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A Review of Flow Saturation Resistant Techniques in Multi-actuators Load Sensing Hydraulic System

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Abstract: The multi-actuator load-sensitive (LS) system has gained widespread usage in engineering machinery applications due to its energy efficiency, exceptional composite action performance, and precise tuning capabilities. However, when the demand for load flow exceeds the supply of hydraulic pumps, flow saturation conditions may arise in hydraulic pumps, thereby impacting the coordination of multi-actuator actions and diminishing the load sensitivity characteristics of the system. To address this issue, scholars have proposed anti-flow saturation technology. Currently effective solutions include reducing the set pressure of pressure compensator valve springs and decreasing the opening degree of each main valve. Anti-flow saturation technologies for multi-actuator load-sensitive systems can be classified into three types based on the location of pressure compensators in different circuits: pre-valve; post-valve and outlet pressure compensation anti-saturation, as well as a novel type known as independent metering (IM) technology. This article provides an overview of significant accomplishments in these three types of anti-saturation technologies before introducing IM technology and discussing research focal points for various types of load-sensitive systems as well as how anti-saturation technologies impact their energy efficiency. Finally, future directions for development in flow saturation resistant technologies within muti-actuators load sensing systems are explored.

1. Introduction

As a major energy consuming, China has always focus on researching energy conservation in the field of engineering machinery. Hydraulic systems in engineering machinery have evolved from open-center to closed-center and then further developed into the current load-sensitive systems[1-5]. Load-sensing hydraulic systems offer advantages such as low energy consumption, high efficiency, and flow distribution that depends only on the opening of the main valve. Compared to traditional open-center and closed-center systems, load-sensitive systems have made significant progress in saving energy. However, when the demand for load flow exceeds the supply capacity of the hydraulic pump, flow saturation can occur[6-8] .

In general, engineering machinery operates under complex conditions and often requires multiple actuators to work simultaneously. The work objects in these machines vary, and the working loads can fluctuate greatly. In traditional load-sensitive systems, pressure feedback based on the maximum load pressure is used to achieve closed-loop control of system pressure, ensuring the required flow rate and pressure. When the demand flow rate of all participating actuators exceeds the maximum supply flow rate of the hydraulic pump, oil is first supplied to the low-pressure actuators due to parallel oil supply[9-11]. This satisfies the needs of the low-pressure actuators, and the pressure drop across the low-pressure control valve reaches the compensating pressure, at that point, the pressure compensator valve controls the flow rate. In other words, when the pump flow rate is insufficient, it first ensures the supply to the low-pressure actuators, and then supplies the excess oil to the high-pressure actuators. However, at this point, the flow rate to the high-pressure actuator control valve is insufficient to activate the pressure compensator valve. As a result, there is a reduced speed of high-pressure actuators operation or even complete stoppage. This phenomenon is known as flow saturation in multi-actuator load-sensitive systems[12-17]. It significantly affects the normal operation of hydraulic equipment, increases maintenance costs, and limits the application prospects of load-sensitive systems. Therefore, research on flow saturation resistance control in load-sensitive hydraulic systems is necessary to ensure that the system can maintain good flow distribution characteristics and actuator coordination even under flow saturation conditions[18-20]. Flow saturation resistance techniques effectively address the coordination issue between output power and load characteristic curves in load-sensitive systems, reducing flow loss and pressure loss, and improving system coordination.

In summary, the research on flow saturation resistance methods and strategies for load-sensitive systems has significant theoretical significance and practical engineering application value, considering the causes and hazards of flow saturation in load-sensitive systems. This paper focuses on analyzing the research achievements and features of flow saturation resistance techniques carried out by domestic and foreign scholars in pre-valve, post-valve and outlet pressure compensation aspects. The potential research directions for flow saturation resistance in load-sensitive systems are proposed.

2. Pre-valve compensation technologies for flow saturation resistance

Pre-valve compensated load-sensitive hydraulic systems are commonly used in hydraulic control. They primarily regulate the flow into the actuator and reduce the impact of load variations on actuator performance by using a pressure differential compensator installed before the actuator. However, due to flow limitations within the system, issues with flow saturation can arise, which affect system performance and stability.

2.1. Flow saturation resistance control based on priority pressure compensation

In 1969, Allen proposed the concept of priority-based pressure compensation[21]. The idea is to assign priority levels to each actuator based on its flow demand utilizing priority valves with pressure compensation capabilities. When flow saturation occurs, the flow rate to each actuator is sequentially reduced in order of priority, from high to low.

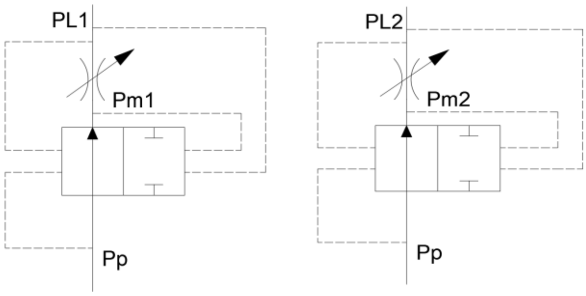
However, in systems with priority-based pressure compensation involved in complex operations, lower priority actuators may stop working. To ensure that even the lower priority actuators continue to function, even when the pump's output flow is severely limited, it is sometimes necessary to weaken the priority of the pressure compensation. This requires the use of pressure compensation based on the pressure differential across the variable throttle.

2.2. Flow saturation resistance control based on shunt ratio adjustable pressure compensation

In 1974, Malott and Paul introduced the concept of ratio-regulated pressure compensation[22]. When the system experiences flow saturation, the flow rate of each actuator decreases proportionally by adjusting the pressure differential at the throttle to maintain a certain proportional relationship between the actuator speeds. This type of pressure compensation, where the pressure differentials at both ends of the throttle need to be equal, is known as ratio-regulated pressure compensation.

Based on this principle, the Linde company developed the Synchronization Control (LSC) System, which is a typical flow saturation resistance circuit consisting of sliding valves[23,24]. As shown in figure 1, this is a one-way pressure compensator valve in Linde's flow saturation resistant load-sensitive system. The left end of the pressure compensator valve is subjected to the oil pump pressure (P_p) and the load pressure (P_L). The right end is subjected to the pre-pressure of the control valve (P_m) and the maximum load pressure (P_{L1}) introduced by the shuttle valve (assuming $P_{L1}>P_{L2}$, $P_{L1}=P_{Lmax}$). To achieve force balance for pressure compensator valve 1 (assuming the left and right areas of the valve spool are equal), we have:

$$P_p+P_{L1}=P_{m1}+P_{L1} \tag{1}$$



(a) (b)

Figure 1: (a) LSC system one compensation valve; (b) LSC system dual pressure compensation.

So $P_p=P_{m1}$, the oil flow through the pressure compensation valve without pressure difference. Differential pressure $\Delta P_1=P_{m1}-P_{L1}=P-P_{L1}$ at inlet and outlet of control valve 1. Similarly, the pressure compensation valve 2 takes the force balance.

$$P_p-P_{m2}=P_{L1}-P_{L2} \tag{2}$$

The differential pressure of oil flow through pressure compensation valve 2 is $P_{L1}-P_{L2}$, which exactly compensates the difference of pressure load between the two actuators.

Control valve 2 inlet and outlet differential pressure:

$$\Delta P_2=P_{m2}-P_{L2}=P_p-P_{L1}=\Delta P_1=\Delta P \tag{3}$$

That is, the inlet and outlet pressure difference of all valve stems is equal, which is the difference between the outlet pressure of the oil pump and the maximum load pressure. The flow through the two joysticks is that.

$$Q_1=K_1\sqrt{\Delta P} \tag{4}$$

$$Q_2=K_2\sqrt{\Delta P} \tag{5}$$

Each valve is the same, and the flow to each actuator depends only on the stroke of each valve stem (K1, K2). Under this pressure difference, each valve stem adjusts the flow rate of the actuator through the throttle size of the valve stem opening, which has nothing to do with the actuator load.

When the actuators operate at the same time, there is no influence on each other, and the flow rate is distributed proportionally according to the stroke of each valve stem.

When each valve stem is in A large opening, flow saturation, $P_p<P_{Lmax}+F_s/A$, the oil pump is at the maximum displacement, the pressure difference of the control valve drops $\Delta P<F_s/A$, but the pressure difference of the control valve stem inlet and outlet is still equal, so the flow of each way is still proportional to the valve stroke.

2.3. Anti-saturation control based on adjustable compensation of differential pressure at ends of the throttle port

According to the two anti-saturation control concepts mentioned above, the shunt control concept of adjustable pressure compensation at both ends of the throttle is proposed. This shunt control is based on the requirements of different working conditions by external adjustment of the pressure difference at both ends of the throttle and can also improve the adaptation performance of the composite action of the system. Then even if the pressure compensator is set upstream of the control orifice, the flow saturation can be achieved.

Based on the principle of adjustable pressure compensation for the pressure difference between the two ends of the throttle, Vickers proposed a power matching (TM) system in 1981 to independently adjust the oil inlet and outlet of the actuator[25]. In the case of flow saturation, the pilot pressure can be adjusted to achieve shunt regulated pressure compensation. Hitachi proposed a scheme in 1985 in which an external electrical appliance controlled the pressure difference at both ends of the throttle. In the case of flow saturation, anti-flow saturation control was realized by adjusting the given value of the pressure difference[26].

There are also relevant studies in China. For example, Yang H Y et al. designed an anti-flow saturation controller of the pressure compensation system in front of the valve, so that the LS system has the function of anti-flow saturation[27].

As shown as in the Figure 2, Yuan D et al. of Yanshan University proposed an anti-flow saturation strategy based on the electro-hydraulic flow matching control system with variable speed[28]. The method realizes the inhibition of flow saturation by dynamically modifying the flow rate of the hydraulic cylinder. Specifically, the method first determines whether the flow saturation phenomenon occurs by detecting the theoretical speed and the maximum speed of the motor. If there is a flow saturation, the flow of the hydraulic cylinder will be dynamically adjusted according to the actual demand, and the secondary flow distribution of each joint actuator will be carried out to ensure the normal operation of the system.

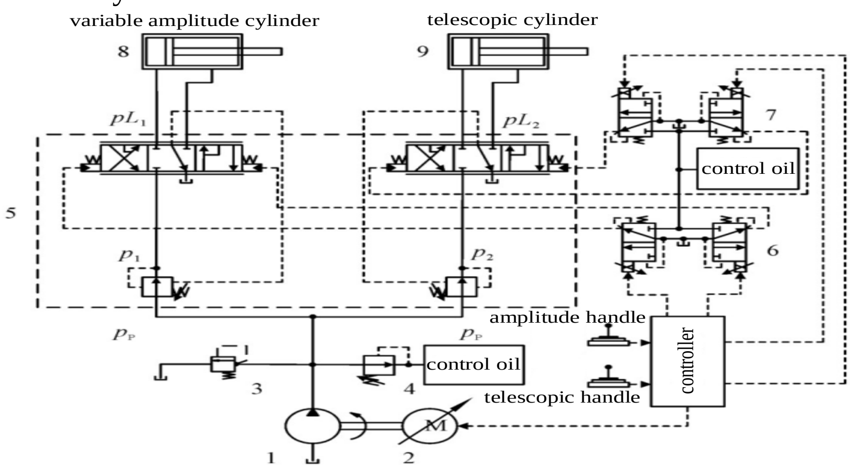


Figure 2: Variable speed electro-hydraulic flow matching system[0].

In summary, the anti-flow saturation technology of pre-valve compensation mainly focuses on two aspects: optimizing the structure of pressure compensators and using control strategies. Pre-valve compensation load-sensitive systems have good speed regulation performance and relatively low cost, but flow saturation is unavoidable. However, current methods for anti-saturation pre-valve compensation increase system costs and complexity while having lower energy efficiency. Therefore, there is still significant room for development in terms of system structure and energy efficiency. In future research, it will be possible to further optimize and improve the pressure compensation characteristics of the system to reduce pressure loss; combine pressure-sensitive and proportional control technologies with load-sensitive systems to reduce hydraulic transmission pressure drops and signal delays; furthermore, global power matching between motors, pumps, and loads will receive widespread attention instead of just local power matching based on flow rates between hydraulic pumps and loads.

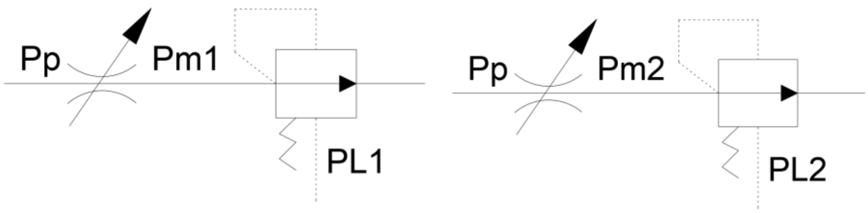
3. Post-valve compensation technology for flow saturation resistant

The most intuitive change in the post valve compensation structure and pre-valve compensation load-sensitive hydraulic system is the position of the pressure compensator, one in front of the reversing valve, one after the reversing valve, in fact, the pressure compensator structure in the two systems is different, which mainly uses the pressure compensation valve to achieve stable operation of the actuator. By setting a pressure compensation valve behind the actuator to control the flow out of the actuator in the system, the flow control and the ability to resist flow saturation are realized [29].

The representative product of the post-valve compensation LS system is the Load independent flow distribution (lastdruck unabhängige durchfluss verteilung, LUDV) system for post-valve pressure compensation developed by German Rexroth Company, which has anti-saturation function[30,31]. Under the action of the pressure compensator, the pressure after the valve of each coupling orifice in the LUDV system is equal, so that the pressure difference between the two ends of the valve is equal[32,33]. Therefore, even when the flow is saturated, the system can still shunt according to the joint valve port area controlled by the control rod, maintain the synchronization of the action, and have the function of anti-flow saturation. As shown in the figure 3, one end of the spool of the pressure compensation valve is acted on by the inlet and outlet pressure of the control valve, and the other end is acted on by the spring force and the maximum load pressure introduced through the shuttle valve ($P_{L1} > P_{L2}$) to balance the pressure compensation valve 1.

$$(P_{m1}-P_{L1})A=F_S \quad (6)$$

$$P_{m1}=\frac{F_S}{A}+P_{L1} \quad (7)$$



(a) (b)

Figure 3: (**a**) LUDV system pressure compensation valve 1; (**b**) LUDV system pressure compensation valve 2.

Force balance on pressure compensation valve 2.

$$(P_{m2}-P_{L1})A=F_S \quad (8)$$

$$P_{m2}=\frac{F_S}{A}+P_{L1} \tag{9}$$

In the design, if the two pressure compensation valves F_s/A are equal, then $P_{m1}=P_{m2}$, where P_{m1}, P_{m2} are the outlet oil pressure of the control valve 1 and 2 respectively; P_{L1} is maximum load pressure; F_S is spring force; A is pressure compensation valve spool pressure area. The inlet of each control valve is the pressureP_p of the pump, and the outlet pressure is P_{m1} and P_{m2} respectively, which are equal, so the inlet and outlet pressure difference of each control valve is equal. If the load pressure of each actuator is different, and the oil supply pressure of the pump is certain, the inlet and outlet pressure difference of the control valve is also equal, obviously the pressure compensation valve plays a compensation role, and the throttle degree is different, resulting in different pressure differences, to achieve the purpose of balancing the load. Where the differential pressure at pressure compensation valve 1:

$$P_{m1}-P_{L1}=F_S/A \tag{10}$$

Pressure drops of pressure compensation valve 2:

$$P_{m2}-P_{L2}=\frac{F_S}{A}+(P_{L1}-P_{L2}) \tag{11}$$

Obviously, the pressure compensation valve compensates exactly the difference between the pressure load of the two actuators.

4. Outlet pressure compensation anti-flow saturation technology

The outlet pressure compensation LS system arranges pressure compensation valves on the outlet of each oil return circuit, representing Toshiba's innovation breed-off load sensing system[34].

The outlet pressure compensation LS system introduces the highest load signal and the connected load signal into the pressure compensator, causing it to adjust the opening degree accordingly to create throttling. This ensures that the pressure difference at both ends of the control valve remains equal, giving the outlet pressure compensation LS system anti-flow saturation capability. As shown in figure 4, balance is achieved through the pressure compensation valve:

$$P_LA+F=P_{Lmax}A \tag{12}$$

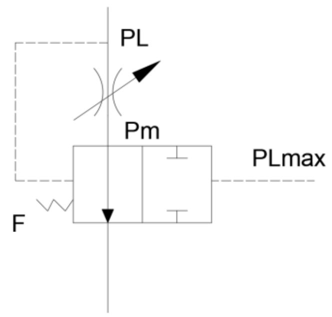


Figure 4: Outlet pressure compensation load-sensing hydraulic system pressure compensation valve.

In the formula, P_L is the load pressure of each valve, P_{Lmax} is the maximum load pressure, F is the spring force, and the spring force can be ignored by using weak spring.

$$P_L=P_{Lmax} \tag{13}$$

The load pressure of each actuator is equal to $\Delta P=P_m-P_L=P_m-P_{Lmax}$; where P_m is the inlet pressure of each valve, and P_L is the load pressure. Since each valve ΔP is equal, the flow through each valve stem is only related to the stem stroke and has anti-saturation function.

The advantage of putting the pressure compensation valve on the oil return circuit is that the throttle compensation effect of the pressure compensation valve can be used to prevent the excessive drop or vacuum due to the action of gravity, and it is easy to use gravity to form a regenerative circuit. For regenerative oil supply, a regenerative check valve can be set on the oil circuit.

5. IM technology for flow saturation resistant

Due to the issue of repetitive throttling losses caused by load-sensitive systems, some scholars have proposed the use of IM control as a solution, as mentioned in references[35,36]. IM technology is a new type of technology where the throttle area of inlet and outlet control valves can be independently adjusted[37-39]. In general, multiple spools are used to independently adjust the oil flow in both inlet and outlet circuits. There are two common layout forms: two three-way three-position valves or four two-way two-position valves, as shown in the figure 5.

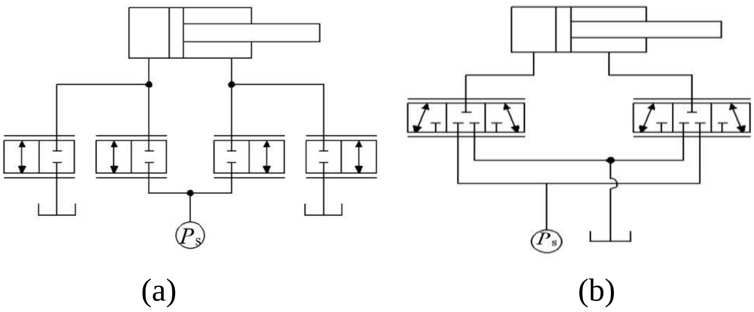


Figure 5: (a) Schematic diagram of type 4-2/2 system; (b) Schematic diagram of type 2-3/3 system [0].

IM system is a new type of hydraulic control system (Figure 6 a), it breaks the restriction of the linkage adjustment of the inlet and outlet orifice area of the traditional valve control system (Figure 6 b)[40,41]. By adjusting the inlet and return valve openings respectively, the pressure of the two cavities of the actuator is no longer coupled with the flow rate, thus significantly improving the energy saving and control performance of the traditional valve control system. Zhang et al[42]. developed a load-sensitive hydraulic system that incorporates both load-sensing technology and inlet/outlet flow control technology to achieve independent flow control. The system can regulate oil outlet pressure to its minimum state, thereby reducing power loss at the oil outlet while maintaining optimal performance levels.

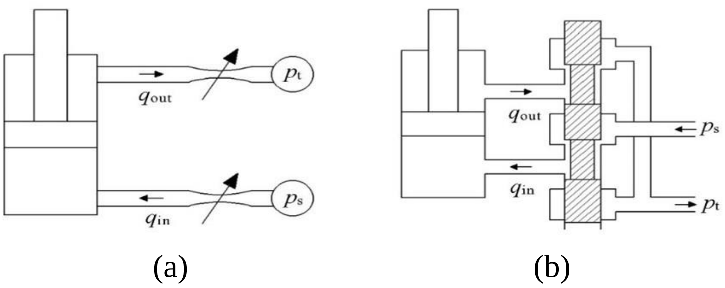


Figure 6: (a) Load-sensing independent Metering control system; (b) Traditional three-position four-way valve control system[39].

Due to the high energy efficiency and low pressure loss of IM technology, some scholars have proposed applying this technology to LS systems. Liu K L et al.[43] improved the traditional per-valve compensation LS system to address flow saturation issues in LS systems and proposed an active anti-saturation control strategy. Zeng Y S[44] from Hefei University of Technology applied independent metering control technology to load-sensitive systems and designed a flow saturation-resistant system based on outlet pressure compensation for IM as shown in the figure 7. When there is flow saturation, the system also proportionally distributes the flow to each actuator, thereby giving it anti-flow saturation functionality. Unlike LUDV systems that directly maintain a constant pressure difference in the inlet oil circuit, here it indirectly controls the main valve pressure difference by controlling backpressure in the oil return circuit.

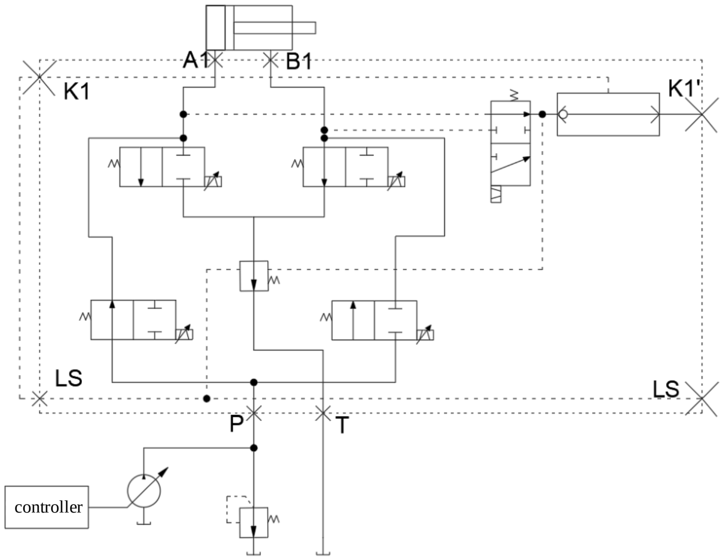


Figure 7: Schematic of the 1-actuator IM system Schematics[0].

6. Conclusions

With the increasing application of load-sensitive systems, their performance requirements are constantly improving. The improvement in lightweight and energy efficiency also relies on the support of anti-flow saturation technology. The existing methods for solving flow saturation in multi-actuator systems mainly rely on LS technology. However, there are still unresolved issues in traditional LS system such as large throttle loss, complex control of electro-hydraulic differential compensator, non-proportional distribution of flow, and failure when there is a significant difference in pressure among different loads. In addition, even for IM technology, although it improves system energy efficiency and reduces throttle loss, it still cannot fully utilize the output power of the motor and there is still some power loss. Therefore, future global power matching technology will receive more attention.

In conclusion, the current anti-saturation technology that can be applied in engineering practice is very limited and not ideal. Therefore, the development direction of anti-flow saturation technology of load sensitive system is to effectively meet the requirements of a single pump driven multi-actuator load sensitive system to ensure the coordination of composite action under any circumstances. With the aim of improving the performance requirements of load sensitive system, it is necessary to carry out research from the following aspects.

1) Accurate prediction of complex loads: When the system is faced with complex load changes, accurate prediction of the required hydraulic flow remains a challenge. In some construction machinery applications, the characteristics of the load may change dynamically over time or involve the interaction of multiple loads. The accurate load flow prediction under such complex conditions still needs further research.

2) High-speed motion and high load control: Under high-speed motion or high load conditions, the control of load-sensitive hydraulic systems is still challenging. This involves the dynamic performance of hydraulic components, flow distribution and pressure control. How to achieve stable flow and pressure control under high speed and high load conditions still needs further research.

3) Energy efficiency optimization: Load-sensitive hydraulic systems face energy efficiency problems in anti-flow saturation technology. In order to avoid flow saturation, the system usually needs to stabilize the load through energy consumption. However, this also results in a loss of energy and a reduction in the overall energy efficiency of the system. Therefore, how to optimize the energy while ensuring the stability of the system is still a difficulty.

4) Overall system integration and optimization: In practical applications, load-sensitive hydraulic systems need to be integrated and optimized with other components and systems. This involves the selection of hydraulic components, the design of control systems, the layout of sensors and so on. How to realize the cooperative work of the whole system and system-level performance optimization still need to be further studied.

References

[1] Padovani, Damiano, et al. The Working Hydraulics of Valve-Controlled Mobile Machines: Classification and Review [J]. Journal of Dynamic Systems, Measurement, and Control, 2020, 142(7).

[2] Casoli P, Scolari F, et al. Energy Comparison between a Load Sensing System and Electro-Hydraulic Solutions Applied to a 9-Ton Excavator. Energies 15. 7(2022).

[3] Zongxia Jiao, Zhenyu Wang, et al. Multi-parameter load sensing pump model simulation and flow rate characteristics research [J]. Chinese Journal of Aeronautics, 2022, 35(12):296-308.

[4] Cheng Min, Zhang Junhui, et al. An Electrohydraulic Load Sensing System based on flow/pressure switched control for mobile machinery [J]. ISA Transactions, 2020, 96367-375.

[5] Lin T L, Lin Y Z, Et al. A double variable control load sensing system for electric hydraulic excavator[J]. Energy, 2021, 223(May 15):119999. 1-119999. 13.

[6] Shen H J, Tao L. Optimization Design and Simulation Analysis of Load-sensing Hydraulic System of Loader[J]. Chinese Hydraulics & Pneumatics. 2022, 46, 117–123.

[7] Li G H, Lu Y F. Research on Energy Saving Technology of Load Sensitive Variable Steering System for Vehicles. International Journal of Plant Engineering and Management 25. 01(2020):24-35.

[8] Anil C Mahato, Sanjoy K Ghoshal. Energy-saving strategies on power hydraulic system: An overview[J]. Proceeding of the Institution of Mechanical Engineers, Part I. Journal of Systems and Control Engineering, 2021, 235(2): 147-169.

[9] Chen Y Z, Ge Y J, et al. Anti-Flow Saturation Method of Load Sensitive Proportional Multi-Channel Valve for Construction Machinery [J]. Mechanical Engineering & Automation, 2022(4):32-34.

[10] Li R C, Sun Q Y, et al. Review of Flow-Matching Technology for Hydraulic Systems. Processes 10. 12(2022).

[11] Luo Y, Chen W, Chi B. Modeling and Simulation Analysis of Pre-Valve Compensation of Flow-saturated Resistant System [J]. IOP Conference Series: Materials Science and Engineering, 2020, 735(1).

[12] Cheng M, Li L N, et al. Real-Time Anti-Saturation Flow Optimization Algorithm of the Redundant Hydraulic Manipulator. Actuators 2021, 10. 11.

[13] Wang G, Tao, L. Energy saving Design and AMESim Simulation Analysis of Load Sensitive Hydraulic System[J]. Machine Tool & Hydraulics. 2021, 49, 164–168.

[14] Karem Abuowda, Ivan Okhotnikov, et al. A review of electrohydraulic independent metering technology, ISA Transactions, Volume 98, 2020, Pages 364-381, ISSN 0019-0578.

[15] Cao B Z. Research on the Flow-Saturated Resistant Control Technology of Load-Sensing Hydraulic System[D]. Dalian University of Technology, 2009

[16] Chen W, Luo Y L, et al. Characteristics research on hybrid load-sensing control system [J]. Machine Tool & Hydraulics, 2021, 49(6):114-117, 128

[17] Walvoil S. P. A. Anti-saturation directional control valve composed of two or more sections with pressure selector compensators: US20040919346 [P]. 2007-02-27.

[18] Eaton Corporation. Anti-saturation valve assembly for load sensing hydraulic system:US20050658134[P]. 2011-01-11.

[19] Wang X, Cao B Z, Song X G, et al. Flow-saturated Resistant Control Simulation of Load-sensing System[J]. Machine Tool & Hydraulics, 2010, 38(7):103-105, 98.

[20] Chang Y H, Zhou J. Analysis of Pre-valve Compensation Flow Anti-saturation Technology in Mine Load Sensing

System [J]. Machine Tool & Hydraulics, 2022, 50(10):129-132.
[21] Allen J D. Adjustable, Metered, Directional Flow Control Arrangement[P]. U. S. Patent. 3, 455, 210. 1969-7-15.
[22] Gu L Y, Xie Y J. Multi-actuators load sensing system[J]. Machine tool & Hydraulics, 2001(3):3-6
[23] Wang W P, Zhou J. Hydraulic systems for Walking construction machinery - Linde Synchronous Control System (LSC) [J]. Construction Machinery and Equipment, 1996(03):21-24.
[24] Zhang S S, Liu Z. Analysis of Linde Synchronous Control System[J]. Power Generation Techology, 2004, 025 (B10):10-11, 74. DOI: CNKI:SUN:SLJX. 0. 2004-S1-004.
[25] Breeden R H. Development of a High Pressure Load Sensing Mobile Valve[M]. Society of Automotive Engineers, 1981: 32-35.
[26] Husco International, INC. Post pressure compensated unitary hydraulic valve:US19860904798[P]. 1987-09-15.
[27] Yang H Y, Liu W, Xu B, et al. Characteristic Analysis of Electro-hydraulic Flow Matching Control System in Hydraulic Excavator [J]. Journal of Mechanical Engineering, 2012, 48(14):156-163.
[28] Yuan D, Yu C, et al. Variable speed electro-hydraulic flow matching control of truck crane[J]. Journal of Mechanical & Electrical Eegineering, 2022, 39(8):1168-1174.
[29] Li Q K, Ke J, Yang Z J, et al. Research on Flow Matching of LUDV Hydraulic System of Electrical Excavator [J]. Machine Tool & Hydraulics, 2021, 49(19):129-134.
[30] Guo K, Luo Y R. Study on flow distribution characteristics of multiway valve with compound action in LUDV [J]. Construction Machinery, 2021(06):35-38.
[31] Tao L, Xu H W, et al. Optimal Design and AMESim Simulation of the After-valve Compensation Load Sensitive Hydraulic System [J]. Machine Tool & Hydraulics. 2021, 49, 150–153.
[32] Liu W, Xu B, Yang H Y, et al. The characteristics of electrohydraulic flow matching control system for excavators based on LUDV multi-way valve [J]. Journal of Zhejiang University (Engineering Science), 2012, 46(08):1360-1368.
[33] Guo K, Luo Y R. Study on flow distribution characteristics of multiway value with compound action in LUDV[J]. Construction Machinery, 2021(6):35-38.
[34] Huang Z Y, Yang Y Z. Toshiba innovation breed-off load sensing to hydraulic system of excavator[J]. Construction Mechanization, 2005, 26(5):29-31.
[35] Shi J Q, Zhang J X et al. Speed Stability of Valve Control Cylinder Hydraulic System Under Variable Load Conditions [J]. Chinese Hydraulics & Pneumatics. 2020, 4, 153–159
[36] Chen G R, Wang J Z, et al. The Separate Meter in Separate Meter Out Control System Using Dual Servo Valves Based on Indirect Adaptive Robust Dynamic Surface Control [J]. Journal of System Science & Complexity, 2019, 32, 557–576
[37] Mikko Huova, Jyrki Tammisto, Matti Linjama. Open-loop Independent Metering Control of a Multi-DOF Forwarder Boom [J]. International Journal of Fluid Power, 2020, 21(2):147-168.
[38] Cao X M, Yao J, et al. Control performance and energy saving of multi-level pressure switching control system based on independent metering control[J]. High Technology Letters, 2020, 26(2):224-234.
[39] Zhang G T. Study on independent metering control valve and system[D]. Yanshan University, 2019.
[40] Zhong Q, Bao H M, et al. Investigation into the Independent Metering Control Performance of a Twin Spools Valve with Switching Technology-controlled Pilot Stage[J]. Chinese Journal of Mechanical Engineering, 2021, 34(05):242-258
[41] Nguyen Thanh Ha, Do Tri Cuong, et al. High Tracking Control for a New Independent Metering Valve System Using Velocity-Load Feedforward and Position Feedback Methods[J]. Applied Sciences, 2022, 12(19).
[42] Zhang P, Guo, Z J. Characteristics and Simulation Analysis of Load Sensitive Hydraulic System with Independent Throttle Control. Chinese Hydraulics & Pneumatics. 2021, 45, 82–86.
[43] Liu K L, Gao Y J, et al. Energy Saving Analysis of the Independent Metering System with Mechanical Hydraulic Pressure Compensated Method [J]. Machine Tool&Hydraulics, 2018, 46(20):49-52.
[44] Zeng Y S, Huang H, et al. Energy saving analysis of the independent metering system based on pressure compensated method in the offside [J]. Machine Tool & Hydraulics, 2022, 50(13):1-6.