Hydraulic Control Research of Working Device of Grab Arm Cleaning Machine for Heavy Load and Large Depth

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Abstract. In this paper, a kind of heavy-duty and deep cleaning machine working device is studied. The closed-loop vector method is used to establish the kinematics model of the hydraulic cylinder rod mechanism, and the Lagrange dynamics is used to establish the dynamic model of working device. MATLAB, AMESim and ADAMS are used to provide excitation signal for the servo valve, build the hydraulic simulation model, and carry out kinematics and dynamics simulation. Using different signal excitation, the displacement tracking of the working device and the change of hydraulic pressure are observed. The results show that the closed-loop vector method and Lagrange dynamics are used to establish the kinematics and dynamics model of the working device, which facilitates the study of the working device of the cleaning machine; the simulation interface is stable, and the co-simulation of control arithmetic is achieved, hydraulic system and structural dynamics; the hydraulic pressure is obtained through the co-simulation analysis. The effect of cylinder displacement tracking and the change of hydraulic pressure provided the basis for working device design and optimization.

1. Introduction
The working device is an important part of cleaning machine. The working force is complicated and the working conditions are bad, thus the structural strength affects the reliability and working performance directly \cite{1,2}. Dynamic analysis of the cleaning machine working device to provide design basis for hydraulic control system and structural optimization\cite{3,4}. Because the grab arm type cleaning machine is similar to a hydraulic excavator \cite{5,6}, therefore, the related research on the excavator can also be applied to the grab arm type cleaning machine. Zou Zhihong\cite{7}, Li Xin\cite{8} established kinematics model of the working device of the hydraulic excavator. The response characteristics of the static action of the working device were analyzed. Chen Jin\cite{9} considered that the difference in media characteristics and operating style, which are important sources of uncertainty in the excavation process. Zhao Pengyu\cite{10} established the dynamic simulation model of the working device by using ADAMS, AMESim and other computational simulation software. Fan Qinhong\cite{11} studied the influence on the performance of the working device, and the maximum digging height and the unloading height are affected most when the boom size is increased.

The subject puts new requirements for the grab-arm type cleaning machine: the cleaning capacity can reach 2000 kg in each working cycle; under the heavy load, the cleaning depth can reach 20 m.
2. Dynamics Analysis of Working Device

2.1. Kinematics Description of Hydraulic Cylinder Rods

The hydraulic cylinder linkage mechanism is a closed-loop mechanism that drives the movement of the rod by the movement of the piston rod. The closed-loop vector analysis diagram is shown in Figure 1. In the figure, the frame hinge point vector (as rod 1), the hydraulic cylinder vector $R_2$ (as rod 2); the execution bar vector $R_3$ (as rod 3). The angle $\theta_1$ between the vector and the two hinge points of the frame is known as $\theta_1 = \theta^\prime$, the angle $\theta_2$ between the hydraulic cylinder and rod 1, $\theta_2 \in (0, \pi)$, and the angle $\theta_3$ between the execution rod and rod 1, $\theta_3 \in (0, \pi)$.

![Figure 1. Closed loop vector model of hydraulic cylinder rod](image)

Figure 1. Closed loop vector model of hydraulic cylinder rod

The definition of the closed-loop vector model is as follows: rod 2 are the original moving parts, and the movement is the linear motion of the hydraulic cylinder piston rod relative to the cylinder tube; the counterclockwise rotation direction of the angle is the positive direction; the rotation angle of the connecting rod relative to the rod 1 is relative corners.

The closed-loop vector model obtained from the graph is:

$$R_3 = R_1 + R_2$$

(1)

Taking the vector $R_1$ as the $x$-axis of the cartesian coordinates, then get the positional equations in the $x$ and $y$ directions:

$$\begin{align*}
R_1 \cos \theta_1 &= R_1 \cos \theta_2 + R_2 \cos \theta_3 \\
R_1 \sin \theta_1 &= R_2 \sin \theta_2 + R_3 \sin \theta_3
\end{align*}$$

(2)

The angular $\theta_1 = \theta^\prime$, $\omega_2$ and $\alpha_3$ are the velocity and angular acceleration of the hydraulic cylinder relative to rod 1. The $\omega_3$ and $\alpha_3$ are the angular velocity and angular acceleration of the actuator relative to rod 1, and the velocity equations are obtained:

$$\begin{align*}
0 &= \dot{R}_2 \cos \theta_2 - \sum_{i=2}^3 \omega_i \sin \theta_i \\
0 &= \dot{R}_3 \sin \theta_3 + \sum_{i=2}^3 \omega_i \cos \theta_i
\end{align*}$$

(3)

The first and second order increments of $\dot{\theta}_2$ caused by the increment of $\theta_2$ are obtained:

$$\begin{align*}
\frac{\partial \dot{\theta}_2}{\partial \theta_2} &= \frac{R_2}{R_1 \cos(\theta_2 - \theta_3)} \\
\frac{\partial^2 \theta_2}{\partial \theta_2^2} &= \frac{R_3 (R_2 \cos(\theta_2 - \theta_3))^{\prime}}{R_3 \cos(\theta_2 - \theta_3) \cot(\theta_2 - \theta_3)}
\end{align*}$$

(4)

The acceleration equation can be expressed as:

$$\begin{align*}
0 &= \ddot{R}_2 \cos \theta_2 - 2 \dot{R}_2 \omega_2 \sin \theta_2 - \sum_{i=2}^3 (R_i \omega_i^2 \cos \theta_i + \alpha_i R_i \sin \theta_i) \\
0 &= \ddot{R}_3 \sin \theta_3 + 2 \dot{R}_3 \omega_3 \cos \theta_3 - \sum_{i=2}^3 (R_i \omega_i^2 \sin \theta_i - \omega_i R_i \cos \theta_i)
\end{align*}$$

(5)
2.2. Working Device Dynamics Model
Using the Lagrange dynamics method, the dynamic equation of the working device can be expressed as \[12\]:

\[
T_i = \sum_{j=1}^{n} K_j(\theta) \dot{\theta}_j + \sum_{j=1}^{n} H_{ij}(\theta) \dot{\theta}_i + G_i(\theta)
\]

\[
K_j = \sum_{p=\max(i,j)}^{n} m_i \left( \dot{\theta}_i \dot{\theta}_j \right) + 2 \gamma_i (\dot{\theta}_i + \dot{\theta}_j)
\]

\[
H_{ij} = \frac{\partial D_{ij}}{\partial \theta_i} - \frac{\partial D_{ji}}{\partial \theta_j}
\]

\[G_i = \sum_{s=1}^{m_s} m_s \delta_i
\]

where \(T_i\) is the driving force acting on the rod; \(K_j(\theta)\) is rod moment of inertia; \(H_{ij}(\theta)\) is the centripetal force or Coriolis force between joints; \(G_i(\theta)\) is the gravity term; \(m_s\) is the quality of the rod \(s\); \(\delta\) is the angle between a tangent to a point and the vector diameter of the point; \(k_s\) is cross-coupling coefficient matrix; \(d_j\) is the measuring distance from \((x,y)\) to \((x',y')\) along \(z\); \(\gamma_s\) is the coordinate position of center of mass of the rod \(s\) in the coordinate system; \(g\) is gravity acceleration; \(\gamma_s\) is the coordinates of the centroid of the member \(s\) in the coordinate system \(i-1\); \(i-1\) \(g = [-g^0 x_{i-1}, g^0 y_{i-1}, 0, 0]\); \(g^0 = [g, 0, 0, 0]\).

3. Control Algorithm Design

3.1. Incremental PID Algorithm
The PID control strategy is often used to perform proportional, differential and integral operations on signal deviations\[13\]. When the control needs the increment of the control amount, the incremental PID algorithm can be used. The mathematical model is:

\[
\Delta u(k) = u(k) - u(k-1) = k_p (e(k) - e(k-1)) + k_i e(k) + k_d (e(k-2) - 2e(k-1) + e(k-2))
\]

3.2. Signal Transition Algorithm
It is unreasonable to make the piston rod move to a certain position suddenly. Han Jingqing\[14\] proposed a discrete nonlinear differential tracker to complete the transition process of a step signal or a square wave signal. The mathematical description of the method is:

\[
r_1(k+1) = r_1(k) + hr_2(k)
\]

\[
r_2(k+1) = r_2(k) + \text{fst}(r_1(k) - y_4(k), r_2(k), \delta, h)
\]

In equation (8) \(\text{fst}\) is the fastest-speed control synthesis function, the expression is:

\[
\text{fst}(x, x, \delta, h) = \begin{cases} 
-\delta \text{sgn}(a) & |a| > d \\
-\frac{a}{h} & |a| \leq d
\end{cases}
\]

\[
x_1 + \frac{a_n - d}{2} \text{sgn}(y) & y > d_0 \\
x_2 + \frac{y}{h} & y \leq d_0
\]

where \(h\) and \(\delta\) is the variable parameters of tracker.

4. Co-simulation Model

4.1. Model Parameters of Working Device
The working device of the cleaning machine mainly includes the claw1, claw2, grab arm, boom, claw1 hydraulic cylinder, claw2 hydraulic cylinder, four grab arm hydraulic cylinder and three boom hydraulic cylinder, et al. The material of the two claw is Q235, the total mass is \(2 \times 488.78\) kg, the
maximum length is 2025 mm; the material of grab arm and boom is Q345, the total mass of the grab arm is 9714.1 kg, the maximum length is 21000 mm. The total mass of the boom is 11730 kg and the maximum length is 5300 mm.

4.2. Dynamic Model

![Figure 2. ADAMS model of working device](image)

The three force variables $\text{force1}_1$, $\text{force1}_2$, and $\text{force1}_3$ are applied to the three hydraulic cylinders of the boom, and the four force variables $\text{force2}_1$, $\text{force2}_2$, $\text{force2}_3$, and $\text{force2}_4$ are applied to the grab arm hydraulic cylinder respectively. The two force variables $\text{force3}_1$ and $\text{force3}_2$ are applied to the two hydraulic cylinders of the claw respectively. The boom hydraulic cylinder stroke variable is $\text{dis1}$, the grab arm hydraulic cylinder stroke variable is $\text{dis2}$, and the two claws hydraulic cylinder stroke variables are $\text{dis3}$ and $\text{dis4}$, respectively.

The stroke of the hydraulic cylinder is set to the distance between the center of the cylinder hinge point. The hydraulic cylinder stroke variable is set to control variable of output, the force variable is set to control variable input, as shown in Figure 3.

There are three plunger variable pumps in the working device. The maximum control pressure of the boom pump, the grab arm pump and the claw pump are 30 MPa, 35 MPa and 28 MPa, respectively. The boom hydraulic cylinder piston diameter is 280 mm, piston rod diameter is 140 mm, maximum stroke is 3 m, travel range is 2.2-2.9 m; the grab arm hydraulic cylinder piston diameter is 180 mm, piston rod diameter is 80 mm, maximum stroke is 5 m, travel range is 2.55-3.9 m; the claw1 hydraulic cylinder piston is 110 mm, the diameter of claw2 is 100 mm, the diameter of piston rod is 50 mm, the maximum stroke is 0.8 m, and the range of travel motion is 0.492-0.772 m.

4.3. Algorithmic Model Design

The constant value signal and sinusoidal signal generator are used to input constant and sinusoidal excitation to the mechanical-hydraulic system. The complex discrete signal generator can be customized by S function. The incremental PID algorithm is created by the Simulink sub-module.

5. Co-simulation results analysis

In Simulink, the proportional constant of incremental PID algorithm of boom is 30000, the integral constant is 1, and the differential constant is 1000; the proportional constant of incremental PID algorithm of grab arm is 30000, the integral constant is 1, and the differential constant is 150; the proportional constant of incremental PID algorithm of claw1 and claw2 is 2000, the integral constant is 1, and the differential constant is 100.
5.1. Device Response under Constant Excitation

In Figure 4. The displacement response of the boom, grab arm and the claw can be divided into four stages: smoothing response stage; intermediate isovelocity response stage; end smoothing response stage and displacement maintaining stage. In maintaining displacement stage, there is no fluctuation of displacement, which coincides with the ideal signal almost and achieves high control accuracy.

Figure 4. Displacement response of working devices under constant excitation

Figure 5. Variation of hydraulic stress of working devices under constant excitation

Figure 5 shows that there are four distinct stages of change between claw1 and claw2. The maximum hydraulic pressure of claw1 is 208485 N, the maximum hydraulic pressure of claw2 is 16399 N, the maximum hydraulic pressure of grab arm is 4×551154 N, and the maximum hydraulic pressure of boom is 3×536037 N. The force oscillation of the boom is intense in the initial smooth response stage and the final smooth response stage. Although the fluctuation amplitude is small, it still has an impact on the overall performance. Therefore, in the actual operation of the working device, the boom, the grab arm and the claw should be operated individually as far as possible.

5.2. Device Response Under Sinusoidal Excitation

The purpose of using sinusoidal signal excitation is to control the motion time and smoothness of the actuator, and to make the displacement, velocity and acceleration of the actuator change continuously.

Sinusoidal excitation is applied to claw1 and claw2. The signal period is 30 seconds, 35 seconds, 38 seconds, 40 seconds, 50 seconds and 60 seconds, respectively. The influence of sinusoidal excitation with different frequencies on the response of claw is studied, and the appropriate sinusoidal excitation period is selected. The tracking is shown in Figure 5. During the initial 0.2 seconds of tracking, the tracking signal oscillates in a small range, which will lead to the hydraulic pressure oscillation in this stage. When the period is 30 seconds, the tracking condition of claw1 is good. Claw2 enters the state of constant velocity motion in about 6 seconds, and tracks the desired signal of deviation of trajectory. When the period is 35 seconds, the tracking performance of claw1 is good, and claw2 also appears a constant velocity motion state, but the time in this state is reduced. When the period is 38 seconds, the equal velocity motion state of the claw2 is eliminated, and both the claw1 and claw2 have good tracking effect. When the period is 40 seconds, the equal velocity motion state of the claw2 is eliminated, and both the claw1 and claw2 have good tracking effect. When the period is 50 seconds and 60 seconds, the claw1 and claw2 have the constant velocity motion state no longer, and the tracking accuracy is gradually improved.
Figure 6. Displacement response of claw under sinusoidal excitation

Figure 7. Variation of hydraulic stress of claw under sinusoidal excitation

Figure 7 shows that when the period is 30 seconds, the hydraulic pressure of claw 1 changes to a sinusoidal law, which corresponds to the displacement tracking of claw 1. When claw 2 enters the stage of constant velocity movement, the hydraulic pressure keeps constant for a period of time, and also appears for a period of time when the period is 35 seconds and 38 seconds, so the period is 30 seconds, 35 seconds and 38 seconds is not suitable for claw 2. When the period is 40 seconds or more, the hydraulic pressure of claw 1 and claw 2 varies obviously according to sinusoidal law, which is suitable for the excitation signals of claw 1 and claw 2. The comprehensive analysis shows that the sinusoidal excitation with a period of 40 seconds or more is suitable as the excitation signal of the claw. The simulation results show that sinusoidal excitation of the grab arm and boom needs a sinusoidal signal with a period of 240 seconds to achieve good control effect and tracking accuracy, the working time is too long. Therefore, a compromise between constant excitation and sinusoidal excitation is needed.

5.3. Constant Signal Transition Process

Complex signal generator and discrete non-linear differential tracker are programmed by using S function, and completed the transition process of constant signals of the grab arm boom. The constant square wave signal of the grab arm is set as follows:

$$y_d = 0.675 \text{sgn} \left( \sin \left( \frac{\pi}{90} t - \pi \right) \right) + 3.225$$ \hspace{1cm} (10)

The constant square wave signal of the boom is set as follows:

$$y_d = 0.35 \text{sgn} \left( \sin \left( \frac{\pi}{90} t - \pi \right) \right) + 2.55$$ \hspace{1cm} (12)

The transition time of the grab arm transition signal is adjusted within 60-80 seconds. The transition signal can be adjusted by adjusting the $h$ and $\delta$ parameters of the differential tracker. As shown in Figure 7 when $h=0.01$ and $\delta=0.001$, the design requirements are met. The transition time of the boom transition signal is adjusted within 60 to 80 s, as shown in Figure 8. When $h=0.01$ and $\delta=0.00055$, the design requirements are met.
5.4. Device Response Under Constant Transition Excitation

Figure 10 shows that the displacement response of the boom and grab arm is smoother from the maximum to minimum. The compromise between sinusoidal excitation and constant excitation is achieved, that is, the motion time of the grab arm and boom can be controlled and the control precision can be achieved.

![Figure 10. Displacement response of boom and grab arm under transition process constant excitation](image)

Figure 11 shows that the hydraulic stress of the grab arm and boom. This is related to the setting of a two-way balancing valve in the hydraulic system. The balancing valve should ensure that the speed of the boom and grab arm cannot be too high in the process of descending. The balancing valve plays a frequent role in the grab arm and boom during descending. The damp of the balance valve can reduce the fluctuation, but at the same time, it needs to increase the control pressure of the hydraulic pump. The maximum hydraulic force of the boom is $3 \times 880260$ N, and the maximum hydraulic force of the grab arm is $4 \times 558940$ N. According to the design and verification theory of the hydraulic cylinder, the parameters of the inner diameter of the hydraulic cylinder and the diameter of the piston rod can meet the design requirements.

![Figure 11. Variation of hydraulic stress of boom and grab arm under transition process constant excitation](image)

6. Conclusion

The co-simulation of MATLAB-AMESim-ADAMS is realized, and the interface is stable. The control algorithm calculation, hydraulic system and dynamic solution are completed. Different excitation signals are used to observe the response of the working device. The results show that the response process of the working device under constant excitation is good, and the appropriate sinusoidal excitation period of the claw is obtained. The excitation signal transition between the grab arm and boom is completed by the transition algorithm, and the displacement tracking accuracy is high, which meets the needs of the subject.

Author’s Brief Introduction

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