Research on Optimal Control of Excavator Negative Control System Based on Secondary Controllable Main Valve

WENBO FU$^{1,2}$, XIAOMING YUAN$^{1,2}$, YONGQUAN LI$^{1,2}$, LIJIE ZHANG$^{1,2}$

1Hebei Key Laboratory of Heavy Machinery Fluid Power Transmission and Control, Yanshan University, Qinhuangdao 066004, China
2Key Laboratory of Advanced Forging and Stamping Technology and Science, Ministry of Education of China, Yanshan University, Qinhuangdao 066004, China

Corresponding author: LIJIE ZHANG (zhangljys@126.com)

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ABSTRACT In order to optimize the energy efficiency and action coordination of negative control excavators, a secondary control circuit of main valve is proposed, which sets an electric proportional pressure reducing valve between joystick-pilot valve and main valve, so that main valve opening can be adjusted twice according to the actual working conditions to meet system control requirements. This paper takes the swing-dipper system as the research object, and studies the overload action and compound action of swing motor and dipper cylinder. In order to reduce the overflow caused by overload, an on-demand flow control strategy is designed to match the pump-valve flow with the demand flow of actuators. In order to solve the problem of uncoordinated compound actions caused by load difference, a flow-ratio control strategy is designed to make the flow ratio of actuators equal to the stroke ratio of joysticks. The system performance test of a 37-ton excavator was carried out, and a simulation model of the swing-dipper system was built. Based on the test and model, the two control strategies were simulated, and the results indicate that, compared with the original hydraulic main valve, the proposed secondary controllable main valve and its control strategies can reduce the motor/pump overflow when the motor/cylinder is overloaded, and can adjust the actuator flow ratio when the excavator performs a compound action, thereby improving the energy saving and manipulation performance of the excavator.

INDEX TERMS Negative control excavator, secondary control, main valve, on-demand flow, flow ratio.

I. INTRODUCTION

Excavator is a typical construction machine with multiple actuators, and it has the characteristics of frequent compound actions, difficult operation and high energy consumption. With the rapid economic development and the emergence of global energy problems, people have higher and higher requirements for manipulation performance [1]-[2] and energy saving of excavators [3]-[4]. The mode that a single pump provides hydraulic oil for multiple actuators is widely used in excavators [5], however, the pump flow always preferentially flows to the lighter-loaded actuator, which makes the coordination of multiple actuators worse and affects the experience of operators. In addition, when the actuator load is large but its flow demand is relatively small, the system is prone to flow mismatch and overflow, which reduces the fuel economy. Therefore, it is of great significance to carry out research on the optimal control of action coordination and energy efficiency of excavators.

The large load difference is the main factor for the uncoordinated actions of multiple actuators. The load sensing system [6]-[8] uses pressure compensation valves to control the pressure drop of each main valve to a constant value, so that the main valve flow is only related to its opening to ensure the action coordination, but this prevents operator from getting load information feedback from joysticks [9]. The electro-hydraulic flow matching control system [10] or the individual metering control (IMC) system adjusts main valve opening by calculating its flow in real time, which can make the main valve flow ratio equal to the joystick stroke ratio [11]-[13]. All in all, we consider that controlling the flow ratio of work units is the key to optimizing the coordination of multiple actuators.
Affected by the load characteristics and the operator-input characteristics, it is difficult to match the supply flow with the demand flow of actuators in real time, which increases the pressure and flow loss in the excavator system. Gao et al. proposed a compound control strategy for the pump displacement of negative flow control (NFC) system [14]-[15], which combines the advantages of NFC, positive flow control [16]-[17], and load sensing control to improve the responsiveness, load adaptability and energy efficiency of the system. Huang W. et al. proposed an excavator swing control strategy based on IMC technology, which limits the inlet pressure and outlet pressure of swing motor by adjusting the IMC valves, which can effectively reduce the pressure and flow loss of the swing system [18]. All in all, we consider that controlling the pump-valve supply flow to adapt to the demand flow of actuators is the key to optimizing the energy efficiency of excavators.

The NFC system is widely used in excavators due to its simple structure [19]-[21], and has a good market reputation due to its excellent performance. However, most NFC systems are equipped with hydraulic main valves, it is difficult for the human-joystick stroke to match the flow demand in real time, and it is difficult to adjust main valve opening according to actual working conditions, so that it is necessary to further improve the coordination and energy efficiency of NFC excavators. Hence, this paper proposes a secondary controllable electro-hydraulic main valve to replace the hydraulic main valve, and designs an on-demand flow control strategy and a flow ratio control strategy for overload actions and compound actions respectively, thereby improving the system performance of NFC excavators.

II. SYSTEM PRINCIPLE

The electro-hydraulic NFC system proposed in this paper mainly includes the NFC hydraulic circuit and the secondary control circuit of main valves, as shown in Fig. 1.

The NFC circuit mainly includes main pump, NFC controller, main valves and actuators, the NFC controller adjusts the pump displacement according to the negative feedback pressure, and limits the bypass flow of main valve within a certain range. As the main valve opening increases, the bypass flow and negative feedback pressure decrease, and the pump displacement is increased. Conversely, as the main valve opening decreases, the negative feedback pressure increase, and the pump displacement is reduced. Thus, the NFC enables the pump to provide flow according to the flow demand of main valve.

The secondary control circuit mainly includes pilot pump, joystick-pilot valves, electric proportional pressure reducing valves (PRVs), pressure sensors and PRV controller. Compared with the traditional pilot circuit of hydraulic main valve, the secondary control circuit only adds a normally opened PRV between the joystick-pilot valve and the main valve, as shown in Fig. 1. The PRV controller can adjust the joystick-pilot pressure twice by controlling the PRV, thereby adjusting the main valve control pressure/flow area to adapt to system control requirements.

This secondary controllable main valve scheme can be used to retrofit hydraulic main valves that have been installed on NFC excavators.

![Hydraulic schematic of electro-hydraulic NFC system.](image)

The frequency response of main valve is much greater than the operating frequency of actuator, so the control characteristics of main valve pilot circuit can be ignored. And then, the relationship between joystick stroke $Y$ and its pilot pressure $p_Y$ can be expressed as

$$Y = k_Y p_Y$$

where $k_Y$ is a constant.

Ignoring the flow force, inertial force and friction force, the force balance equation of main valve spool can be expressed as

$$p_c A_c = k_s (X_v + X_o)$$

where $p_c$ is the control pressure of main valve, $A_c$ is the end area of main valve spool, $k_s$ is the spring stiffness, $X_v$ is the spool displacement of main valve, $X_o$ is the main valve overlap corresponding to zero displacement.

According to (2), the relationship between main valve opening and its control pressure can be expressed as

$$X_v = \frac{A_c}{k_s} (p_c - p_o)$$

where $p_o$ is the control pressure that makes the valve overlap equal to zero.

The main valve flow characteristic equation is

$$Q_v = K_v A_f \sqrt{p_p - p_l}$$

where $K_v$ is the comprehensive flow coefficient, $A_f$ is the flow area of main valve, $p_p$ is the valve inlet pressure/pump pressure, $p_l$ is the valve outlet pressure/load pressure.

In actual application, main valve opening is approximately proportional to its flow area within a certain opening range,
and the relationship between them can be approximately expressed as

$$A_f = K_f X_v$$  \((5)\)

where \(K_f\) is proportional gain of valve opening-flow area link.

Here, let the coefficient \(K_{of}\) satisfy (6).

$$K_{of} = K_v K_f$$  \((6)\)

Combining (4), (5), and (6), the relationship between main valve flow and its opening can be expressed as

$$Q_v = K_v X_v \sqrt{p_p - p_L}$$  \((7)\)

### III. CONTROL STRATEGY

During the construction of the NFC excavator, there are many swing actions and dipper actions. However, the system overload condition occasionally occurs in the excavator’s typical working cycle, and the swing-dipper system often overflows excessively due to overload. Moreover, the swing-dipper compound actions are not coordinated enough, which is due to the mismatch between the actual actuator flow ratio and joystick-control demand. Therefore, this paper analyzes the overload actions and compound actions of the system, and designs an on-demand flow control strategy and a flow-ratio control strategy to optimize the energy efficiency and action coordination of NFC excavator.

#### A. ON-DEMAND FLOW CONTROL

The system performance characteristics of swing motor overload condition and dipper cylinder overload condition are different. And then, the following two on-demand control strategies for the two actuators are designed.

1) MOTOR OVERLOAD

During the acceleration of swing motor, due to the huge inertia load, the motor is overloaded, and it cannot fully absorb all the main valve flow, and the excess flow flows back to oil tank through motor relief valve, which causes motor overflow.

Hence, the on-demand flow control strategy of swing motor is designed as follows, the controller recognizes the motor overload condition by monitoring its inlet pressure, and reduces main valve opening by controlling PRV to limit the inlet pressure, thereby reducing the overflow, as shown in Fig. 2.

When swing motor is overloaded, its inlet pressure \(p_{Ls}\) exceeds the limit pressure \(p_{mrelief}\) of motor relief valve.

$$p_{Ls} \geq p_{mrelief}$$  \((8)\)

When the system working condition meets (8), the PRV controller takes \(p_{mrelief}\) as desired value, and adopt PI control for the PRV to reduce the control pressure of swing valve, thereby reducing the flow from the valve into swing motor. The PI control signal \(u_s\) can be expressed as

$$u_s = k_{pswing} e_s + k_{iswing} \int e_s \, dt$$  \((9)\)

where \(e_s\) is the control deviation, \(k_{pswing}\) is the proportional coefficient, and \(k_{iswing}\) is the integral coefficient.

The block diagram of the on-demand flow control strategy when the swing motor is overloaded is as follows.

#### FIGURE 2. On-demand flow control of swing motor.

2) CYLINDER OVERLOAD

When the dipper moves, there is always the case that dipper cylinder piston moves to its limit position or the cylinder is overloaded. In this case, the demand flow of the cylinder is equal to zero, and the excess pump flow can only flow back to oil tank through the relief valve, which causes pump overflow.

Hence, the on-demand flow control strategy of dipper cylinder is designed as follows, the controller recognizes the cylinder overload condition by monitoring the outlet and inlet pressure of dipper cylinder, and reduces main valve opening by controlling PRV to increase the negative feedback pressure, thereby reducing pump displacement and its overflow, as shown in Fig.3.

When the piston moves, the outlet pressure of dipper cylinder is not equal to zero. Then, when the cylinder is overloaded, its piston is stationary, the outlet pressure is equal to zero. Therefore, when the cylinder is overloaded, its inlet and outlet pressure must meet (10).

$$p_{doutlet} \leq 0; \quad p_{Id} \geq p_{ldmax}$$  \((10)\)

where \(p_{doutlet}\) is the outlet pressure of dipper cylinder, \(p_{Id}\) is the inlet pressure of the cylinder, \(p_{ldmax}\) is the preset value for judging whether the cylinder is overloaded, and it is set according to the limit pressure of pump relief valve.

In order to increase the negative feedback pressure and reduce pump displacement, the main valve control pressure \(p_{cea}\) should be reduced to
\[ p_{cd} = p_{cx} \]  \hspace{1cm} (11)

The PRV controller takes \( p_{cx} \) as the desired value, and adopt P control for the PRV to reduce the control pressure of dipper valve, and the control signal can be expressed as

\[ u_{d1} = k_{pd1} e_{d1} \]  \hspace{1cm} (12)

where \( e_{d1} \) is the control deviation, \( k_{pd1} \) is the proportional coefficient.

The block diagram of the on-demand flow control strategy when the dipper cylinder is overloaded is as follows.

\[ p_d = \frac{Q_{dv1} + Q_{dv2}}{Q_{swing}} \]  \hspace{1cm} (14)

where \( p_d \) is the control pressure of dipper valve, \( Q_{dv1} \) is the flow of dipper valve 1, and \( Q_{dv2} \) is the flow of dipper valve 2.

According to (7), \( Q_{dv1} \) can be expressed as

\[ Q_{dv1} = K_vf (p_{cd} - p_{od1}) \sqrt{p_{p1} - p_{ld}} \]  \hspace{1cm} (15)

where \( p_{cd} \) is the control pressure of dipper valve, \( p_{od1} \) is the control pressure of dipper valve 1 corresponding to the zero overlap, \( p_{p1} \) is the working pressure of pump 1.

\[ Q_{dv2} = K_vf (p_{cd} - p_{od2}) \sqrt{p_{p2} - p_{ld}} \]  \hspace{1cm} (16)

where \( p_{od2} \) is the control pressure of dipper valve 2 corresponding to the zero overlap, \( p_{p2} \) is the working pressure of pump 2.

\[ Q_{swing} = K_vf (p_{cs} - p_{os}) \sqrt{p_{p1} - p_{ls}} \]  \hspace{1cm} (17)

where \( p_{cs} \) is the control pressure of swing valve, \( p_{os} \) is the control pressure of swing valve corresponding to zero overlap.

When the dipper joystick-pilot pressure \( p_{yd} \) and the swing joystick-pilot pressure \( p_{ys} \) meet the conditions of (18), the PRV controller can determine that the system is performing a swing-dipper compound action.

\[ p_{yd} \geq \min\{p_{od1}, p_{od2}\}; \quad p_{ys} \geq p_{os} \]  \hspace{1cm} (18)

In order to achieve the flow-ratio control, the control pressure of dipper valve \( p_{cd} \) should be adjusted to \( p_{cdx} \).

\[ p_{cdx} = \frac{p_{yd} (p_{cs} - p_{os}) \sqrt{p_{p1} - p_{ls}}}{p_{ys} (\sqrt{p_{p1} - p_{ld}} + \sqrt{p_{p2} - p_{ld}}) + \frac{p_{od1} (p_{p1} - p_{ld}) + p_{od2} (p_{p2} - p_{ld})}{p_{ys} (\sqrt{p_{p1} - p_{ld}} + \sqrt{p_{p2} - p_{ld}})}} \]  \hspace{1cm} (19)

The PRV controller takes \( p_{cdx} \) as the desired value, and adopt PI control for the PRV in the control circuit of dipper valve. The PI control signal can be expressed as

\[ u_{d2} = k_{pd2} e_{d2} + k_{id} \int e_{d2} dt \]  \hspace{1cm} (20)

where \( e_{d2} \) is the control deviation, \( k_{pd2} \) is the proportional coefficient, \( k_{id} \) is the integral coefficient.
The block diagram of the flow-ratio control strategy when NFC excavator performs a swing-dipper compound action is shown as in Fig. 4.

Combining the on-demand flow control strategy and the flow-ratio control strategy, the block diagram of swing-dipper motion control strategy is shown in Fig. 5. \( u_{PRV/d/s} \) represents the control signal of the PRV in the control circuit of dipper/swing valve.

FIGURE 4. Flow-ratio control of swing-dipper system.

FIGURE 5. Swing-dipper motion control strategy.

IV. TEST AND SIMULATION

In order to verify the feasibility and correctness of the proposed swing-dipper motion control strategy, a simulation model of the swing-dipper system was built based on the hydraulic, structural parameters and multi-way valve test data of a 37-ton NFC excavator provided by the manufacturer, as shown in Fig. 6. Simulations of the overload actions and compound action were carried out, and the operating characteristics of the hydraulic NFC system with hydraulic main valves and the electro-hydraulic NFC system with the secondary controllable main valves are compared and analyzed.

FIGURE 6. Multi-way valve test and system simulation model.
A. OVERLOAD ACTION

When the excavator performs a swing action and the swing motor is overloaded, the operating characteristics of swing system before and after applying the on-demand flow control strategy are shown in Fig. 7. The ramp signal shown in Fig. 7a is used to simulate the actual control signal.

In the original swing system, when the main valve is opened, its flow increased rapidly (Fig. 7a, 7b). However, affected by the load inertial, the swing motor could not fully absorb the valve flow (Fig. 7b), resulting in excessive motor overflow (Fig. 7d).

In the optimized swing system, when the motor is overloaded during acceleration, the main valve control pressure is adjusted and reduced by PRV (Fig. 7a), so that the valve flow is adapted to the flow absorption capacity of the motor (Fig. 7c), and the motor overflow is greatly reduced (Fig. 7d).

![Control pressure](image1)

![Flow vs. time](image2)

![Optimized flow vs. time](image3)

![Motor overflow](image4)

**FIGURE 7.** Operating characteristics of swing system.

When the excavator performs a dipper action and the dipper cylinder is overloaded, the operating characteristics of dipper system before and after applying the on-demand flow control strategy are shown in Fig. 8.

In the original dipper system, a large load is applied to the dipper cylinder at 2s, the outlet pressure of the cylinder rapidly drops to zero (Fig. 8b), and the piston rod of the cylinder stops moving (Fig. 8c). At this time, the inlet pressure of the cylinder reaches the maximum pressure limited by pump relief valve, and almost all of the pump flow flows back to oil tank through pump relief valve, resulting in excessive pump overflow (Fig. 8d).

In the optimized dipper system, when the cylinder is overloaded at 2s, the control pressure of dipper valve is reduced to a certain value by PRV (Fig. 8a), and the pump flow and overflow are greatly reduced (Fig. 8d). In addition, there is still a certain pump overflow in the system, so that the system can maintain sufficient supply pressure to overcome the external load of the cylinder.
B. COMPOUND ACTION

When the excavator performs a swing-dipper compound action, the operating characteristics of the swing-dipper system before and after applying the flow-ratio control strategy are shown in Fig. 9. The ramp signal shown in Fig. 9a is used to simulate the actual control signal.

In the original system, during the compound action, the working pressure of swing motor is greater than that of dipper cylinder (Fig. 9b), and the flow of pump 1 is preferentially flow to the cylinder (Fig. 9c). At about 2.5s, the cylinder reaches its limit position (Fig. 9e) and its inlet pressure exceeds the limit pressure of system. At this moment, pump 1 continues to supply oil for swing motor, while the flow of pump 2 flows back to oil tank through pump relief valve (Fig. 9f).

In the optimized system, between 0.5s and 5s, PRV is used to adjust the control pressure of dipper valve, so that the flow ratio of the two actuators is approximately equal to 1, which is flow-ratio control. In addition, after the piston rod of dipper cylinder reaches its limit position at about 5s, the PRV controller adopts the on-demand flow control for the cylinder to reduce the overflow of pump 2 (Fig. 9f).
V. CONCLUSION
The existing NFC swing-dipper system has low energy efficiency and poor coordination. For this reason, this paper proposed a secondary controllable main valve, designed an on-demand flow control strategy and a flow-ratio control strategy, carried out system simulations based on a 37-ton excavator. Compared with the original system, the electro-hydraulic NFC system with the secondary controllable main valve has the following advantages.

When the swing motor is overloaded, the overload condition can be identified by detecting the motor inlet pressure, and the control pressure of swing valve can be adjusted twice to reduce the flow supply of pump-main valve, thereby limiting the inlet pressure and motor overflow.

When the dipper cylinder is overloaded, the overload condition can be identified by detecting the outlet/inlet pressure of the cylinder, and the control pressure of dipper valve can be adjusted twice to increase the negative feedback pressure of the NFC system, thereby reducing the pump displacement and pump overflow.

When the excavator performs a swing-dipper compound action, the control pressure of lighter-loaded valve can be reduced to increase its pressure drop and eliminate the load difference between swing motor and dipper cylinder, so that the actuator flow ratio is equal to the joystick stroke ratio, thereby improving the coordination of the swing-dipper compound action.

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WENBO FU is currently pursuing the Ph.D. degree in mechanical engineering at Yanshan University, Qinhuangdao, China. His research interests mainly include multi way valve of excavator, digital simulation of hydraulic system, performance optimization of multi-actuator hydraulic systems, innovative design of hydraulic system. Applications are in construction machines and road vehicles.

XIAOMING YUAN received the Ph.D. degree in mechanical engineering from Yanshan University, Qinhuangdao, China, in 2015. He was a postdoctoral in XCMG Construction Machinery from 2015 to 2018. Since 2020, he has become an associate professor in Yanshan University. He is a Senior Member of the Chinese Mechanical engineering Society (CEMS). His research interests include fluid-structure interaction dynamics, fluid transmission and control.

YONGQUAN LI received the Ph.D. degree in mechanical engineering from Yanshan University, Qinhuangdao, China, in 2013. Since 2017, he has become an associate professor in the School of Mechanical Engineering, Yanshan University. He is a Senior Member of the Chinese Mechanical engineering Society (CEMS). His research interests include mechanics and robotics, hydraulic control, performance optimization, and innovative design of hydraulic system.

LIJIE ZHANG received the Ph.D. degree from the School of Mechanical Engineering, Yanshan University, Qinhuangdao, China. He has become a professor/postdoctoral supervisor in the School of Mechanical Engineering, Yanshan University. He is a Senior Member of the Chinese Mechanical Engineering Society (CEMS) and a Review Expert of the National Natural Science Foundation of China (NSFC). His research interests include the reliability and fault diagnosis of hydraulic components, multi-physics coupling analysis, and mechanics and robotics.