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Velocity and Position Hybrid Control for Excavator Boom Based on Independent Metering System

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ABSTRACT Excavators are widely used in construction, mining, and other projects. However, there are certain environments, such as chemical substance leakage and conflagration sites, which are not suitable for on-site operation. In such situations, the necessity for automatic control and position control is considerably high and it is the development trend of the excavators. In this paper, a position control strategy combined with velocity feedforward is proposed for the excavator boom to achieve position and velocity control simultaneously. Moreover, an independent metering system is introduced to reduce throttling loss. In this work, the controller is designed with two modes—velocity control and position control—based on the difference between the target and real displacements. When the target position is given, if the difference is sufficiently large, the system operates in the velocity control mode. In this mode, the velocity feedforward signal is generated as a designed type to control the cylinder velocity, and the desired trajectory can be obtained by integrating the generated velocity. In order to account for the velocity error and realize trajectory tracking, displacement control is employed to compensate for the velocity feedforward control. During this process, the valve can be fully open to reduce throttling loss. When the boom approaches the target position, the system operates in the position control mode. With this strategy, position control and velocity control can be achieved simultaneously, fast positioning and low energy consumption are also realized. In order to verify the feasibility of the foregoing strategy, a test rig is installed on a 6-t excavator. The test results show that the boom can move smoothly to the target position along the desired trajectory and achieve fast positioning. The investigation can provide some reference for the automatic operation of mobile machinery.

INDEX TERMS Desired trajectory, excavator boom, fast positioning, independent metering system, trajectory tracking, velocity and position hybrid control.

I. INTRODUCTION

A hydraulic excavator is a type of multi-functional engineering machinery that is widely used in construction, mining, and other industries [1]–[3]. In the traditional hydraulic excavator, the operator controls the velocity of the actuator by manipulating the joystick. Evidently, position control and its accuracy are realized based on the operator's visual observation and impression [4]. However, in dangerous environments, this type of operation is not suitable on-site.

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With the development of intelligent mobile machines and more stringent task quality requirements [5]–[9], the necessity for automatic control and position control is considerably high, and this is also the development trend of the excavators. However, the research on the position control of the hydraulic system is mainly focused on the control strategy to reduce the effects of nonlinear parameters and improve the robustness of systems, such as the working systems of metal forming machinery and injection molding machine [10], [11]. And, in the traditional control system of excavators, the difference between the target and the actual positions is used to generate the signal for controlling the opening of the valve, and the pump works in a constant pressure mode [12]–[14].

When the difference between the aforementioned positions is large, the valve fully opens. As this difference decreases, the valves opening decrease which causing the considerable throttling loss. When the difference is small, the velocity also decreases and causes large energy consumptions and slow positionings. In order to improve the position control, Yu et al. [15] added the feedforward compensation controller to improve the position control performance of the system on the basis of position closed-loop control with PID. Li et al. [16] reduced position overshoot by adding a position pseudo derivative feedback control to ensure fast position tracking performance. Chang and Lee [17] achieved the straight-line motion tracking control of hydraulic excavator by adopting Time-delay control as the baseline control, and by enhancing it with compensators on the basis of insights obtained from the plant dynamics.

In the traditional position control system, a servo proportional valve with four-side linkage is employed to control the cylinder and with this valve, the throttling loss is large because the inlet and outlet of the hydraulic cylinder are throttled simultaneously. The independent metering system (IMS) is proposed to solve this problem by decoupling the connection between the meter-in and meter-out orifices of the hydraulic cylinder [18]. Several studies have been conducted on the applications of IMS [19]. For example, on the basis of the independent metering system, Huang et al. [20], Xu et al. [21], Ge et al. [22], and Liu et al. [23] further realize energy saving through coordinating the control of pump and valves. Wang et al. [24] and Choi et al. [25] further achieved energy saving by using flow regeneration. In addition, Lee et al. [26] and Lübbert et al. [27] studied and improved the control strategy of the independent metering system to improve the energy-saving characteristics and operation characteristics of the system. Liu [28], [29] designs an independent metering system based on hydraulic pressure compensation. Despite these investigations, there is practically no relevant research and report about hybrid control of the velocity and position for the excavator boom with IMS.

In this paper, a hybrid control strategy of velocity and position based on the independent metering system is proposed for the excavator boom. With this strategy, once the target position is given, the joystick or intelligent input device generates the velocity curve. And the desired displacement curve is then obtained by integrating the velocity. Then, the velocity and displacement signals are transmitted to the controller. In this work, the controller is designed as having two modes according to the difference between target and real displacement: velocity control mode and position control mode. If this difference is sufficiently large, then the system works in velocity control mode. Here, a closed loop displacement control signal is employed to compensate for the velocity feedforward control to reduce velocity error and realize the real-time tracking of the boom trajectory. When the boom is lifting, the system adopts open-circuit displacement control, and when the boom is falling, the system adopts flow regeneration to realize energy saving. When the

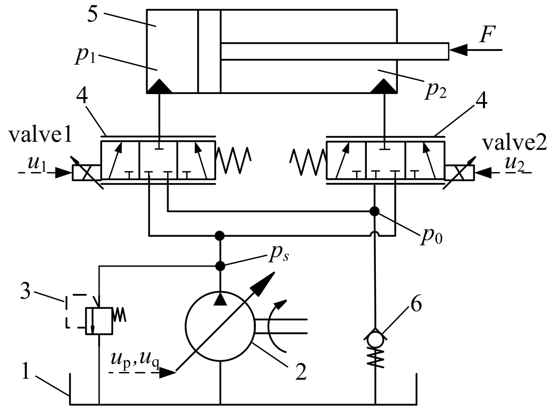

FIGURE 1. Independent metering system for excavator boom. 1-Tank; 2-Pressure and flow control pump; 3-Relief valve; 4-Proportional valve; 5-Hydraulic cylinder; 6- Back pressure valve.

boom approaches the target position, the system works in position control mode which works just like the traditional position control principle. With the proposed hybrid control strategy, fast positioning and low energy consumption are also realized apart from achieving simultaneous position control and velocity control. In addition, operators can complete tasks accurately and smoothly just by focusing on the operation target in the interface instead of relying on their visual observation and personal impression. In order to study the feasibility of the strategy, a test rig is established on a 6-t excavator with IMS. Thereafter, experiments are performed, and the operational characteristics of the excavator boom are analyzed.

The rest of this paper is organized as follows. In section II, the analysis of independent metering principle and the energy consumption characteristics of certain control methods are presented. On the basis of these analyses, appropriate control methods for different working modes are selected. In section III, the hybrid control strategy of velocity and position is introduced in detail. In section IV, relevant tests are performed and the analysis of operational characteristics of the excavator boom are expounded. The conclusion is given in section V.

II. INDEPENDENT METERING SYSTEM FOR EXCAVATOR BOOM

In this paper, the independent metering system (IMS) is adopted for the excavator boom to reduce throttling loss and its principle is shown in Figure 1.

The hydraulic cylinder is controlled by two proportional valves with which the meter-in and meter-out orifices of the hydraulic cylinder can be decoupled to reduce throttling loss. A pressure and flow control pump is utilized to provide power for the system. In Figure 1, F represents the load force on the hydraulic cylinder. Control signals u_1 and u_2 are employed to control the spool displacement of valve 1 and valve 2 respectively. Control signals u_p and u_q are used to control the pressure and flow of the variable pump respectively.

For the boom, there are three different working modes: lifting mode, falling mode and positioning mode, which are recognized by the difference between target position and actual displacement feedback value. The distinction criteria are as follows:

(1) Boom lifting: $|\Delta x| \geq x_{th}$, and $\Delta x > 0$
(2) Boom lowering: $|\Delta x| \geq x_{th}$, and $\Delta x < 0$
(3) Boom positioning: $|\Delta x| < x_{th}$

where x_{th} is the threshold of working modes recognition and it is usually set to a smaller value to reduce the positioning time. Δx is the difference between the target position x_d and actual displacement x_{rea}.

In the process of boom movement, the energy E provided by the pump is mainly used in seven parts: pump efficiency loss E_p, working energy consumption E_L (which is for driving the boom movement), throttling loss E_1 of valve 1, throttling loss E_2 of valve 2, back pressure energy consumption E_T, fluid pipeline loss E_f, and mechanical friction loss E_m. The relationship between them is given by the following:

$$E = E_p + E_L + E_1 + E_2 + E_T + E_f + E_m \tag{1}$$

In this IMS system, the four control signals—u_1, u_2, u_p, and u_q—can be controlled independently and a number of combinations can also be made among them. Hence, there are several different control methods in this control system. Among them, only the four control signals u_1, u_2, u_p, and u_q are different, while the other conditions such as boom mass, load force, velocity, hydraulic pipeline and so on are consistent. Therefore, in different control methods, the pump efficiency loss E_p, working power consumption E_L, back pressure energy consumption E_T, fluid pipeline loss E_f and mechanical friction loss E_m can be assumed as fixed values, and only the throttling loss of the two valves is different. Thus, when choosing the appropriate control methods for boom operation, those with larger valve openings should be preferred. Accordingly, the corresponding throttling losses are reduced. The throttling losses in the two valves are as follows:

$$E_s = E_1 + E_2 \tag{2}$$

$$E_1 = \int_{t_0}^{t_1} vA_1 \Delta p_1 \mathrm{d}t \tag{3}$$

$$E_2 = \int_{t_0}^{t_1} vA_2 \Delta p_2 \mathrm{d}t \tag{4}$$

$$\Delta p_1 = p_s - p_1 \tag{5}$$

$$\Delta p_2 = p_2 - p_0 \tag{6}$$

where, t_0 represents the start time of the operation process, t_1 represents the end time of the operation process, E_s represents the overall throttling loss of valves, Δp_1 represents the pressure difference between the inlet and outlet of the valve 1, Δp_2 represents the pressure difference between the inlet and outlet of the valve 2, p_s represents the pump output pressure, p_1 is the pressure in piston chamber, p_2 is the pressure in rod chamber, p_0 represents the back pressure, A_1 is the piston chamber area, A_2 is the rod chamber area.

Next, the appropriate control methods will be selected for different working modes of the boom.

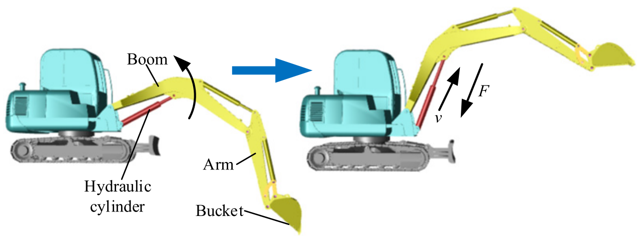

FIGURE 2. Lifting process of excavator boom.

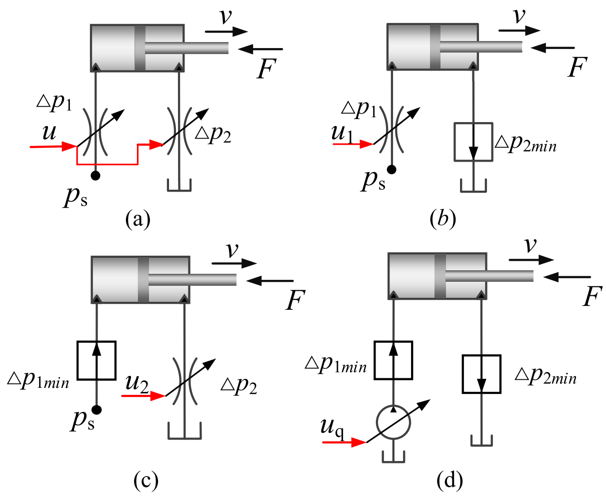

FIGURE 3. Principle of four control methods for boom lifting. (a) Four-side linkage valve control. (b) Meter-in control. (c) Meter-out control. (d) OPen-circuit.

A. BOOM LIFTING

Figure 2 shows the lifting process of the excavator boom. In Figure 2, v is the velocity of the hydraulic cylinder and F is the load force which acts on the hydraulic cylinder. As can be seen, when the boom is lifting from low to high under the action of the boom hydraulic cylinder, the velocity direction of the boom cylinder is opposite to that of the load force. In this process, the piston chamber of the hydraulic cylinder is connected to high-pressure oil, and the rod chamber is linked to the oil tank.

According to the different control signals of the two valves and pump, there may be four control methods involved in boom lifting: four-side linkage valve control, meter-in control, meter-out control, and open-circuit displacement control. The principle of these control methods is shown in Figure 3.

The four-side linkage valve control which represents the traditional control methods means that valve 1 and valve 2 obtain the same control signal u, and the spool displacements of the two valves are the same. At this instance, the two valves throttle simultaneously, and their function is similar to that of one proportional valve. The relationship between the pressure differences between the inlet and outlet of the two valves is as follows:

$$\Delta p_1 = \left(\frac{A_1}{A_2}\right)^2 \times \Delta p_2 \tag{7}$$

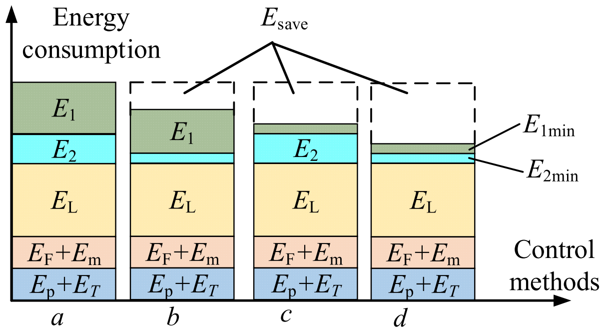

FIGURE 4. Energy consumption comparison. a-Four-side linkage valve control; b- Meter-in control; c- Meter-out control; d- Open-circuit displacement control.

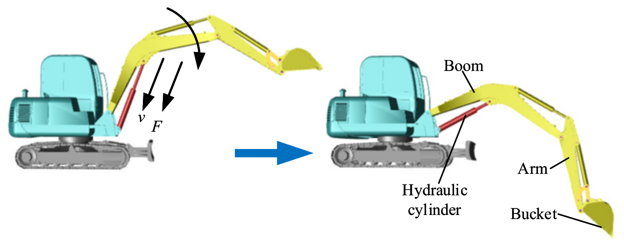

FIGURE 5. Lowering process of excavator boom.

Evidently, the throttling loss in valve1 is more than that in valve 2. The relationship is as follows:

$$E_1 = \left(\frac{A_1}{A_2}\right)^3 \times E_2 \tag{8}$$

The meter-in control method means that the valve 2 is fully open and the valve 1 is throttling. Because the valve 2 is fully open, the pressure difference between the inlet and outlet of the valve 2 is the minimum and the throttling loss is also the minimum. The meter-out control method means that the valve 1 is fully open and the valve 2 is throttling. At this instance, the throttling loss of valve 1 reduces to the minimum. The open-circuit displacement control method means that the valve 1 and valve 2 are fully open. The flow control signal u_q controls the output flow of the pump by adjusting the pump displacement and then controls the operation velocity of the boom. In this control method, there is practically no throttling loss because the two valves orifices are fully open. Based on the above analysis, the energy consumption comparison of these four control methods is shown in Figure 4.

As can be seen from the Figure 4, the energy consumption of open-circuit displacement control is less than the other three control methods. So, the appropriate method is the open-circuit displacement control for boom lifting.

B. BOOM LOWERING

Figure 5 shows the lowering process of the excavator boom. v is the velocity of the boom hydraulic cylinder and F is the load force which acts on the hydraulic cylinder. As the boom is lowered, the velocity direction of the boom cylinder is the same as the load force direction. Under this overload condition, the pressure in the piston chamber should be sufficiently large to balance the load force. Hence, the valve 1 cannot be fully opened and there may be three available control methods for lowering the boom: four-side linkage valve control, meter-out control, and flow regeneration. The principle of these methods is shown in Figure 6.

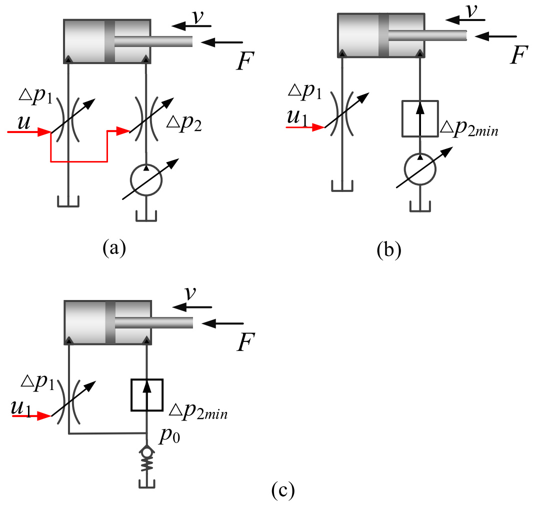

FIGURE 6. Principle of three control methods for boom lowering. (a) Four-side linkage valve control. (b) meter-out control. (c) flow regeneration.

The four-side linkage valve control means that valve 1 and valve 2 obtain the same control signal u and throttle at the same time. The throttling loss at both ends of the valves is the same as that in the boom lifting analysis. The meter-out control method means that the valve 2 is fully open and valve 1 is used for throttling. The throttling loss in the valve 2 is the minimum. Between these two control methods, valve 1 sustains considerable throttling loss to balance the load force. Moreover, it is necessary for the pump to continuously input the required flow and pressure into the rod chamber.

The flow regeneration means that the inlet and outlet of the cylinder are coupled, and both of them are connected to the oil tank through a backpressure valve. In this way, a certain amount of the oil flowing out from the piston chamber can be delivered into the rod chamber to achieve flow regeneration and the boom hydraulic cylinder moves under the action of the load force F. At this instance, the energy consumed by the system is the gravitational potential energy of the boom, arm, and bucket et al, while the pump almost does not need to output additional energy to the system. Hence, the energy consumption of the system is practically zero. Based on the above analysis, the energy consumption comparison of these three control methods is shown in Figure 7.

Obviously, the energy consumption of flow regeneration is less than the other methods. So, the appropriate method is flow regeneration for boom lowering.

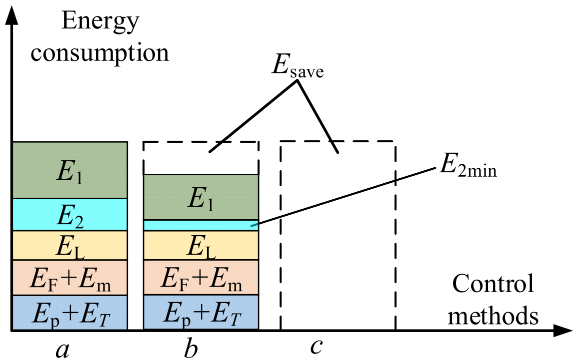

FIGURE 7. Energy consumption comparison. a-Four-side linkage valve control; b-Meter-out control; c-Flow regeneration.

C. BOOM POSITIONING

When the boom is positioning, the required boom positioning accuracy is considerably high. Thus, it is the most important factor in boom positioning.

Pressure gain is crucial in positioning accuracy. It represents the change in the load pressure value when the spool displacement variation range is small. As the system's pressure gain becomes larger, system accuracy becomes higher. The relationship between the load pressure and the pressures within the two chambers is described as:

$$p_L = p_1 - \frac{A_2}{A_1} p_2 \tag{9}$$

where, p_L is the load pressure.

When the valve spool displacement changes Δx, the pressures within the two chambers of the hydraulic cylinder changes Δp_1 and Δp_2. Accordingly, the load pressure changes as follows:

$$\Delta p_L = \Delta p_1 - \frac{A_2}{A_1} \cdot \Delta p_2 \tag{10}$$

Thus, the pressure gain k_p is described as:

$$k_p = \frac{\Delta p_L}{\Delta x} = \frac{\Delta p_1}{\Delta x} - \frac{A_2}{A_1} \cdot \frac{\Delta p_2}{\Delta x} = f_1(\Delta x) - f_2(\Delta x) \tag{11}$$

For the four-side linkage valve control, the pressures inside the two chambers of the hydraulic cylinder both change in opposite directions when the valve spool changes. Thus, the pressure gain is described by the following:

$$k_{p1} = |f_1(\Delta x)| + |f_2(\Delta x)| \tag{12}$$

Equation (12) indicates that the pressure gain of four-side linkage valve control is large. Accordingly, the positioning accuracy of this control is high and may be used for boom positioning. Although the throttling loss in the four-sided linkage valve control is relatively large when the boom is positioning, the threshold x_{th} of the working modes recognition is usually set to a smaller value. Thus, the positioning time is considerably short and the energy consumption is extremely small when the boom is positioning.

After selecting the appropriate control methods, the corresponding control strategies are designed to control the boom operation. In the following section, the hybrid control strategy of velocity and position for the excavator boom is introduced.

III. CONTROL STRATEGY DESIGN

A. OVERALL CONTROL STRATEGY DESIGN

The overall velocity and position hybrid control strategy for the excavator boom is shown in Figure 8.

The interface is used to monitor the status and position of the actuator. According to the information in the interface and actual operating requirements, the operator can provide control signals by using a joystick or intelligent input device. Based on the control signals from the signal source, the corresponding target trajectory including desired velocity curve v_r and desired displacement curve x_r can be generated, and the desired displacement curve is obtained by integrating the velocity. Compared with the traditional excavator, there are no sudden changes in the desired curves generated in this control strategy. As a result, the rigid and flexible impact can be avoided during operation.

In this work, the controller is designed as having two modes: velocity control mode and position control mode. The controller can adopt corresponding control strategies for different working modes which are recognized by the difference between target position x_d and actual displacement feedback value x_{rea}. And there are three working modes: lifting mode, lowering mode, and positioning mode.

When the boom is being lifted or lowered, the controller works in velocity control mode. At this instance, the velocity feedforward control (VFF) is employed to control the cylinder velocity. However, because of the influence of various factors, such as leakage, oil compression, and pump response time, certain velocity errors are introduced. Moreover, it is difficult to achieve the operational requirement by simply relying on the VFF. Accordingly, a displacement control signal which is based on the displacement difference between desired displacement x_r and actual cylinder displacement x_{rea} is added to compensate and correct the VFF. By using the combination of the velocity feedforward and displacement control (CVD), not only can the boom operate at the desired velocity, but the real-time tracking and control of the boom trajectory can also be realized. Although the CVD can make the boom operate along the desired trajectory, the limit of the displacement control is extremely large that it results in a long positioning time. Thus, as the boom approaches the target position, the controller should switch to the position control mode. The positioning control (PC) strategy, which is based on the difference between the target position x_d and the actual displacement x_{rea}, is applied to improve the positioning velocity and accuracy.

According to the control strategy in the different working modes, the controller outputs the corresponding control signals u_1, u_2, u_P, and u_q, which are separately used to control the opening of the valve 1 and valve 2, the output pressure and output flow of the pump. Hence, the boom will move to the target position along the desired trajectory.

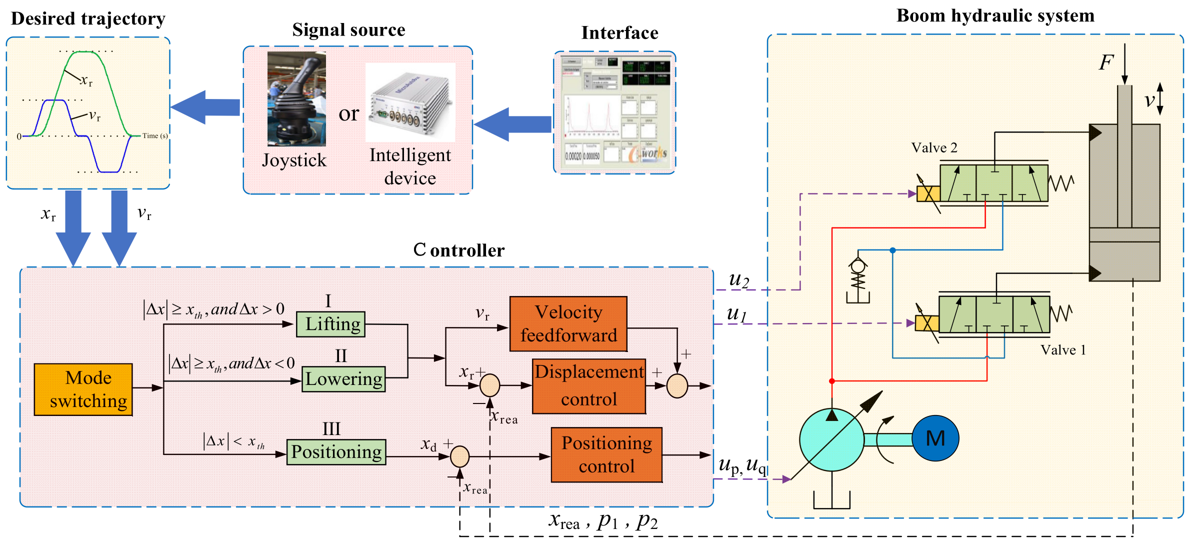

FIGURE 8. Overall velocity and position hybrid control strategy for excavator boom.

With this hybrid control strategy of velocity and position, the operators can complete the task by simply focusing on the interface instead of repeatedly adjusting the actuator based on their visual observation. Consequently, work efficiency and quality can be significantly improved.

B. DESIRED TRAJECTORY

The desired velocity and displacement curves can be generated by two different approaches: by using a joystick and by using an intelligent input device.

As for by using an intelligent input device, operators can enter the target position and velocity into the intelligent device according to the actual operating requirements. Thereafter, the desired velocity curve is generated. Figure 9 shows the designed curves generated during boom lifting and the similar curves can be generated during boom lowering. The desired velocity curve can be divided into seven segments: starting fillet, accelerating section, accelerating fillet, constant velocity section, decelerating fillet, decelerating section and flat fillet section. The smooth displacement curve can be obtained by the integration of velocity. As can be observed in the figure, the desired curves are smooth and no sudden changes. When the hydraulic cylinder moves along this trajectory, its operation is stable, and there is no rigid and flexible impact compared with the operation of the traditional excavator.

As for by using a joystick, the joystick swing angle corresponds to the desired velocity signal, and there is no necessity for external input devices compared with the way by using an intelligent input device. The desired displacement curve is also obtained by the integration of velocity. Accordingly, the desired trajectory similar to that shown in Fig. 9 can be obtained. Thus, the joystick's function is to control the velocity and position simultaneously rather than controlling only the velocity as that in the traditional excavator system. Although the operators are not directly provided with a definite target position value, they can determine the position of the boom based on the integral value on the interface rather than their vision and impression as they have typically done in the operation of traditional excavators. Consequently, they can complete tasks by simply focusing on the desired curves rather than depending on their own sight, which has poor repeatability, accuracy, and efficiency.

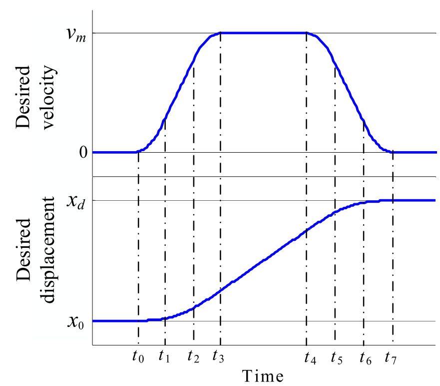

FIGURE 9. Desired velocity and displacement curves.

After obtaining the desired velocity and displacement curves, the controller can adopt corresponding control strategy for different working modes introduced as follows.

C. CONTROL STRATEGY FOR DIFFERENT MODES

There are three working modes: boom lifting, boom lowering, and boom positioning. The control principle of these three modes is shown separately in Figure 10.

1) BOOM LIFTING

Based on the analysis and comparison in section II-A, the most suitable control system for boom lifting is the open-circuit displacement control. At this moment, the system works in velocity control mode, and the controller adopts

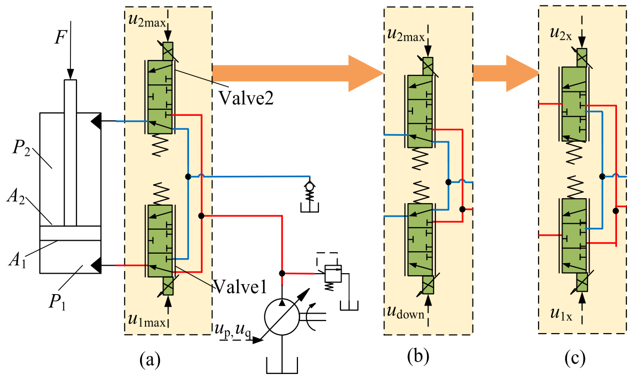

FIGURE 10. Control principle of different working modes. (a) Boom lifting. (b) Boom lowering. (c) Boom positioning.

the combination of velocity feedforward and displacement control (CVD).

The control principle of open-circuit displacement control for boom lifting is shown in Figure 10(a). And $u_{1\max}$ represents valve 1 is fully opened, $u_{2\max}$ represents valve 2 is fully opened, control signals u_{p} and u_{q} are used to control the pressure and flow of the variable pump, respectively. The signal of u_{q} is related to the velocity feedforward signal U_{v1} and the displacement control signal U_{c1} as:

$$u_q = U_{\mathrm{v1}} + U_{\mathrm{c1}} \tag{13}$$

The relationship between the desired velocity v_{r} and velocity feedforward signal U_{v1} can be expressed as follows:

$$U_{\mathrm{v1}} = \frac{v_{\mathrm{r}} \cdot A_1}{K \cdot n \cdot V_{\mathrm{pmax}}} \tag{14}$$

where, A_1 is the piston area, K is the leakage coefficient of the pump, n is the rotational velocity of the motor, and V_{pmax} is the maximum displacement of the pump.

Because of the influence of various factors, such as leakage, oil compression, and pump response time, it is difficult to achieve the desired operation requirement by merely relying on the velocity feedforward function. Thus, based on the difference between the desired displacement x_{r} and actual cylinder displacement x_{rea}, the displacement control signal U_{c1} with a proportional integral (PI) controller is added for compensation and correction as given by follows:

$$U_{\mathrm{c1}} = K_{\mathrm{p1}} \left[(x_{\mathrm{r}} - x_{\mathrm{rea}}) + \frac{1}{T_{\mathrm{I1}}} \int (x_{\mathrm{r}} - x_{\mathrm{rea}}) \,\mathrm{d}t \right] \tag{15}$$

where, K_{p1} and T_{I1} are the proportional and integral coefficients of the displacement control for boom lifting, respectively.

2) BOOM LOWERING

According to the comparison in section II-B, the most suitable control system for boom lowering is flow regeneration. The system also works in velocity control mode and the controller adopts the control strategy of CVD.

The control principle of flow regeneration for boom lowering is shown in Figure 10(b). $u_{2\max}$ represents valve 2 is fully open, u_{down} represents the partial opening of valve 1 to control the back pressure in the piston chamber and return flow rate. The control signal of u_{down} is determined by the combination of velocity feedforward U_{v2} and displacement control signal U_{c2} as given by follows:

$$u_{\mathrm{down}} = U_{\mathrm{v2}} + U_{\mathrm{c2}} \tag{16}$$

When the electro-hydraulic proportional valve port is fully open, the rated flow through the valve is q_{N} under the rated pressure difference Δp_{N}. When the valve port is fully open and the pressure difference is Δp, the flow through the valve is defined as follows:

$$q = q_{\mathrm{N}} \cdot \sqrt{\frac{\Delta p}{\Delta p_{\mathrm{N}}}} \tag{17}$$

During the working process of the valve, when the pressure difference is Δp and the control signal is U_{v2} which can control the valve opening size, the flow through the valve is:

$$q_1 = U_{\mathrm{v2}} q = U_{\mathrm{v2}} q_{\mathrm{N}} \cdot \sqrt{\frac{\Delta p}{\Delta p_{\mathrm{N}}}} \tag{18}$$

The actual pressure difference between the inlet and outlet of valve 1 is the following:

$$\Delta p = p_1 - p_0 \tag{19}$$

where p_1 is the piston chamber pressure, p_0 is the back pressure of the back pressure valve.

The desired flow through the valve 1 is as follows:

$$q_1 = v_{\mathrm{r}} \cdot A_1 \tag{20}$$

Accordingly, the signal of the velocity feedforward for valve 1 is the following:

$$U_{\mathrm{v2}} = \frac{v_{\mathrm{r}} \cdot A_1}{q_{\mathrm{N}}} \cdot \sqrt{\frac{\Delta p_{\mathrm{N}}}{p_1 - p_0}} \tag{21}$$

In the above equation, p_1 is related to the load force and v_{r} is related to the desired velocity. Thus, different calculating equations can satisfy various velocity and load force conditions. Moreover, the displacement control signal U_{c2} with a PI controller is added as compensation as follows:

$$U_{\mathrm{c2}} = K_{\mathrm{p2}} \left[(x_{\mathrm{r}} - x_{\mathrm{rea}}) + \frac{1}{T_{\mathrm{I2}}} \int (x_{\mathrm{r}} - x_{\mathrm{rea}}) \mathrm{d}t \right] \tag{22}$$

where, K_{p2} and T_{I2} are the proportional and integral coefficients of the displacement control for boom lowering, respectively.

3) BOOM POSITIONING

Based on the analysis in section II-C, the most suitable control system for boom positioning is the four-side linkage valve control. The system works in the position control mode, and the controller adopts the positioning control strategy (PC).

The control principle of boom positioning is shown in Figure 10(c). Control signals $u_{1\mathrm{x}}$ and $u_{2\mathrm{x}}$ are used to control the spool displacement of valve 1 and valve 2 respectively.

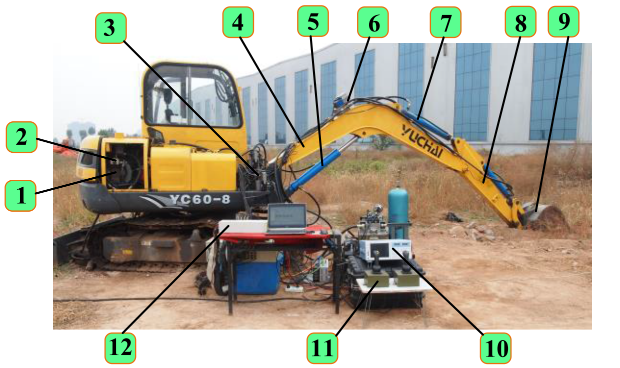

FIGURE 11. Test prototype and system components. 1-Pressure and flow control pump; 2-Electric motor; 3- Boom control valves; 4-Boom; 5-Boom cylinder; 6- Arm control valves; 7-Arm cylinder; 8-Arm; 9-Bucket; 10-Power meter; 11-Joysticks; 12-dSPACE.

If the control signals u_{1x} and u_{2x} are equal, the function of the two valves is similar to that of a proportional valve which represents the traditional four-side linkage valve control. Accordingly, the function of the system is equivalent to a symmetric valve control asymmetric cylinder. It can cause problems associated with pressure mutation, pressure overrun, and cavitation phenomena. This is because the inlet and outlet flow in the hydraulic cylinder does not match the area of the two chambers [30]. In order to match the inlet and outlet flow with the area of two chambers, the two signals of the control valves should be proportional as given by the following:

$$u_{2x} = Ru_{1x} \tag{23}$$

where, the ratio R is determined by the ratio of rod area to the piston area.

One of the signals is produced by PI-controller as follows:

$$u_{1x} = K_p \left[(x_d - x_{rea}) + \frac{1}{T_i} \int (x_d - x_{rea})\, dt \right] \tag{24}$$

where, x_d represents the target position, K_p is a proportional coefficient of positioning control, T_i is an integral coefficient of positioning control.

In this way, the function of the two valves is equivalent to an asymmetric valve, and the system is similar to an asymmetric valve to control an asymmetric cylinder. This can reduce the problems related to pressure mutation, pressure overrun, and cavitation phenomena. In addition, the traditional asymmetric valve is only applicable to the asymmetric cylinder with a specific area ratio because the area gain in the two throttles of the traditional asymmetric valve is fixed. However, the function of the asymmetric valve in this study is realized by adjusting the spool displacements, and the displacement ratio of the two spools can be set arbitrarily. Hence, the asymmetric valve in this paper can be applied to the asymmetric cylinder with any area ratio.

IV. TEST RESEARCH

In order to study the operational characteristics of the boom, a test rig is established on a 6-t excavator and the components of the test rig are shown in Figure 11. The test system principle of hydraulic excavator equipped with an independent metering control system is shown in Figure 12.

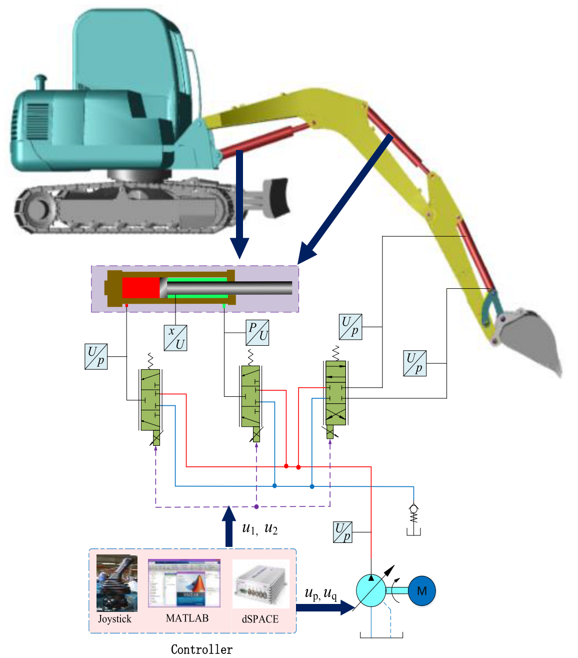

FIGURE 12. System principle of excavator with IMS.

The boom cylinder and the arm cylinder are separately controlled by two proportional valves, which can decouple the connection of the meter-in and meter-out orifices of the hydraulic cylinder to reduce throttling loss. This differs from the traditional control system with a single proportional valve. The displacement sensor is integrated into the hydraulic cylinder to measure the displacement of the hydraulic cylinder. Pressure sensors are separately arranged in each chamber of the cylinder and pump outlet. The entire system is controlled by the hardware in a loop system DS1103 produced by dSPACE company in German. Relevant test results are analyzed as follows.

A. RESULTS CONTROLLED BY THE INTELLIGENT INPUT DEVICE SIGNAL

The test results whose desired trajectory of the excavator boom is generated by using the intelligent input device is shown in Figure 13. Three types of results are given for comparison. The first type is controlled by the velocity feedforward (VFF), which represents conventional open-loop control. In the velocity control of traditional excavators, the boom velocity is theoretically proportional to the swing angle of the joystick. However, because of the influence of leakage, oil compression, and other non-linear factors, there is a considerable deviation between the velocity of the boom and joystick swing angle. Moreover, the closed-loop control of velocity and displacement is based on human visual feedback. Consequently, the velocity and displacement control of traditional excavators is poor. The second type of result is

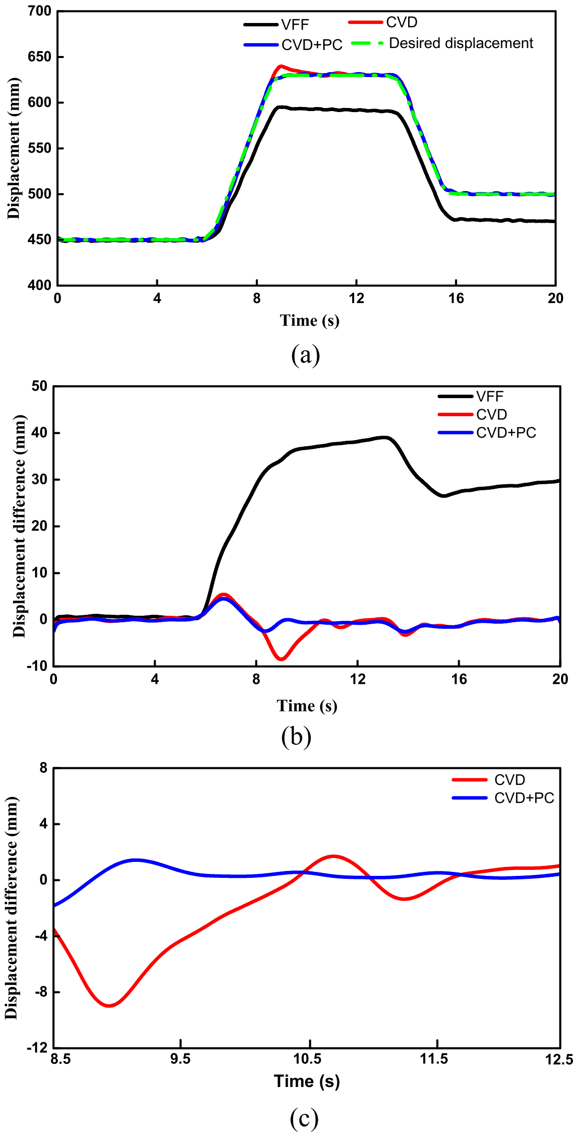

FIGURE 13. Test results of excavator boom controlled by the intelligent input device signal.

controlled by the combination of velocity feedforward and displacement control (CVD), which can achieve real-time trajectory tracking and control. However, positioning control is absent. The third type of result is controlled by the combination of CVD and positioning control (CVD+PC), which can achieve real-time trajectory tracking and fast positioning.

Figure 13(a) describes the actual displacement under the three types of control strategies. As shown in this figure, the actual displacement of the VFF deviates from the desired displacement and the final position also deviates from the target position because of the influence of the pump response time, system leakage, oil compression, and so on. However, the actual displacement of CVD is similar to the desired displacement, and the final position approaches that of the target. In this control strategy, the VFF is compensated by the displacement control signal which is based on the difference between the desired displacement and the actual displacement. By using the CVD control strategy, not only can the boom operate at the desired velocity, but the real-time tracking of the boom trajectory can also be realized. However, there is a certain overshoot in the displacement of CVD when the boom is positioning after 8.5s. And the reason for this is that the limiting value of its displacement control is extremely large. This leads to the actual velocity is slightly higher than the desired velocity at this instance. Thereafter, with the displacement control action, the boom is gradually adjusted to the target position. Although the final position is close to the target position, it requires a long time to achieve positioning. In order to solve this problem, a positioning control strategy (PC) is added on the basis of CVD control strategy. Figure 13(a) shows that there is practically no overshoot in the actual displacement when the boom is positioning by using the CVD+PC, and the boom can achieve fast positioning. When the boom is being lifted or lowered, the system works in velocity control mode and the control strategy of CVD is adopted to achieve real-time tracking of the boom trajectory. When the difference between the actual displacement and the target position is less than the set threshold, the system switches to the position control mode, and the PC control strategy based on the difference between the target position x_d and actual displacement x_{rea} is adopted to achieve fast positioning.

Figure 13(b) describes the difference between the actual and desired displacements. The system is in the positioning mode from 8.5 s to 12.5 s, and the detailed displacement difference is shown in Figure 13(c). The final position difference resulting from the application of the VFF control strategy is more than 35 mm. In contrast, with the CVD and CVD+PC control strategies, all final position differences are less than 1 mm. This is because the CVD can achieve real-time tracking and control of the boom trajectory. As can be observed from Figure 13(c), the actual displacement has a 10 mm overshoot when the boom is positioning under the CVD control strategy. After 11.5s, the displacement of the boom is basically maintained at a fixed value and positioning is completed. However, the actual displacement by using the CVD+PC control strategy only has a 1.5 mm overshoot when the boom is positioning. After 9.5s, the position of the boom is basically maintained at a fixed value and positioning is completed. Hence, the CVD+PC control strategy can realize real-time trajectory tracking and fast positioning. Compared with traditional control strategy, better position and velocity characteristic can be achieved by using the proposed CVD+PC strategy.

B. RESULTS CONTROLLED BY THE JOYSTICK SIGNAL

As for using joystick, although the operator cannot provide a definite target position value directly, they can determine the position of the boom according to the integral value on the interface rather than according to their sight and impression as they have done in operating a traditional excavator. In order to compare the characteristics of different control strategies, the control strategies of VFF, CVD, and CVD+PC are

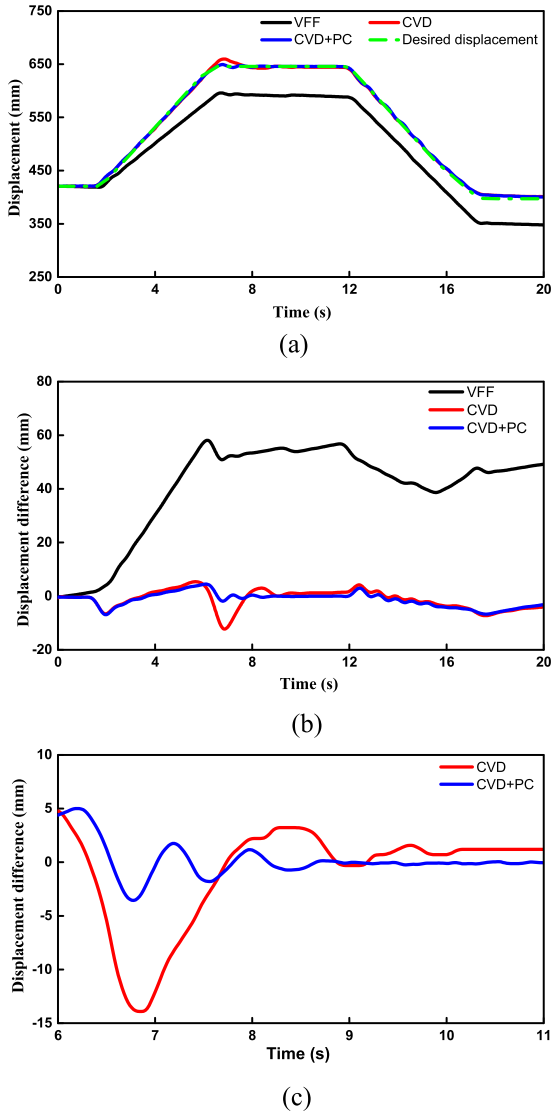

FIGURE 14. **Test results of excavator boom controlled by the joystick signal.**

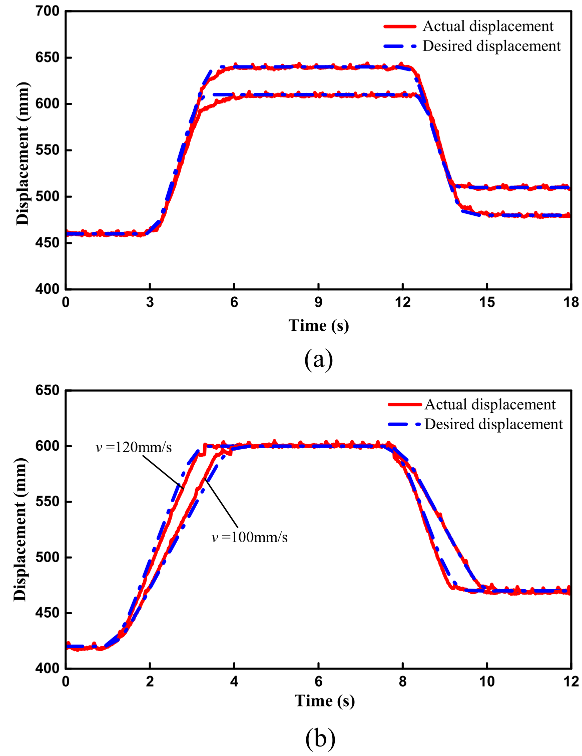

FIGURE 15. **Test results of different velocity and target position requirements.**

individually tested and the corresponding results are shown in Figure 14.

Figure 14(a) describes the actual displacements using the three types of control strategies. Figure 14(b) describes the difference between the actual and desired displacements, and Figure 14(c) shows the details of displacement difference under the control strategy of CVD and the control strategy of CVD+PC during the positioning process. It can be observed that there is a considerable difference between the actual displacement of VFF and the desired displacement. And the final position difference under the VFF control strategy is more than 45 mm. However, the actual displacements under the control strategy of CVD and CVD+PC are close to the desired displacement because the displacement control can compensate for the control strategy deficiency of the VFF to achieve real-time tracking of the boom trajectory. The final position differences under the control strategy of CVD and CVD+PC are all less than 1 mm, which is the same as the results controlled by the intelligent input device signal.

Based on Figure 14(c), it is known that the actual displacement under the CVD control strategy has a 14mm overshoot when the boom is positioning, and after 10s, the displacement of the boom is basically maintained at a fixed value and positioning is completed. However, under the CVD+PC control strategy, the boom completes positioning only after 8.5s. Thus, the CVD+PC control strategy can realize fast positioning. Compared with the traditional control strategy, better position and velocity characteristic can be achieved by using the proposed CVD+PC strategy.

In addition, the joystick is originally intended to simply output the velocity signals under the VFF control strategy. However, under the CVD+PC control strategy, it is used to transmit velocity and position signals concurrently. Thus, the joystick attains better operating characteristics.

C. TEST RESULTS OF DIFFERENT REQUIREMENTS

During actual operation, various working conditions correspond to different velocity and target position requirements. The test results of different desired velocities and target positions using the CVD+PC control strategy are shown in Figure 15.

Figure 15(a) shows the actual and desired displacements when the boom moves to different target positions with the same required velocity. Because the same velocity is maintained, the slope of the displacement curve during the operation remains the same. When the target position requirements

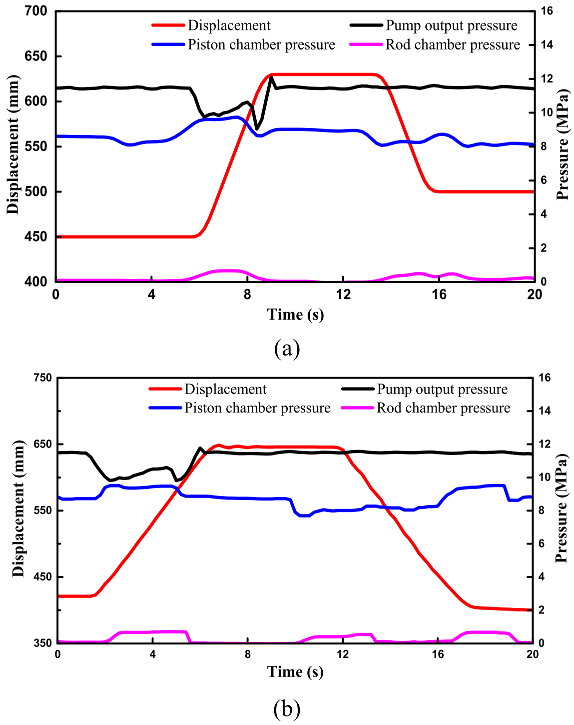

FIGURE 16. Pressure results controlled by CVD+PC.

are different, the boom can move to the target position along the desired trajectory and achieve a final position that approximates the target. The large difference between the actual and desired displacements at the beginning of the positioning mode is the result of a large change in the spool displacement caused by mode switching. However, the positioning process can be completed in a short time, and the final position difference is the same as that in the previous analysis. Figure 15(b) shows the test results when the boom moves to the same position at different velocities of 100mm/s and 120mm/s respectively. It can be seen from Figure 15(b) that the boom can reach the target position along the desired trajectory, and the final position approximates the target.

D. PRESSURE RESULTS

Figure 16 shows the test results of pressure, and these results are controlled by the proposed CVD+PC control strategy. The pressure results controlled by the intelligent input device signal is shown in Figure 16(a) and the pressure results controlled by the joystick signal is shown in Figure 16(b).

It can be observed that whether using intelligent input device or joystick, the pressure in the piston chamber remains at approximately 8MPa to balance the gravity acting on the boom cylinder, and it changes little during the whole process. There is a slight pressure fluctuation of approximately 1.5MPa when the boom begins to lift. This indicates that the starting stability is good. Moreover, there is a small pressure fluctuation of approximately 1MPa as the target position is approached. The reason for this is that the valve spool slightly varies at the switching instance. The pressure in the rod chamber remains less than 1.5MPa, which can reduce energy consumption. In its entirety, the pressures inside the two chambers of the hydraulic cylinder are basically stable, and there is no significant pressure fluctuation. This indicates that by using this proposed control strategy, the rigid and flexible impact on boom operation is considerably small.

As for the pump output pressure, when the boom is lifting, the pump output pressure approximates the piston chamber pressure, because at this instance, the control system used is the open-circuit displacement control, and the energy consumption is considerably small. When the boom is being lowered, the pump output pressure remains at approximately 11.5Mpa, and there is basically no output energy because the control system used at this instance is flow regeneration. Moreover, the pump output pressure is relatively stable, and there is no significant fluctuation.

V. CONCLUSION

In order to satisfy the requirements for the automatic control and position control of excavators in dangerous environments, such as chemical substance leakage and conflagration sites, this paper proposes a hybrid velocity and position control strategy for the excavator boom. And, an independent metering system is introduced to reduce throttling loss. The energy consumption of different control methods is analyzed, and appropriate control methods for different working modes of the excavator boom are selected. Moreover, a detailed hybrid control strategy of velocity and position is designed. The desired velocity and displacement curves are generated by the joystick or intelligent input device according to different target positions and operation requirements. Then, the controller will adopt corresponding control strategy. If the difference between the target and actual displacements is sufficiently large, the controller adopts the velocity control mode, and the control strategy that combines velocity feedforward and displacement control (CVD) is employed to realize the real-time trajectory tracking. In this velocity control mode, the displacement control signal is used to compensate for the deficiency of the traditional velocity feedforward signal. When the boom approaches the target position, the controller adopts position control mode, and the positioning control strategy (PC) is employed to realize fast positioning. In order to verify the feasibility of the strategy, a test rig is established on a 6-t excavator. The test results show that by using this proposed control strategy, the actual displacement approximates the desired displacement with no evident fluctuation. The final positioning error is less than 1 mm and the boom can achieve fast positioning. Compared with traditional control strategy, better position and velocity characteristic can be achieved by using the proposed strategy.

The results of this research can aid operators in moving the boom to the target position smoothly and accurately by simply focusing on the operation target in the interface rather than depend on their visual observation and impression. Moreover, the traditional joystick function of merely controlling velocity is extended to control velocity and position simultaneously.

In this way, the work efficiency and quality can be greatly improved.

In addition, the independent metering system used in this paper can reduce the throttling loss compared with the traditional four-sided linkage valve control system. When the open-circuit displacement control system is employed in boom lifting, the orifices of the two control valves are practically fully open, and there is almost no throttling loss. When the flow regeneration is used in lowering the boom, the pump practically requires no output energy. So, when using this independent metering control system, energy consumption is small in the process of boom operation.

The conduct of this research is limited to the excavator boom. However, during actual engineering, multiple actuators may concurrently operate. In future work, the corresponding control strategy for the aforementioned will be studied. In this paper, although a full composite of position control and velocity feedforward is investigated, a better control algorithm will be studied to improve operation characteristics. Furthermore, future work will focus on various desired trajectories to complete specific tasks during operations.

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