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Research on Maneuverability Optimization of Negative Control Excavator

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ABSTRACT In order to improve the swing braking stability and flow distribution characteristics of negative control excavator, this paper proposes a hybrid electro-hydraulic main valve, which sets a pressure reducing valve in each of the two control chambers of main valve to adjust its control pressure difference, so that the valve opening can be adjusted to optimize the excavator maneuverability. For the braking oscillation tendency of swing action, an anti-reverse control strategy is designed, which actively releases the motor brake pressure by adjusting the flow area of oil return orifice, thereby preventing the brake pressure from outputting power to the motor in the reverse direction. For the uncoordinated flow distribution of swing-boom compound action, an action priority control strategy is designed, which redistributes the dual-pump flow to swing motor and boom cylinder according to the operator's manipulation needs. Based on the key hydraulic-structural parameters and test data, a simulation model of a 37-ton negative control excavator that can accurately simulate the swing action and boom lifting action is built, and the system operating characteristics before and after optimization are analyzed, the results show the proposed control strategies can suppress the swing rebound phenomenon and improve the controllability of actuator flow ratio.

INDEX TERMS Excavator, electro-hydraulic valve, swing braking stability, flow distribution, optimization.

I. INTRODUCTION

Excavator is an important multi-actuator construction machinery, with the development of social economy and the upgrading of human-machine friendly interaction, people have higher and higher requirements for maneuverability of excavators [1]–[3]. Negative flow control (NFC) system is widely used in excavator due to its simple structure [4]–[6], however, it mainly suffers from poor stability and uncoordinated actions, which seriously affects the operator's manipulation experience. Therefore, it is of great significance to carry out research on the maneuverability optimization of NFC excavators.

The poor swing braking stability is a significant excavator performance issue, which seriously affects the excavator operating comfort. In addition, excessive oscillation can reduce the reliability of swing system [7]. Although the swing motor is equipped with an anti-reverse valve, it still suffers from motor flow oscillations. In order to improve the swing braking stability, many researches have been carried out. Qin *et al.* proposed a dual power source coordinated control strategy of hydraulic-electric hybrid swing system, which can effectively suppress the swing rebound phenomenon by synchronously controlling the servo motor and hydraulic motor [8]. Lee *et al.* proposed a fuzzy logic control method with feedback based on independent metering control (IMC) technology, which improves the swing braking stability by adjusting the pressure difference between the motor inlet and outlet [9]. Zhang *et al.* proposed a new swing valve spool structure, which can open the flow channel between swing motor and oil tank to release the braking pressure by appropriately changing the spool position, thereby suppressing the swing rebound and oscillation [10]. Wang and Quan proposed an active damping method, which pre-calculates the arrival time of peak pressure and adjusts the variable damping valve used to adjust the system damping accordingly, thereby attenuating valve-controlled motor impact [11]. Jin *et al.* proposed a sliding mode control method for suppressing the swing vibration of electric swing motor, which designs a sliding mode observer is designed to estimate the system states,

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and designs a sliding mode controller to control the motor, so as to improve the swing stability of hybrid excavator [12]. In general, the above control technologies can effectively improve the braking stability of swing motor, however, they require modifications to the hydraulic control circuit or main control valve structure, which makes it difficult for them to be directly applied to NFC systems.

In the multi-way valve system, pump flow always preferentially flows to the lighter-loaded actuator [13], which is not the flow distribution characteristic the operator wants. The uncoordinated flow distribution can lead to a serious mismatch between joystick stroke ratio and actuator speed ratio [14], which makes the operator need to adjust the joystick frequently to obtain better action coordination, and this increases the operator's labor intensity and reduces the operating comfort. Therefore, when the excavator performs multi-actuator compound actions, the coordination of flow distribution is particularly important, and it is better that the system can set the flow ratio of the actuators according to the operator's manipulation needs. In order to make the excavator get excellent flow distribution characteristics, the researchers mainly studied the following systems. Load sensing system uses pressure-compensated valve to eliminate the large load difference between the actuators, so that the main valve flow is only related to its opening [15], [16]. The displacement-controlled system configures a variable displacement pump for each actuator, and uses pump displacement to control actuator motion, which makes each actuator-load not interfere with each other [17], [18]. The IMC system electronically adjusts the opening of independent metering valve according to the joystick stroke-flow demand, and obtains a good flow distribution characteristic [19], [20]. The common pressure rail (CPR) system makes each actuator absorb energy from the constant pressure oil source by adjusting the displacement of hydraulic transformer, the displacement of variable displacement motor and the number of driving chambers of multi-chamber cylinder, and this transmission method eliminates the interference between different actuators [21], [22]. All in all, the above system technologies have good flow distribution characteristics, but it is difficult to apply them to NFC system. Coincidentally, the NFC system uses priority valves to prioritize boom/swing action over other actions [23], which improves the system flow distribution coordination, however, this increases the application cost of priority valve and makes the structure of multi-way valve more complex. In addition, there are few researches on how to adjust the priority of boom or swing action in real time.

Generally, the existing NFC multi-way valve is designed according to the working conditions of the excavator, but it is still difficult to adapt to some working conditions, such as swing braking conditions, and compound action conditions, so that it suffers from poor swing braking stability and uncoordinated flow distribution. For this reason, this paper takes the swing-boom system of a 37-ton NFC excavator as the research object, proposes a hybrid electro-hydraulic main valve which can be refitted from a hydraulic main valve, designs an anti-reverse control strategy and an action priority control strategy to optimize the maneuverability of the NFC excavator.

II. SYSTEM PRINCIPLE

A. SWING-BOOM NFC SYSTEM

The swing-boom NFC system studied in this paper is a dual pump dual circuit system, and it mainly includes two NFC pumps and its controller, two (open-center) boom valves, a swing valve, a swing motor and two boom cylinders, as shown in Fig. 1. The pump 1 supplies flow to boom valve 1 and swing valve, and the pump 2 only supplies flow to boom valve 2. The NFC controller adjusts the pump displacement in a negative linear relationship with the negative feedback pressure, so that the pump can provide the corresponding flow according to main valve opening. However, the valve opening is randomly adjusted by human-joystick, and this artificial operation is often difficult to make the valve opening match the system control requirements in real time. Therefore, it is necessary to perform auxiliary adjustment on the valve opening at an appropriate time. Hence, from the perspective of upgrading the original hydraulic valve, we propose a hybrid electro-hydraulic valve.

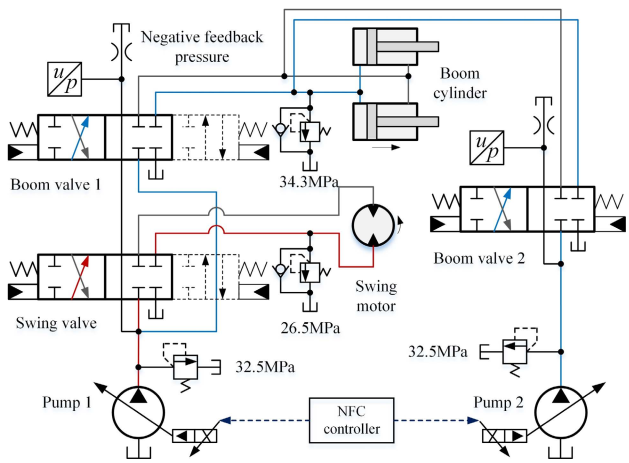

FIGURE 1. Hydraulic schematic of swing-boom NFC system.

B. HYBRID ELECTRO-HYDRAULIC VALVE

The working principle of hybrid electro-hydraulic main valve is shown in Fig. 2. It replaces the hydraulic pilot control circuit with a hybrid electro-hydraulic pilot control circuit to adjust the valve opening. Compared with the original hydraulic valve, the hybrid electro-hydraulic valve is equipped with a pressure reducing valve (PRV) in each of its two control sides, and a PRV controller is added.

In Fig. 2, the side where the pilot valve is opened is defined as the main control side, and the other side is defined as the auxiliary control side. The PRV controller can increase main valve opening by adjusting the main control pressure

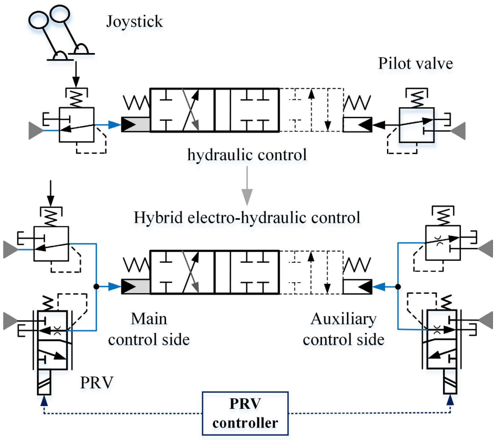

FIGURE 2. Hybrid electro-hydraulic main valve.

at the main control side. Similarly, the PRV controller can reduce main valve opening by adjusting the auxiliary control pressure at the auxiliary control side, which is used to offset the main control pressure.

In other words, the PRV controller adjusts the valve spool displacement by adjusting the pressure difference between the two control chambers of main valve, which makes the valve opening can be adjusted arbitrarily according to the control requirements. The working principle of hydraulic valve and hybrid electro-hydraulic valve can be expressed as (1) and (2).

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

$$p_v A = k_s X_v \tag{1}$$

where p_v is the control pressure of hydraulic valve, A is the spool end area of the valve, k_s is the stiffness of return spring, X_v is the spool displacement of the valve.

The spool force balance equation of the hybrid electro-hydraulic valve can be expressed as

$$p_{vmain}A_{main} - p_{vauxiliary}A_{auxiliary} = k_s X_v \tag{2}$$

where p_{vmain} is the main control pressure of hybrid electro-hydraulic valve,$p_{vauxiliary}$ is the main control pressure of the valve, A_{main} is the spool end area on the main control side of the valve, $A_{auxiliary}$ is the spool end area on the auxiliary control side of the valve.

III. CONTROL STRATEGY

This paper analyzes the swing braking action and swing-boom lifting action of the swing-boom NFC system, and designs an anti-reverse control strategy and an action priority control strategy based on the hybrid electro-hydraulic main valve to optimize the working condition-adaptability and maneuverability of NFC excavator.

A. ANTI-REVERSE CONTROL

In the braking process of swing motor, there is a swing rebound phenomenon at the moment when the motor speed is reduced to zero. The reason is that the motor passively releases its brake pressure during its braking process, and the brake pressure at the motor outlet outputs power to the motor in the reverse direction, which makes the motor to reverse and oscillate.

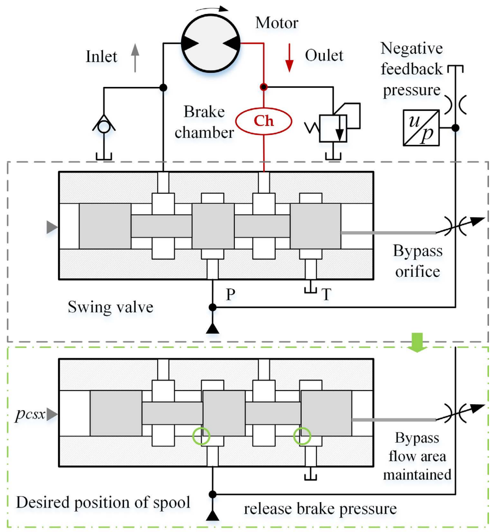

FIGURE 3. Control scheme for motor brake pressure.

In order to suppress the swing rebound phenomenon, an anti-reverse control strategy is designed. The basic idea is to actively release the pressure in the motor brake chamber before the motor speed drops to zero, which can be achieved by adjusting the spool position of the hybrid electro-hydraulic valve and opening the oil return channel of swing motor, as shown in Fig. 3. In addition, it is necessary to set a speed sensor to measure the motor speed, and set a pressure sensor to measure the control pressure of swing valve.

By measuring the size of the spool-orifice, the spool stroke-flow area curve of swing valve can be calculated, as shown in Fig. 4, when the outlet orifice of swing valve is opened, its inlet orifice is also opened at the same time. Therefore, when designing the anti-reverse control strategy, the spool stroke-orifice flow area should be limited to a small value, and the opening time of the orifice should be short enough to ensure that the motor can be fully braked.

When the motor speed meets (3), the control pressure of swing valve should be adjusted to p_{csx}, which can push the spool to the desired position shown in Fig. 3.

$$0 < \omega_m \leq \omega_x \tag{3}$$

where ω_m is the real-time speed of swing motor, ω_x is the preset speed, which is used to judge whether the motor speed is close to zero.

Then, the PRV controller takes p_{csx} as the desired valve and adopts P control for the PRV, as shown in Fig. 5.

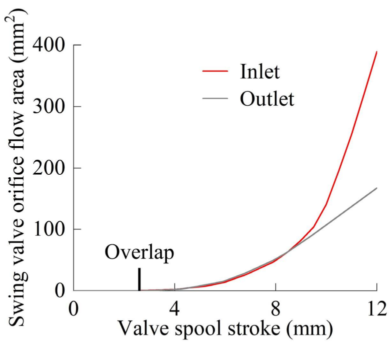

FIGURE 4. **The spool stroke-flow area of swing valve.**

The P control signal u_{s1} can be expressed as

$$u_{s1} = k_{ps1} e_{s1} \tag{4}$$

where e_{s1} is the control deviation, k_{ps1} is the proportional coefficient.

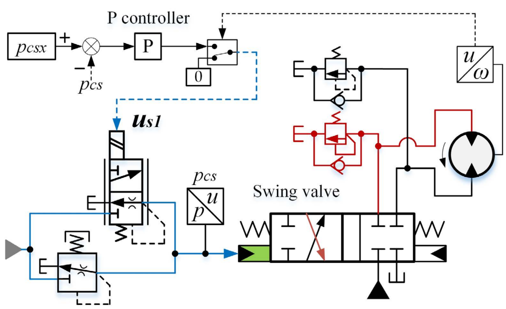

FIGURE 5. **The spool stroke-flow area of swing valve.**

B. ACTION-PRIORITY CONTROL

When the NFC excavator performs swing-boom lifting actions, the operator has different requirements for the speed ratio of swing motor and boom cylinder under different working conditions. However, in the dual pump dual circuit system, the flow ratio of the two actuators is difficult to meet the operator's real-time manipulation needs due to the load difference and the improper flow distribution. As shown in Fig. 1, the flow of pump 2 only flows into boom cylinder, and the flow of pump 1 is distributed to boom cylinder and swing motor according to the actuator load ratio and the main valve opening ratio, which makes the flow ratio of the two actuators uncertain. Therefore, this paper designs an action-priority control strategy, which reduces the flow of the non-priority actuator by reducing the valve opening, so that the excavator can perform swing or boom-priority actions, thereby improving the flow distribution coordination of the dual-pump system. In addition, pressure sensors are required to measure pump pressure, swing motor inlet pressure, boom cylinder inlet pressure, main control pressure and auxiliary control pressure of swing valve and boom valve, as shown in Fig. 6 and Fig. 8.

When the relevant parameters meet (5), it can be determined that the excavator is performing a swing-boom lifting action.

$$p_{cb} > min\left\{p_{ob1}, p_{ob2}\right\}; p_{cs} > p_{os} \tag{5}$$

where p_{cb} is the main control pressure of boom valve, p_{cs} is the main control pressure of swing valve, p_{ob1} is the control pressure that makes the underlap of boom valve 1 equal to zero, p_{ob2} is the control pressure that makes the underlap of boom valve 2 equal to zero, and p_{os} is the control pressure that makes the underlap of swing valve equal to zero.

1) SWING PRIORITY

Swing priority control should allow swing motor to get relatively more pump flow. Considering that the flow of pump 2 only flows into boom cylinder, and in order to increase the motor flow, we can make the flow of pump 1 only flow into the motor, which can be achieved by closing boom valve 1.

When the NFC excavator needs to perform a swing priority action, the operator switches the mode switching control signal C_{mode} to 0.

$$C_{mode} = 0 \tag{6}$$

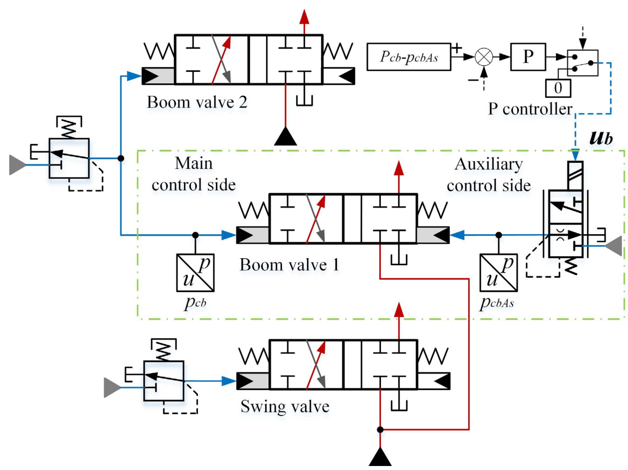

FIGURE 6. **Swing priority control of swing-boom NFC system.**

The PRV controller takes $p_{cb} - p_{cbAs}$ as the desired value, and adopts P control for the PRV at the auxiliary control side of boom valve 1, as shown in Fig. 6. Here, p_{cbAs} is the auxiliary control pressure of boom valve 1, and it is equal to p_{cb}. The P control signal u_{b1} can be expressed as

$$u_{b1} = k_{pb1} e_{b1} \tag{7}$$

where e_{b1} is the control deviation, k_{pb1} is the proportional coefficient.

2) BOOM PRIORITY

Boom priority control should allow boom cylinder get relatively more pump flow. Therefore, we consider that the flow of pump 1 can be distributed to swing motor and boom cylinder according to the stroke ratio of joysticks, and the flow of pump 2 is still only supplied to the cylinder as before.

Ignore the control characteristics of main valve pilot control circuit, the relationship between joystick stroke Y and joystick-pilot pressure p_Y can be expressed as

$$Y = k_Y p_Y \tag{8}$$

where k_Y is the proportional gain.

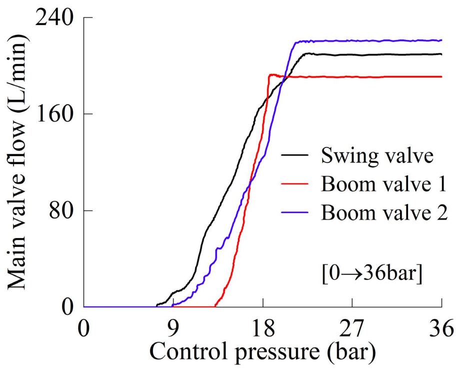

FIGURE 7. Main valve control pressure-flow characteristics.

In practice, according to the main valve control pressure-flow characteristics, as shown in Fig. 7, the valve flow is approximately proportional to its control pressure. Thus, ignoring the flow force, friction force and inertial force, the main valve flow Q_v can be approximately expressed as

$$Q_v = K_{flow} (p_v - p_o) \sqrt{p_p - p_L} \tag{9}$$

where K_{flow} is the comprehensive flow coefficient, p_o is the control pressure that makes the valve overlap equal to zero, p_p is the pump pressure, p_L is the load pressure. In order to achieve boom priority control, the flow Q_{b1} of boom valve 1, and the flow Q_s of swing valve, the boom-joystick stroke Y_b, and the swing-joystick stroke Y_s should meets (10).

$$\frac{Q_{b1}}{Q_s} = \frac{Y_b}{Y_s} \tag{10}$$

Combining (8), (9), and (10), we can get (11).

$$\frac{p_{Yb}}{p_{Ys}} = \frac{(p_{cb} - p_{ob1}) \sqrt{p_{p1} - p_{Lb}}}{(p_{cs} - p_{csH} - p_{os}) \sqrt{p_{p1} - p_{Ls}}} \tag{11}$$

where p_{Yb} is the boom-joystick pilot pressure, p_{Ys} is the swing-joystick pilot pressure, p_{p1} is the pressure of pump 1. When a boom priority action is required, the operator switches the mode switching control signal C_{mode} to 1.

$$C_{mode} = 1 \tag{12}$$

At this moment, the auxiliary control pressure of swing valve should be adjusted to p_{csAb}.

$$p_{csAb} = p_{cs} - p_{os} - \frac{p_{cs} (p_{cb} - p_{ob1}) \sqrt{p_{p1} - p_{Lb}}}{p_{cb} \sqrt{p_{p1} - p_{Ls}}} \tag{13}$$

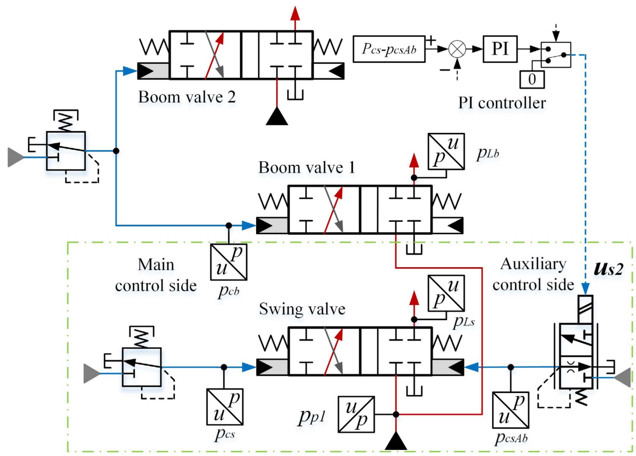

FIGURE 8. Boom priority control of swing-boom NFC system.

The PRV controller takes $p_{cs} - p_{csAb}$ as the desired value, and adopts PI control for the PRV on the auxiliary control side of swing valve, as shown in Fig. 8. The PI control signal u_{s3} can be expressed as

$$u_{s2} = k_{ps2} e_{s2} + k_{is2} \int e_{s2} dt \tag{14}$$

where e_{s2} is the control deviation, k_{ps2} is the proportional coefficient, and k_{is2} is the integral coefficient.

Finally, the control logic of the swing-boom NFC system is shown in Fig. 9. u_{PRVs} is the main control pressure of swing valve, u_{PRVb} is the main control pressure of boom valve, u_{PRVsA} is the auxiliary control pressure of swing valve, u_{PRVbA} is the auxiliary control pressure of boom valve 1.

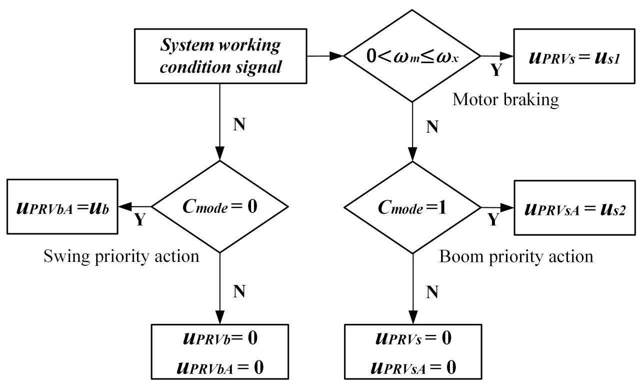

FIGURE 9. The control logic of the swing-boom NFC system.

IV. TEST AND SIMULATION

In order to investigate the correctness and beneficial effect of the proposed maneuverability optimization control strategy, we built a virtual excavator (simulation model) that can accurately simulate the swing action and boom lifting action based on the key parameters and test data of a 37-ton excavator and its NFC multi-way valve (diameter is 32mm), as shown in Fig. 10. Here, the maximum pump displacement

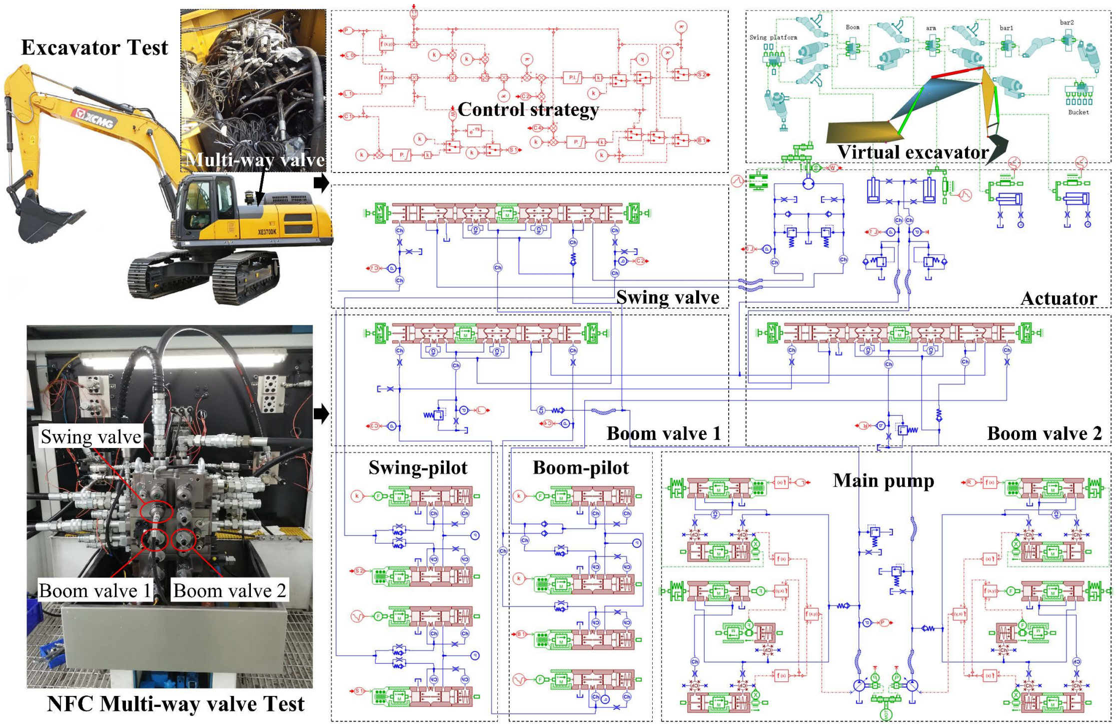

FIGURE 10. Tests and simulations of 37-ton NFC excavator.

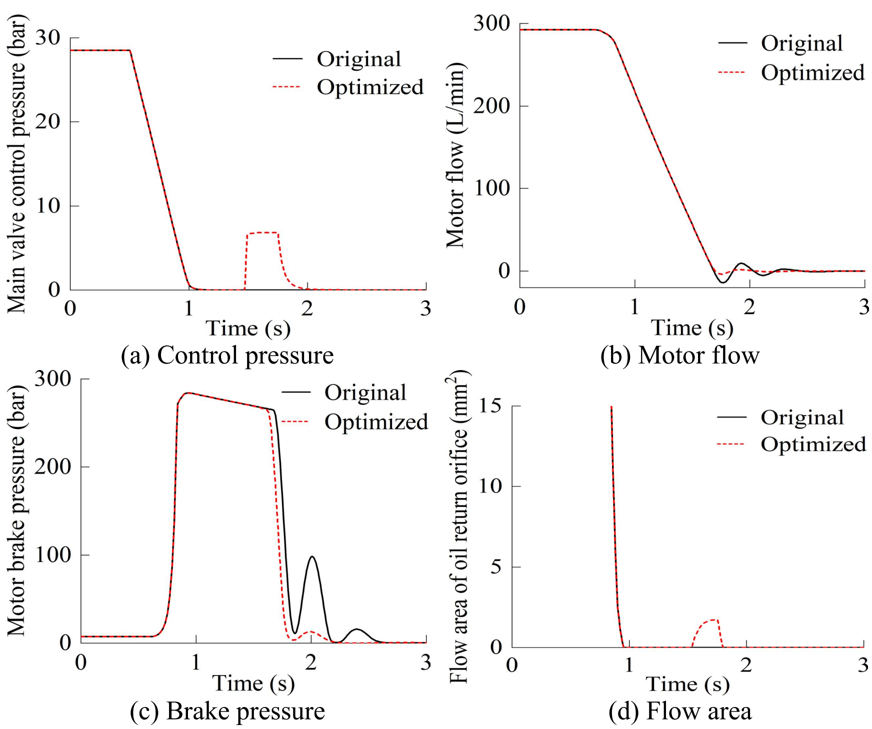

FIGURE 11. The braking characteristics of swing system.

is 160 ml/r, the swing motor displacement is 180 ml/r, and the piston/rod diameter of boom cylinder is 145/100 mm. When the pump speed is 1850 r/min, the swing braking stability and flow distribution characteristics of the swing-boom system before and after optimization are compared and analyzed.

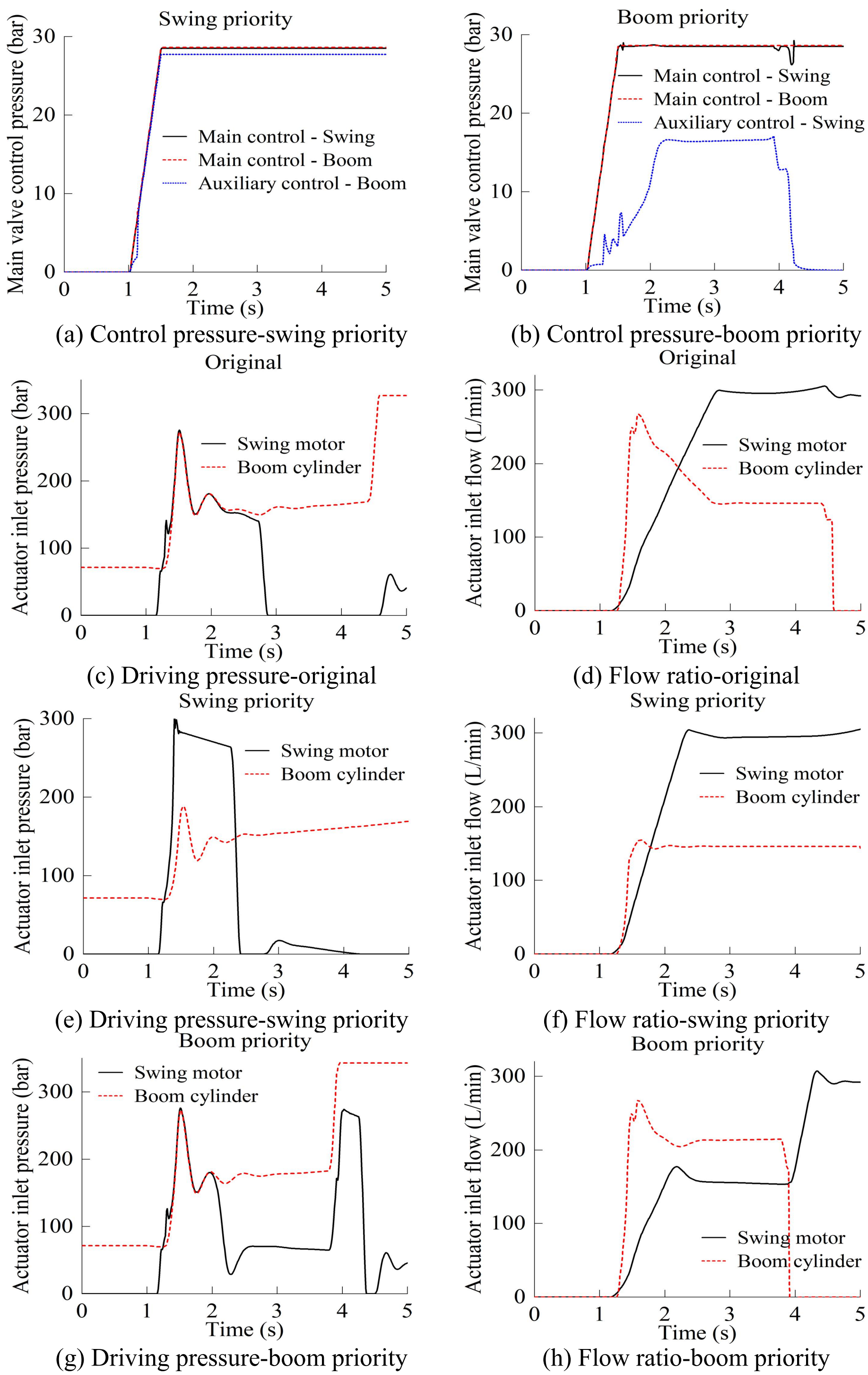

FIGURE 12. The flow distribution characteristics of swing-boom system.

A. SWING BRAKING ACTION

The braking characteristics of the 37-ton NFC excavator swing system before and after applying the anti-reverse control strategy are shown in Fig. 11.

In the original swing system, the swing valve control pressure is rapidly reduced (Fig. 11a), the flow area of motor oil return orifice is rapidly reduced to zero (Fig. 11d), the motor speed drops to zero for the first time at about 1.7s (Fig. 11b), and the brake pressure does work on the motor in the reverse direction, causing the swing rebound phenomenon of the motor pressure and flow oscillation (Fig. 11c, d).

In the optimized swing system, when the motor speed decreases close to zero, the control pressure/flow area of the hybrid electro-hydraulic swing valve is actively adjusted as shown in Fig. 11a, d, so that the channel between motor and oil tank is opened. Thus, the motor brake pressure is released in advance (Fig. 11c), and the swing rebound phenomenon and motor flow oscillations are quickly suppressed (Fig. 11c, d). In addition, the anti-reverse control strategy opens the oil return orifice before the motor speed drops to zero, so the moment when the optimized motor brake pressure begins to drop is relatively early, as shown in Fig. 11c.

B. SWING-BOOM LIFTING ACTION

When the 37-ton NFC excavator performs a swing-boom lifting action, the flow distribution characteristics of the swing-boom system before and after applying the action-priority control strategy are shown in Fig. 12.

Original swing-boom lifting action. The flow of pump 2 only flows into boom cylinder, while the flow of pump 1 flows into swing motor and the cylinder. Due to the huge inertia of the motor load, when the motor speed is low, the flow of pump 1 is mainly distributed to the cylinder, and as the motor speed increases, the flow of pump 1 mainly flows into the motor, as shown in Fig. 12d, which is not the flow distribution characteristic expected by the operator.

When the excavator is required to perform a swing priority action, the auxiliary control pressure of boom valve 1 is increased to offset its main control pressure (Fig. 12a), so that the valve opening is completely closed. At this moment, pump 1 only provides flow to the motor, and pump 2 only provides flow to the cylinder, compared with Fig. 12d, the motor flow is relatively increased. Moreover, the swing priority control can realize the pressure decoupling of the two actuators (Fig. 12e), and their flow no longer interfere with each other due to load difference (Fig. 12c, g).

When the excavator is required to perform a boom priority action, the auxiliary control pressure of swing valve is increased (Fig. 12b) to reduce its opening, and the boom priority control distributes the flow of pump 1 to the two actuators according to the joystick stroke ratio. Compared with Fig. 12d, the cylinder flow is relatively increased. In addition, when the boom cylinder moves to its limit position, all the flow of pump 1 is distributed to the motor, and the motor flow begins to increase (Fig. 12g, h).

V. CONCLUSION

The existing swing-boom NFC system mainly suffers from poor swing braking stability and uncoordinated flow distribution, for this reason, this paper proposes a hybrid electro-hydraulic main valve technical scheme which adjusts the valve opening by adjusting the pressure difference between its two control chambers, designs an anti-reverse control strategy and an action-priority control strategy, and carries out system tests and simulations, the results show the control strategies have the following beneficial effects.

In the braking process of swing motor, the anti-reverse control strategy open the channel between the motor and oil tank by controlling the oil return orifice of the hybrid electro-hydraulic swing valve before the motor speed drops to zero, and the motor brake pressure is actively released in advance, which weakens the motor pressure and flow fluctuations and suppresses the swing rebound phenomenon. In addition, the application of this control strategy does not require modifications of the structure of main valve spool and hydraulic circuit.

When the excavator performs a swing-boom lifting compound action, the action-priority control strategy adjusts the flow ratio of swing motor and boom cylinder according to the operator's manipulation needs by controlling the auxiliary control pressure of the hybrid electro-hydraulic boom/swing valve, that is, the boom valve 1 is closed to allow a single pump to provide flow specifically to swing motor, or the swing valve is adjusted according to the swing-boom joystick stroke ratio to allow the dual pumps to distribute more flow to the cylinder, so as to realize the swing or boom priority control and improve the controllability of actuator flow ratio.

Moreover, the scheme of the hybrid electro-hydraulic valve can be used for electronic modification of hydraulic valve. The proposed anti-reverse control strategy and action-priority control strategy can assist humans in construction under specific excavator working conditions, and play a positive role in improving the maneuverability of NFC excavator.

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