Performance Simulation on the Secondary Hydraulic Lifting System of the Excavator Bucket

Fa-ye ZANG*, Zheng-hong CHEN and Xiang-zhen KONG
Department of Engineering Mechanical, Shandong Jiaotong University, Jinan 250357
*Corresponding author

Keywords: Excavator, Lifting system, Fuzzy-neural network control, Performance simulation.

Abstract. The flow coupled secondary hydraulic lifting system of the excavator bucket was presented, also its structure and working principle. The fuzzy-neural network control strategy which was combination of fuzzy control and neural network has been adopted, and the math model of the lifting system is established, then the simulations of the performance of the lifting system has been conducted. The flow coupled hydraulic system with secondary regulation can regenerate gravitational energy of load. By controlling the hydraulic accumulator, the process controlling of the energy recycling and reusing has been realized. The system pressure range was expanded, and the energy reusing effect and efficiency were improved.

Introduction

At present, the gravitation energy of the hydraulic lifting system of the excavator bucket is not usually recycled and reused when its bucket and load was working under lifting and falling down, which causes the energy waste and the environmental pollution. So a secondary hydraulic lifting system of the excavator bucket was presented, in which, the flow coupled secondary hydraulic transmission system was used to recycle and store the gravitation energy of the excavator bucket when its bucket and load was working under lifting and falling down, and reusing the energy when it was working, so the installation of the motor was induced to realize energy saving and environmental protection.

The Structure and Working Principle

As shown in Figure 1, the system was made up of storage secondary components 2, control components 1 for storage secondary components, electromagnetic change valve 3, balancing valve 6, load secondary components 7, motor 8, control components 9 for load secondary components and load cylinder 10, and so on. The hydraulic storage components 4 and pressure limiting storage components 5 was connected parallel with storage secondary components 2, the high pressure oil of storage secondary components 2 was connected with the main hydraulic system of the excavator through electromagnetic change valve 3, the shaft of the storage secondary components 2 and load secondary components 7 were connected rigidly.

When the bucket began to fall, the high pressure oil of storage secondary components 2 was switched off connection with the main hydraulic system. The load secondary components 7 was adjusted to make it work under motor state, and also the storage secondary components 2 work under pump state. The lower chamber oil of load cylinder 10 flowed to load secondary components 7 rapidly in the influence of gravitation of bucket and gravity, the shaft of load secondary components 7 rotated to output torque and speed, and then drive the storage secondary components 2 working in pump state to transport high pressure oil for the hydraulic storage components 4 and pressure limiting storage components 5. The hydraulic storage components 4 was refueling in order from lowest to highest setting pressure, if the storage secondary components 2 no longer delivered high pressure oil or little, the refueling was end, otherwise, the refueling would be continued until reaching to the limited pressure of pressure limiting storage components 5. So by controlling the accumulator, the energy recycling was realized, this would ensure higher oil pressure of the accumulator, the reusable effect was improved.
When the bucket began to lift, the high pressure oil of storage secondary components 2 was connected with the main hydraulic system. The storage secondary components 2 was adjusted to make it work under motor state, and also the load secondary components 7 work under pump state. The high pressure oil was discharged from hydraulic storage components 4 and pressure limiting storage components 5 to drive storage secondary components 2, it would rotate with the motor to drive the load secondary components 7 jointly, and then they provided power for load cylinder 10 to lift bucket and load. In working, one or more hydraulic storage components 4 and pressure limiting storage components 5 could be controlled in accordance with the weight of bucket and load, lift speed.

Math Model for the Flow Coupled Secondary Hydraulic Lifting System

The system worked in load lifting and falling state.

Math Model for Lifting

**Math Model of the Electro-Hydraulic Servo Valve.** Usually, the natural frequency of servo valve is very high, and the bandwidth of the controlled hydraulic system is lower, so the electro-hydraulic servo valve can be acted as a proportional component, as following:

\[
\frac{Q_{sf}(s)}{I(s)} = K_v
\]  

(1)

here, \(K_v\) is flow gain of the servo valve((m^3/s)/A), \(Q_{sf}\) is output flow of the servo valve(m^3/s), \(I\) is input current of the servo valve (A).

**Math Model of the Lifting System.** 1) The continuity equations of load secondary components 7 and load cylinder

\[
D_1 n = A_e \frac{dy}{dt} + C_{pc} p_1 + \frac{V_0}{\beta_e} \frac{dp_1}{dt}
\]  

(2)

here, \(D_1\) is volume(m^3/rad), \(n\) is motor speed (r/s), \(A_e\) is the piston effective area(m^2), \(y\) is piston displacement(m), \(C_{pc}\) is total leakage coefficient of load secondary components 7, \(p_1\) is the load cylinder pressure of rod chamber(Pa), \(V_0\) is the volume of rod chamber at median (m^3), \(\beta_e\) is oil bulk modulus.
2) Balance equation of load cylinder and load

\[ A_c P_1 = m_1 \frac{d^2 y}{dt^2} + B_c \frac{dy}{dt} + m_1 g + f \]  

(3)

Here, \( m_1 \) is the total mass of load, piston rod and piston components (kg), \( y \) is the displacement of piston rod (m), \( B_c \) is viscous damping coefficient, \( f \) is friction force of piston components and cylinder cube, piston rod and orientation cover and sealing rings (N).

3) Input flow of storage secondary components 2 working in motor \( q_2 \)

\[ q_2 = D_2 n + C_{i_2} p_2 + \frac{V_{i_2}}{\beta_c} \frac{dp_2}{dt} \]  

(4)

Here, \( D_2 \) is volume (m\(^3\)/rad), \( C_{i_2} \) is total internal leakage coefficient ((m\(^3\)/s)/Pa), \( p_2 \) is pressure between accumulator and secondary components 2(Pa), \( V_{i_2} \) is the total volume from secondary components 2 to accumulator (m\(^3\)).

4) Output torque of storage secondary components 2 working in motor \( T_{ac} \)

\[ T_{ac} = \frac{p_2 q_2}{2\pi\eta_2} \]  

(5)

Here, \( \eta_2 \) is efficiency of secondary components 2.

5) Balance equation of accumulator

\[ (p_a - p_2) A_{ac} = m_{ac} \frac{d}{dt} \left( \frac{q_2}{A_{ac}} \right) + \frac{B_d V_a}{A_{ac} dt} \]  

(6)

Here, \( p_a \) is the working pressure of accumulator (Pa), \( A_{ac} \) is the cross-sectional areas of chamber (m\(^2\)), \( m_{ac} \) is oil mass of pipes and accumulator (kg), \( B \) is viscous damping coefficient, \( V_a \) is volume of the accumulator (m\(^3\)).

6) Input torque of load secondary components 7 working in pump

\[ T_{cp} = T_{ac} - T_f \]  

(7)

Here, \( T_f \) friction torque (N \cdot m).

**Math Model for Falling**

1) The motion equations of load cylinder 10

\[ m_1 g = m_1 \frac{d^2 y}{dt^2} + B \frac{dy}{dt} + p_1 A_c + f \]  

(8)

2) Continuity equations of load secondary components 7 working in motor

\[ A_c \frac{dy}{dt} = D_1 n + C_c p_1 + \frac{V_0}{\beta_c} \frac{dp_1}{dt} \]  

(9)

3) Output torque of load secondary components 7 working in motor

\[ T_{cp} = \frac{p_1 q_1}{2\pi\eta_1} \]  

(10)

Here, \( \eta_1 \) is the total efficiency of secondary components 7.

4) Continuity equations of storage secondary components 2 working in pump
\[ D_2 \dot{n} = q_2 + C_{in} p_2 + \frac{V_{in}}{\beta_c} \frac{dp_2}{dt} \]  
(11)

(5) Balance equation of accumulator

\[
(p_2 - p_a)A_{ac} = m_{ac} \frac{d(q_2/ A_{ac})}{dt} + \frac{BdV_{ac}}{A_{ac}} dt
\]  
(12)

(6) Input torque of storage secondary components 2 working in pump

\[
T'_{ac} = T'_{cp} + T_m - T_f
\]  
(13)

The continuity equation was the same for the accumulator working under load lifting and falling.

**Performance Simulation**

Main parameters of hydraulic excavator are as below: work quality is 7000 kg, bucket capacity is 0.3m³, power is 48kW/2300rpm, the arm length is 3500mm, the bucket rod length is 2000mm, the working pressure is 22MPa. The main parameters of the lifting system are as below: the displacement of load secondary element 7 in the motor mode is 80mL/r, the nominal maximum displacement of energy storage secondary component 2 in variable pump mode is 100mL/r and accumulator charging pressure and volume are 12MPa and 16L. Control arithmetic adopts the fuzzy neural network control.

In order to get more reasonable simulation load, and can reflect the working characteristics of hydraulic excavator, choose the international general of a typical cycle: drop, mining to lifting rotate 90 degrees, and put the shovel, rotating back. The excavator is a typical cycle is 20s [5].

The displacement curve of hydraulic cylinder 10 is obtained by simulation as Figure 2. The speed curve of the load secondary components is shown in Figure 3. The pressure curve of the accumulator is shown in Figure 4[6].

![Figure 2. Displacement curve of hydraulic cylinder 10.](image1)

![Figure 3. Speed curve of load secondary components 7.](image2)

![Figure 4. Pressure curve of accumulator.](image3)

The simulation results are as follows:

Movable arm decline can be divided into three stages: acceleration, stability and deceleration. during the acceleration phase, and the potential energy of the lifting system has been transformed to kinetic energy to make the working device to accelerate the decline, while driving a load secondary element rotation speed. At the stage of stable operation, control system filling accumulator with liquid by real-time regulating the displacement of the storage secondary component, the potential energy has been transformed into hydraulic energy. In the deceleration stage, by real-time regulating the displacement of the storage secondary component, the kinetic energy and potential energy have been converted into hydraulic energy and deposited in the accumulator to realize the movable arm rapid brake.

At the movable arm lifting stage, the accumulator drives the storage secondary component rapid accelerating. The control system adjusts the displacement of the load secondary component to lift the movable arm in real time.
The recovery energy is 0 when the movable arm is accelerating to decline. After the completion of the movable arm declining, the accumulator pressure is increased from the initial 12MPa to 22.6MPa, which realizes the recovery of potential energy.

Conclusions

The flow coupled secondary hydraulic lifting system of the excavator bucket, when it worked in non-constant pressure network, compared to the pressure coupled of constant pressure network, its pressure range was expanded. So by controlling the accumulator, the energy recycling was realized, this would ensure higher oil pressure of the accumulator, the reusable effect was improved.

With secondary regulation flow coupled contact hydrostatic transmission technology, the gravitational energy of the excavator bucket and load can be reclaimed in the falling process, and can be reused in the lifting process of the excavator bucket and load. So the engine installed power has been reduced to achieve the purpose of energy saving and environmental protection.

References


