affected by the pressure change of the hydraulic system. When the pressure of the hydraulic system rises above the load pressure, the actuator starts to move. There is a certain delay in the pressure change of the hydraulic system, which affects the response speed of the system. Xie et al. [58] proposed a control strategy of the positive-flow system of an electric excavator based on variable speed. According to the flow control characteristics of a multi-way valve, the flow required for the operation of actuating elements is predicted based on the output signal of the handle. By controlling the speed of the motor, the output flow of the hydraulic pump changes, the flow-matching between actuating components and the hydraulic pump is realized, the overflow loss is reduced, and the response speed of the system is increased. Gao et al. [59] put forward the principle of load sensing control of negative flow. The principle is shown in Figure 6. By utilizing the characteristic that the output pressure of the pump is always higher than the bypass return pressure in the negative flow control, controlling the bypass return pressure is always higher than the load pressure, the output pressure of the pump is always higher than the load pressure, and the system maintains a better response speed.

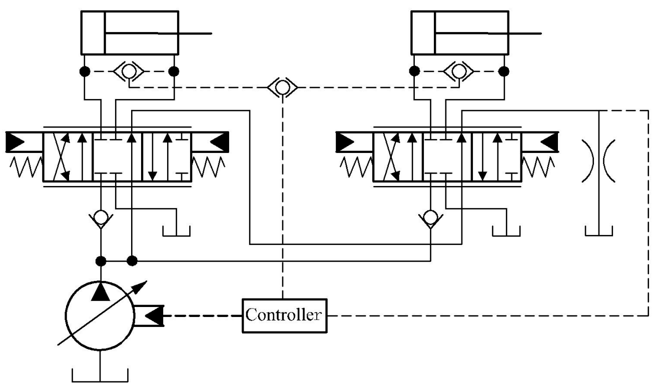


Figure 6. Negative flow load sensitive control system.

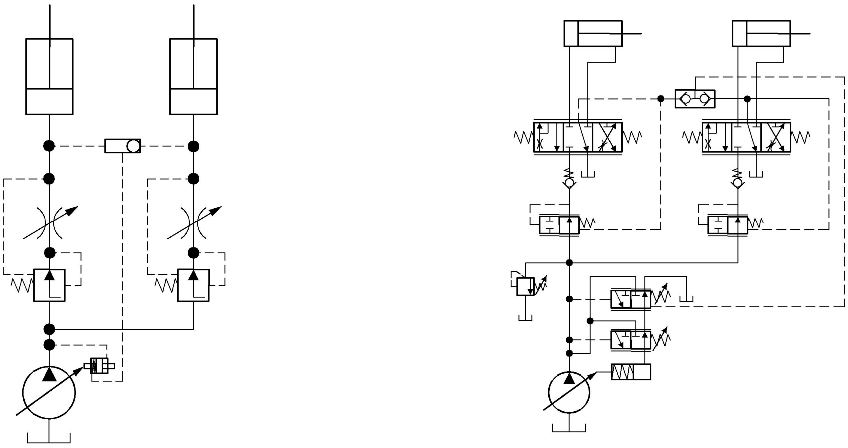
3. Load-Sensitive Control Technology

The load-sensitive system has become one of the most widely used hydraulic systems of construction machinery due to its good energy-saving effect, composite operating performance, and fine-tuning performance.

3.1. Working Principle

The load-sensitive system is based on the characteristics of the preset pressure margin between the pump outlet and the highest load, and uses the long pipeline transmission of load-sensitive pressure for feedback closed-loop control. The shuttle valve at the inlet of the actuator is used to select the maximum flow to control the pressure compensation valve located in front of and behind the main valve core, so as to control the area of the throttle port and pressure drop, avoid the tendency that the hydraulic oil in the hydraulic system only flows to the low-pressure oil circuit, and make the matching relationship between the energy-saving, stability, and dynamic characteristics of the traditional hydraulic system have a certain restrictive effect [60,61]. The load-sensitive control technology solves the problem of throttling loss in the open center hydraulic system, and sets a pressure compensation valve in front of the main valve to ensure that the pressure difference between the front and back of the main valve is constant, so that the flow to the actuating element is independent of its load and only related to the opening amount of the main valve spool, ensuring good handling performance under the working condition of mechanical composite action [62]. Load-sensitive control is divided into LS system (load-sensitive) and LUDV system (Lastdruck unabh ä ngige Durchfluss verteilung) according to the impact of load on traffic distribution.

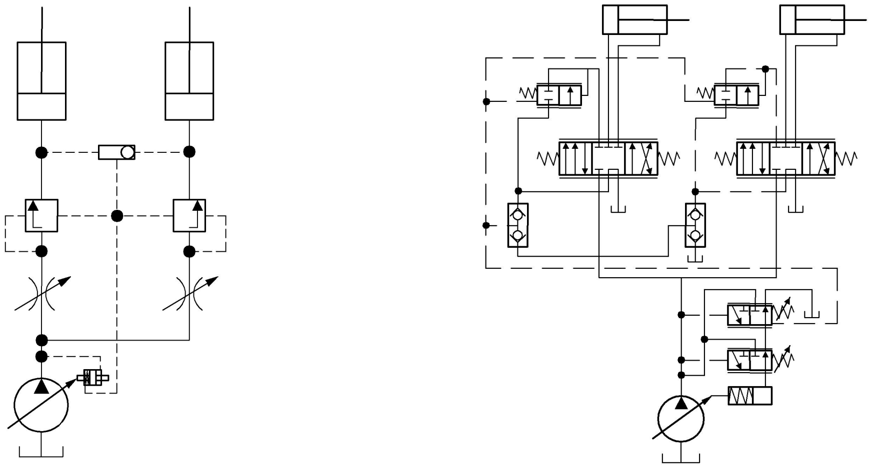
The LS system places the pressure compensation valve in front of the main valve to compensate the system pressure before the valve. The LS system principle is shown in Figure 7a,b. The shuttle valve selects the highest system pressure to control the LS valve of the hydraulic pump. The pressure drop at the front and rear throttle ports is kept constant through the pressure compensation valve. The variable displacement pump adjusts the swashplate swing angle of the pump according to the load pressure at the LS port, so that the pump output flow is equal to the flow required by the actuator.



(**a**) (**b**)

Figure 7. LS System. (**a**) Structure of diagram LS system. (**b**) Schematic diagram of LUDV system.

The LUDV system places the pressure compensation valve behind the main valve to compensate the system pressure. The LUDV system principle is shown in Figure 8a,b. The highest pressure of the system is selected by the shuttle valve to control the displacement of the hydraulic pump. The pressure of the actuator with the highest pressure is used to compensate the pressure of the actuator with the lower pressure, so that the pressure difference of each actuator is kept constant at any time. Therefore, the proportional distribution of the flow of multiple actuators can be achieved.



(**a**) (**b**)

Figure 8. LUDV System figure. (**a**) Structure of diagram LUDV system figure. (**b**) Schematic diagram of LUDV system.

Scholars at home and abroad have studied energy-saving optimization strategies of load-sensitive control systems in different directions, but they basically focus on three aspects: optimizing and improving the pressure compensation characteristics of the system to reduce the pressure loss in the process; independently controlling the load port according to the flow and pressure distribution characteristics of the system; and the pressure-sensitivity and proportional control technology combined with the load-sensitive system to reduce the pressure drop generated by the hydraulic transmission of the system and the delay of the transmission signal.

3.2. Development Status

3.2.1. Pressure Compensation Optimization

The principle of the load-sensitive system is shown in Figure 9a. The pressure difference on both sides of the valve is adjusted to maintain the stability of the system flow, avoid the stopping of the hydraulic cylinder at the load end of the system due to insufficient flow, and ensure that the flow of each load branch is reduced proportionally to ensure the stability of the system. However, adjusting flow by compensating differential pressure will cause energy loss, reduce system efficiency, and affect the service life of components. Wang et al. [63] proposed a valve back-compensated load-sensitive system with hydraulic resistance in series. The system principle is shown in Figure 9b. The compensated differential pressure on the pressure compensation valve is reduced through pilot control valves in series. The compensated differential pressure and energy loss of the pressure compensation valve are reduced, and the service life of the system and components is also improved. Tao et al. [64] proposed a load-sensitive system for compensating behind the valve with parallel liquid resistance shunt. The system principle is shown in Figure 9c. Two pressure compensation valves are connected in parallel to reduce the flow of the high-pressure differential pressure compensation valve, which can flexibly reduce the energy loss on a single pressure compensation valve and improve the response speed and working efficiency of the system. Shen et al. [65] connected one energy-saving control valve in series between the outlet of the load sensitive multi way valve and the pump flow regulating valve. The energy-saving control load-sensitive hydraulic system is shown in Figure 9d. The highest working pressure of the system collected by the system shuttle valve first acts on the right chamber of the energy-saving control valve, and the outlet pressure acts on the left end of the energy-saving control valve. The maximum pressure fed back to the flow regulating valve at the pump outlet is reduced by dynamically adjusting the size of the liquid resistance opening of the energy-saving control valve, thereby reducing the pump outlet pressure, that is, the pressure at the inlet of the load sensitive multi-way valve. The flow through the load sensitive multi-way valve remains unchanged by increasing the opening area of the load sensitive multi-way valve. This control mode reduces the pressure loss of the load sensitive multi-way valve, plays an energy-saving role while maintaining the responsiveness of the pump and the operability of the loader, reduces the energy loss of the system, improves the working efficiency of the system, and at the same time, also has certain benefits for improving the service life of the system and components.

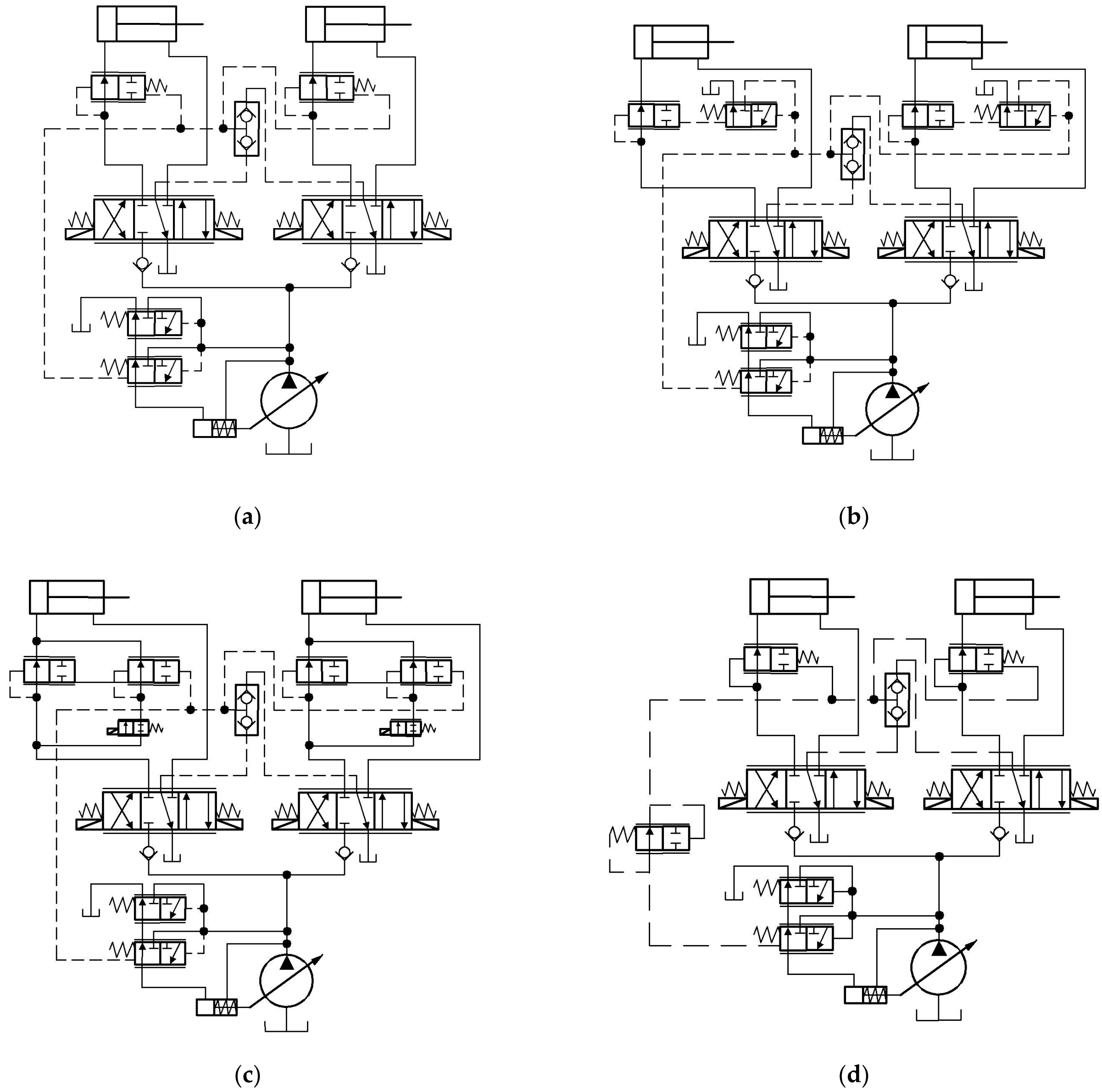


Figure 9. Load-sensitive system figure. (**a**) Structure diagram of traditional load-sensitive system. (**b**) Structural diagram of series hydraulic resistance load-sensitive system. (**c**) Structural diagram of parallel hydraulic resistance load-sensitive system. (**d**) Energy saving control load-sensitive system structure.

3.2.2. Independent Load Control

Due to the mechanical connection of the inlet and outlet throttling edges of the load sensitive system, the inlet is throttled while the outlet is throttled, resulting in repeated throttling losses [66–68]. In view of the problems existing in the linkage throttling control, some scholars proposed to use the independent control method of the inlet and outlet to control the pressure and flow of the two chambers of the actuator, respectively. Liu et al. [69] studied the dynamic and static characteristics of the load-independent control system that uses the proportional relief valve to regulate the inlet pressure. Aiming at the switching problem between different working conditions, he proposed a control strategy of pressure feedforward compensation to reduce the switching impact. Aiming at the impact of the structural parameters of the independent direction valve at the load port on the speed control performance of the actuator, he proposed a control mode of feedforward dead zone compensation to improve the overall control and energy-saving performance. Cao et al. [70] studied the high response energy-saving control valve used for independent load control. On the premise of ensuring the high response performance, the system energy conservation was realized by using independent control of inlet and outlet and differential regeneration loop. Liu et al. [71] used five two-position two-way proportional valves as the main control valves to replace the three-position five-way directional valves of the load-sensitive system, reducing repeated throttling losses, and improving the energy saving efficiency of the system by 14.47%. Zhang et al. [72] comprehensively considered load-sensitive technology and inlet and outlet throttling control technology, designed a load-sensitive hydraulic system with independent throttling control, which can independently control the oil outlet cavity to obtain the lowest pressure state, thus reducing the power loss at the oil outlet. Dong et al. [73] proposed an independent control system for the inlet and outlet of the pump valve compound flow-matching control. The test results show that the pressure fluctuation of the system is significantly reduced, and the energy consumption is reduced by 15%. Xu et al. [74,75] put forward a joint control strategy for the pump and valve of the independent energy-saving control system at the load port. Through pressure matching, flow/pressure valve control configuration and a damping compensator, the valve port opening was controlled. The variable pressure margin electro-hydraulic load-sensitive method is used to control the discharge of the variable pump, reducing the system pressure and flow, and saving more than 6% energy consumption compared with the traditional load-sensitive control method. Liu et al. [76] designed an independent control system of the electric drive control subsystem to solve the problem of throttling loss of the orifice valve of the load sensitive system. On the basis of independent flow distribution, combined with the consistent flow and pressure, and the static coordination strategy of the pump valve, this system reduced the pressure fluctuation in the load sensitive system, improved the energy efficiency and stability of the system, and reduced the energy consumption of the system by 15% compared with the load-sensitive system. Ding et al. [77–79] analyzed the coupling characteristics in the pressure and speed composite control of the load-independent control system, and proposed a hybrid control method combining dynamic pressure feedback and active damping control for the vibration phenomenon caused by the lack of damping at the inlet and outlet of the flow independent control system. By introducing pressure feedback, the damping characteristics were optimized to ensure the high stability and fast response of the system. Lyu et al. [80] proposes a strategy that combines independent control valves with pump direct control. The performance of this system reaches the same level as that of load-independent control system, and since the variable displacement pump is directly controlled, there is little throttling loss. The general form of parallel coordination control unit for pump valves [81] is further studied. A practical feed-forward pump controller is synthesized to improve the control design so as to improve the energy efficiency. Its energy consumption is only about half of the total energy consumption.

3.2.3. Electric Control Load Sensitive System

The traditional load-sensitive system transfers the load pressure to the pressure control port of the load sensitive system through the control oil circuit, so as to adjust the displacement of the variable displacement pump to adapt to the load change. This mechanical hydraulic feedback control system has poor robustness and an unstable transmission signal, which can generate pressure drop and delay of transmission signal through the hydraulic oil circuit transmission. In view of the above shortcomings of the traditional mechanical hydraulic feedback control load-sensitive system, domestic and foreign scholars have proposed an electronically controlled load-sensitive system based on pressure-sensitive technology and proportional control technology. The electronic load sensitive system can be divided into two types: electronic load sensitive control system (ELS) [82], and electrohydraulic flow matching control system (EFM) [83].

In the ELS system, the system pressure and load pressure are detected by sensors, and then transmitted to the controller to regulate the pump displacement, thus controlling the pressure margin to maintain the desired value. Therefore, the principle of ELS system is the same as that of traditional LS system. Hansen et al. [84] added a feedforward signal to the ELS control system to improve the system response when the pressure margin is preset. Lenzgeiger et al. [85] proposed an ELS system with a variable pressure margin by covering differential pressure control. Hu et al. [86] integrated the electric proportional three-way pressure-reducing valve into the load-sensitive pump, realized variable pressure margin through differential pressure control, removed the pressure feedback oil path, reduced the pressure loss in the oil path transmission process, and improved the dynamic response speed. Du et al. [87] proposed a variable supply valve-control method based on load estimation, but the actual load of mobile machinery changes frequently and suddenly, which is difficult to predict. In the ELS system, the main disadvantage is that the pressure control loop still exists, and it is difficult to eliminate the oscillation phenomenon.

The EFM system removes the pressure control circuit and directly regulates the pump displacement according to the load demand. EFM system has the characteristics of fast response, high efficiency, and good damping. The main problem of EFM system is the difficulty of flow matching between pump and valve [88]. Due to the nonlinearity of the system and the uncertainty of the parameters, the flow matching problem is still a prominent problem. By adding pressure relief unloading valve or position sensor [89], the use of homotopy perturbation method [90] can improve the flow matching degree of EFM system. However, such methods increase the complexity of EFM system and hinder the application of EFM system in mobile machinery. Axin et al. [91] proposed a hybrid control scheme, which superposed the outputs of ELS controllers and EFM controllers with different weight factors. It has the advantages of high energy efficiency, fast system response, and high stability margin, but both dynamic performance and energy efficiency deteriorate. Cheng et al. [92,93] proposed an electro-hydraulic load-sensitive system based on flow/pressure composite control to solve the problems of pressure shock and low efficiency caused by flow mismatch. The flow feedforward controller was used to calculate the actual flow, the pressure feedback controller maintains the pressure margin, and the flow controller controls the pump displacement. The improved system avoids the pressure impact caused by the flow mismatch, thereby reducing the energy loss. Wang et al. [94] proposed an electronically controlled linear motor variable displacement load-sensitive system to solve the problem of the accuracy of displacement adjustment of the mechanical hydraulic feedback control load-sensitive system. The linear motor is used to replace the variable cylinder to adjust the displacement of the axial piston pump, and the linear motor is controlled by using flow feedforward and differential pressure feedback to realize the load-sensitive function of the hydraulic system.

4. Discussion

In conclusion, by improving the flow-matching degree of the hydraulic system, the energy loss and energy-saving levels of the hydraulic system can be reduced, but there are many challenges in flow-matching technology. The difficulties of flow-matching technology of the hydraulic system are mainly divided into two aspects. On one hand, flow-matching technology of hydraulic systems only realize local power-matching. The positive flow-control system, negative flow-control system and load-sensitive system introduced in this paper can realize local power-matching of hydraulic pump-load, while the power-matching and coordinated control of engine-hydraulic pump-load as a whole has not been realized. At present, the global power-matching technology is still immature [95]. The research mainly focuses on flow-matching between the hydraulic pump and load [6] and power-matching between engine and hydraulic pump [96,97]. Engine-load matching undergoes a change from mechanical to hydraulic transmission. There are difficulties in matching and coordination between engine-hydraulic pump power=matching and hydraulic pump-load flow-matching. On the other hand, load flow independent distribution technology and electronic control technology also have their own defects. Load-independent control technology relies on rule-based switching between multiple operation modes, which results in a discontinuity of control signal and system dynamics and affects response speed. Load-independent control technology reduces energy loss by expanding orifices, but this reduces controllability and speed oscillation due to a lack of damping in expanding orifices. Electronically controlled technology reduces the efficiency and controllability of a hydraulic system due to the non-linearity of the system and the uncertainty of parameters resulting in difficult flow-matching between pump and valve.

Positive flow-control technology, negative flow-control technology, and load-sensitive control technology have been mainstream technologies for flow-matching in hydraulic systems of construction machinery for a period of time, but relying on flow-matching alone cannot completely exert the output power of engine on load; there is still a certain power loss. Based on the power source matching control system. Therefore, in addition to using high-performance hydraulic components, it is also an effective way to achieve the global power-matching of the engine hydraulic pump and load. Therefore, the global power-matching technology will be paid more attention to in the future. With the continuous development and maturity of the global power-matching technology, it will be widely used in the hydraulic system of construction machinery. At the same time, the combination of flow-matching technology and load flow independent distribution and electronic control technology shows excellent performance, which will be integrated into continuous improvement to improve the matching degree of system flow.

5. Conclusions

At present, flow-matching technology of hydraulic systems is mainly divided into positive flow-control technology, negative flow-control technology and load-sensitive control technology.

Positive flow-control technology regulates pump displacement through pilot control, reduces bypass throttling losses and has better energy saving effects. However, positive flow-control requires the secondary pilot pressure to be retrieved from the shuttle valve block to achieve pump displacement control, so the control oil circuit is complicated. Therefore, the complexity of the positive flow-control system is reduced by replacing the shuttle valve with the cylinder piston rod controlled by pilot pressure in parallel. Based on the output signal of the handle, the flow required for the operation of the actuating element is predicted, the output flow of the hydraulic pump is changed, and the flow matching degree is reduced, thus the overflow loss is reduced. Changing the confluence position of the system and changing the internal confluence of the multi-way valve to the external pipeline confluence of the multi-way valve reduces pressure loss and energy consumption. Therefore, improvement of the control strategy and structural innovation of the positive flow-control system may be a future development direction.

Negative flow-control technology regulates pump displacement by detecting return flow, which effectively reduces throttle loss and overflow loss and has better energy-saving effects. However, the maneuverability and system stability of negative flow-control technology are greatly affected by load and flow, and the operation performance is slightly poor. Therefore, by enlarging the adjustment range of the hydraulic pump, the hydraulic pump can absorb as much power as possible from the engine with the change of load, so as to achieve high-efficiency utilization of power in the full speed range of the engine. Based on the principle of power control, by controlling the variable pump, the power consumed by the actuating element is within the maximum power of the engine, so that the absorbed power of the variable pump approaches the output power of the best working point of the engine. The output pressure of the pump in the control system is always higher than that of the bypass return pressure, which makes the system maintain good speed control. Therefore, improvement of control strategy based on bypass return and global matching of the engine, hydraulic pump, and load may be a future development direction of negative flow-control system.

Load-sensitive control technology provides the required flow and pressure according to the load demand, with low power loss, and can simultaneously meet the working requirements of multiple flow and pressure requirements of different actuating elements. It has good energy-saving effects, composite operation performance, and fine-tuning performance. However, adjusting the flow rate by compensating differential pressure in load-sensitive systems will cause energy loss and reduce system efficiency. Therefore, by changing the hydraulic resistance of the pressure compensating valve, the compensating differential pressure of the pressure compensating valve can be adjusted to reduce the energy loss. Load-sensing technology is combined with import and export throttle-control technology and load-independent control technology to reduce the throttle loss of the system. By designing an electronically controlled load-sensitive system, the pressure drop generated by transmission of hydraulic oil circuit and the hysteresis of transmission signal are reduced. Load-sensitive control technology has broad prospects and shows good performance when combined with load-independent control technology and electronic control technology. At the same time, it realizes high-efficiency flow matching between hydraulic pump and load by providing flow on demand, which is more in line with the development trend of global matching.

In view of the current situation and development trend of the above flow matching control is no longer limited to the coordinated control between hydraulic the pump and load. The power matching and coordinated control of engine–hydraulic pump–load as a whole will effectively improve the flow matching degree, improve the energy-saving levels of hydraulic systems, and lay a good foundation for the steady development of construction machinery.

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