Research on Secondary regulation in Swing System of different tonnage Hydraulic Excavator

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Abstract

The paper regarded the different tonnage hydraulic excavator as the research objects, proposes a hydraulic slewing system based on secondary regulation control, calculating the rotary system energy recovery efficiency, verify scope of application and energy saving effect of accumulator. In the constant pressure network, secondary regulation system can make variable motor reach the set speed quickly and smoothly through the motor PID feedback control, which can control power of the whole system and the general volume transmission system mainly through changing the flow of pump. Choosing the bag type accumulator that was widely used as the energy storage component, obtaining the working parameters and through building the model of rotary system, theoretical calculation and AMESim simulation software, acquiring recycling of energy of three different tonnage hydraulic excavators. At the same time, the research that energy recovery efficiency of different tonnage hydraulic excavator provides the theory basis for enterprise to improve excavator energy saving efficiency.

Keywords

different tonnage Hydraulic Excavator; Swing System; Secondary regulation; energy accumulator; AMESim.

1. Introduction

The excavator is widely used as primary production equipment in mining, coal, water conservancy, open-pit mining, and other fields. As shown by Fig. 1, hydraulic excavator mainly consist of upper structure, boom, stick, bucket and chassis. Except the chassis and walk mechanism ,the other parts are arranged on the upper structure in integral structure of excavator. The shovel attachment is taken a connection on the upper turning platform in the form of a hinge. And the swing bearing connects upper structure with lower walk mechanism, which is driven by rotary motor with retarding mechanism and divided into two parts. The upper structure and work attachment, as illustrated by Fig. 1 can be rotated about the axis OO' passing through the machine cabin. The machine cabin is located beside arm in the front of platform, that ensure the driver can observe fully the working of work attachment , improve the working efficiency and avoid safety accident. The crawler walking is composed of four wheels and a caterpillar, which's straight and turn is driven by travel motor independently.

Swing motion is one of the fundamental motions of a hydraulic shovel, which is usually driven by hydraulic motors. Statistics show that swing motion accounts for 35% of the shovel's total operational time [1]. The braking potential energy is dissipated into heat in the motor of the hydraulic swing system. The time in rotary movement of hydraulic excavator slewing system take up the entire work cycle by 50% ~ 70%, While the energy consumption accounts for about 25% ~ 25% of total energy loss[2]. So it is required for us to make maximum use of regenerative energy for further improvement of fuel consumption and also to ensure higher system control performance equivalent to that of conventional control system[3-5,6].

Since the 1970 s foreign researchers began to study the electromechanical integration technology and applied to the excavator. After entering the 80 s, the United States, Germany, Japan and other countries started developing hydraulic excavator with the electronic energy saving. Many excavator manufacturers in the world is developing energy recovery of rotary system, such as Komatsu Hydraulic Energy Recycling System[7]. The small quantitative pump supply power for motor, which connect with an accumulator by an oil filled valve. And the oil filled valve is made up of the pressure valve and hydraulic controlled check valve[8]. The system makes full use of the accumulator recycling the loss of kinetic energy when excavator braking, and then provides energy for the next rotary movement. The recycling energy can be stored in accumulator in KHER, and release in the next exercise. The energy consumption rate reduce about 5%and volume of the unit time increases about 3% with KHER system. For energy recovery problems in slewing system of excavator, Yan-ting zhang et al put forward the solid of revolution driven by hydraulic motor as external load in hydraulic system for a experiment. By comparing with the system energy consumption without energy saving device, it concludes that energy saving rate is about 30.1% with energy recovery system[18]. The energy recovery system technology research of hydraulic excavator main including: firstly, the system structure and principle of design; Secondly, the components selection and parameter matching optimization; thirdly, it is analysis of load model and power matching; Fourth, energy recovery and distribution control strategy[9] . Above all, these researchers emphasize on hydraulic accumulator to realize energy recovery. Hydraulic accumulator has the characteristics of higher power density and is well suited for frequent acceleration and deceleration under city traffic conditions. It can provide high power for accelerations and can recover more efficiently power during regenerative braking [10] in comparison with electric counterparts. However, the relatively lower energy density brings the packaging limit for the increasing accumulator size [11].

The negative flow control technology was used in the famous PC series excavator in Japan komatsu named as OLSS (Open Center Load Sensing system) ,which is also the earliest pushed and applied by komatsu [12-15]. The negative flow control keeps the flow back to tank in small constant value by controlling the hydraulic pump displacement, and eventually eliminate the loss of oil return to tank in technology. Among them, the control signal of hydraulic pump is decided by flow detection device connected with the middle of reversing valve. The positive flow control is also applied to the excavator, which is EX400 hydraulic excavator producted by the most typical HITACHI[16]. The positive flow control directly controls the displacement of the pump through the pilot pressure signal, and the displacement's increase and decrease of pump is proportional to the pilot pressure. In addition to hydraulic system, the research of energy saving measures also involved in power matching control method and technology between the engine and hydraulic system. SK200 dynamic model is a kind of typical pump and engine joint control system [17]. Literature [18] explain the fuel efficiency experiments between full power ordinary excavator and pump – energy saving control system of excavator, and found that the latter's fuel efficiency is about 18% higher than the former.

In the 1970 s, Germans first advanced the theory of secondary regulation, which can avoid overflow and throttling loss, and has good dynamic and static characteristics. The secondary regulation technology is a new kind of energy-saving way to hydraulic system with strong feasibility , there are relative traditional energy-saving ways ,such as power adaptive control and power matching control [19]. Secondary regulation transmission technology is a hydraulic transmission technology, which controls secondary element (hydraulic motor/pump) in closed-loop in constant pressure network. This kind of hydraulic transmission technology can not only directly adjust the load displacement, speed, torque and power, but also have played an important role in improving the efficiency because of accumulator as energy storage element. In modern buildings, the elevator is the indispensable transport equipment, and the elevator energy consumption is about 3/7 of the building energy consumption. Therefore, the secondary regulation based on energy recycling is used in drive system of elevator, and there is a significant energy saving effect. If the loss kinetic energy when braking used for the next starting, as the car needs frequent starting and braking, it realized save fuel and reduce emissions. In 1997 (RIQ), Pawe1Ski, R.E published an article, that the city public transport vehicles are equipped with secondary regulation device, the results show that modified accumulator provided energy about 150 kw for city bus, and the engine only provide 30 kw. When the secondary regulation system is used in excavator, Hydrostatic secondary control exhibits good dynamic performance and promotes power recovery and can therefore be used in a loading system with power recovery[20-21]. And this paper will use secondary regulating system for different tonnage hydraulic excavator for energy saving and reuse, to solve the problem of the energy consumption. At the same time, it proves the accumulator's applicable scope and effect of energy-saving technology.

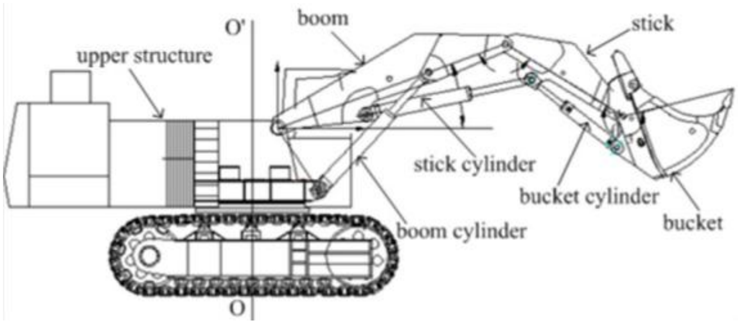

Fig.1 diagrammatic sketch of a large hydraulic excavator

2. Parameters Settings

2.1 Parameters of Hydraulic Components

The model of grasp steel machine is obtained the full load moment of inertia of rotation is 905900 kg• m^2, no-load rotation inertia is490334 kg• m^2 by calculation.

$$T=(t_Q+t_Q^o)+(t_y+t_y^o)+(t_z+t_z^o)=\frac{J_o(1+\lambda)\omega_Q}{2KM_Q}\times(1+\frac{1}{C})+\frac{2\phi}{\omega_Q}(s) \quad (1)$$

t_Q - starting time of full bucket on turntable; t^o_Q - starting time of empty bucket on turntable; t_y, t^o_y - rotation time in uniform speed with full and empty bucket; t_z, t^o_z - rotation time in braking with full and empty bucket; ω_Q - rotary angular velocity; M_Q - rotary starting torque; m; ϕ - corner; C - coefficient, C = 1.361; $\lambda=J/Jo$, Jo, J - rotary inertia of empty and full bucket; K - related with the friction coefficient, the value is 0.87 ~ 0.92.

Put $M_Q=\frac{1000N\eta_Q}{K\omega_Q}$ into the formula 2-1:

$$T=\frac{J_o(1+\lambda)\omega_Q^2}{2000N\eta_o}\times(1+\frac{1}{C})+\frac{2\phi}{\omega_Q} \quad (2)$$

In the formula, N - hydraulic power of slewing mechanism; ηo - total efficiency of slewing mechanism.

The formula of best speed of the slewing platform from $\frac{dT}{d\omega_Q}=0$, $\frac{d^2T}{d^2\omega_Q}>0$:

$$\omega_Q=\omega_{\max}=\sqrt[3]{\frac{2000N\eta_o\phi}{J_o(1+\lambda)(1+\frac{1}{C})}} \quad (3)$$

Highest rotary motor speed:

$$M = \frac{\mathrm{p} \times q \times \eta_m^N}{6.28} = \frac{26 \times 160 \times 0.97}{6.28} = 643(N \cdot \mathrm{m}) \tag{4}$$

In the formula, P - import and export pressure of motor, turn rotary overload pressure is 26/12 Mpa; η_m^N , η_v^M - the volume efficiency and mechanical efficiency of motor are 0.97.

The rotary deceleration machine is GFB110T3, speed ratio i_1 = 80.52, the output gear Z_1 = 13. The rotary rolling plate is 134.45.2139, Z_2 = 82, the speed ratio i_2 = 82/13 = 6.31.

Maximum speed of slewing platform:

$$\mathrm{n}_{\max} = \frac{n_{\max}}{i_1 \times i_2} = \frac{3872}{80.52 \times 6.31} = 7.6(r / \min) \tag{5}$$

$$\omega_{\max} = \frac{n_{\max} \times 2\pi}{60} = \frac{7.6 \times 2\pi}{60} = 0.795(rad / s) \tag{6}$$

In this paper, the research object is three different tonnage of excavator in factory, the weight is respectively 7 tons, 100 tons and 220 tons. The selection of accumulator in slewing system is decided by excavator’s weight, and the needs to satisfy the following goals:

1) P_2 is determined by the maximum pressure of the whole system, and P_2 is 26.4MPa;

2) Accumulator as to be an auxiliary power source, the general P_1 is 0.6~0.85P_2 .if we consider prolonging service life of bladder accumulators, concluding $P_2 \le 3P_1$. Based on the above conditions, P_1 is 95~20MPa.

3) Hydraulic accumulator to store and release energy is

$$E = \int_{V_{1a}}^{V_{2a}} pdV = -\int_{V_{1a}}^{V_{2a}} (\frac{V_0}{V})^{1.4} dV = \frac{P_0 V_0}{0.4}[(\frac{P_{2a}}{P_0})^{0.286} - (\frac{P_{1a}}{P_0})^{0.286}].$$

When $P_{1a} = P_0$ and $P_{2a} = P_2$, hydraulic accumulator has maximum energy absorption, and we can get P_0=0.308P_2=8MPa.

4) The inflatable volume of the accumulator is $P_0 V_0^{\ n} = P_1 V_1^n = P_2 V_2^{\ n} = const$;

When the accumulator in an adiabatic process, the volume of the inflatable is $V_0 = \frac{V_w}{P_0^{\frac{1}{n}}[(\frac{1}{P_1})^{\frac{1}{n}} - (\frac{1}{P_2})^{\frac{1}{n}}]} = \frac{V_1 - V_2}{8^{0.714}(0.05^{0.714} - 0.038^{0.714})} = \frac{V_1 - V_2}{0.0925}$, and $V_0 \approx 18L$.

The parameters of accumulator of hydraulic energy-saving system in type of 7 tons and 220 tons excavator can be obtained in the same way, as follows:

Tab.1 Basic parameters of Accumulator

	initial pressure of accumulator P0(MPa)	volume of accumulator V0(L)
7T	4.7	11
100T	20	18
220T(Double rotary)	25	25

2.2 The Parameter of PID

The PID control is proportional, integral and derivative control. Select the PID coefficients is critical, it is related to the stability of the entire system, the proportional coefficient K_p can improve the response speed of the system, the integral coefficient K_i can improve the stability of the system, the differential coefficient K_d can eliminate the error of the system. PID control method for solving a lot, for example: Ziegler-Nichols entire titration, Cohen-coon entire titration, critical proportion of the law, trial and error method.

In this paper, we choose the method of Ziegler-Nichols.

Ziegler-Nichols method is a design method based on the frequency domain, the design method in the frequency domain to some extent, avoided the accurate modeling of the system, and has a clear physical meaning more than the conventional PID controller can be adapted to the case of more. In a real industrial control systems, most of the controlled object can be used in order inertia plus dead links to summarize the mathematical model [7]is: $G(s) = \dfrac{Ke^{-\tau s}}{Ts+1}$.

In the above formula K is the amplification factor, T is the delay time constant [5], Programming parameters in Matlab obtained graph shown in Figure 3. Among them, the value of $K_p = 1$, $K_i = 0.01$, $K_d = 0.1$.

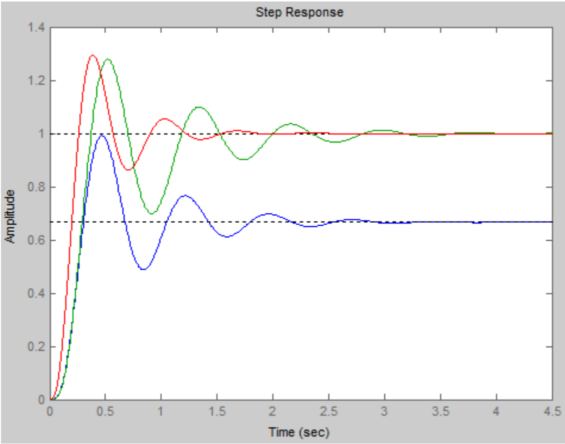

Fig.2 Curve graph of Kp, Ki and Kd

3. Simulation and Analysis of Excavator Slewing Energy-Saving Model

3.1 The Simulation and Analysis of the Original Model

The slewing system of hydraulic excavator in some company, as shown in figure 3. In order to verify the correctness of the energy-saving system, original rotary system of excavator is built firstly. And the model is setted up in AMESim, as shown in figure 4.The rotation of motor 9 is accomplished by pressure difference of oil, which is from constant power pumps 2 to drive motor 7 through pilot control reversing valve 4. The overflow valve 7,8 and check valve can control the starting and braking pressure of motor, when platform is turning. If the slewing platform turn too fast, check valve 5,6 can fill oil in time. And the main relief valve 3 ensure the system security. The pressure simulation curve of motor is shown in figure 5.

As shown in figure 7, the curve of motor speed shows a "double trapezoid" that corresponds to the actual condition. According to the pressure characteristic curve, the speed of the rotary motor starts to increase when the excavator slewing system is starting, then less oil is absorpted by motor and redundant oil has a larger impact on the hydraulic system, this oil will overflow through the overflow valve When the time between 0 to 7.01 s and 25.89 to 32.03 s, the motor is at the accelerating stage and needs large starting torque, so one side pressure of motor will reach 260 bar, however the other side pressure is almost zero. When the time between 7.01 to 15s and 32.02 to 39.98s, the motor displays uniform rotation, the inlet pressure drop to 58 bar and the outlet pressure is about 3 bar. When the time between 15 to 20.36s and 32.03 to 45.51s, the motor is braking, the oil is blocked by motor, so the inlet pressure is zero and the outlet pressure will reach about 130 bar. At this point, all kinetic energy of motor will convert to heat dissipation. Motor inlet and outlet pressure simulation curve are basically match up with the measured curve. Motor inlet and outlet pressure curve and motor speed simulation curve are also consistent with the actual working condition, which can be used for further research.

Fig.3 The Slewing mechanism of Excavator

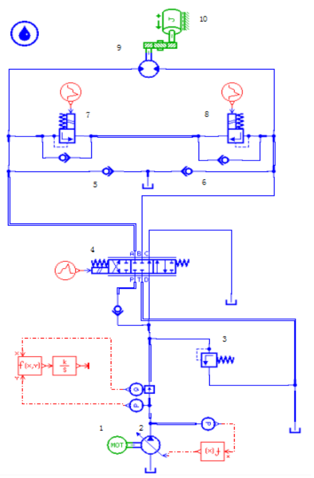

Fig.4 The Simulation Model of Slewing System of grasp steel machine

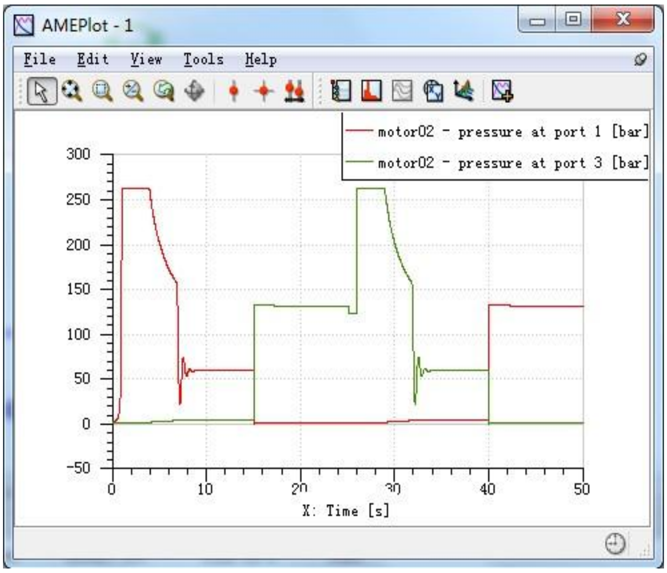

Fig.5 The actual measurement inlet and outlet oil pressure of motor

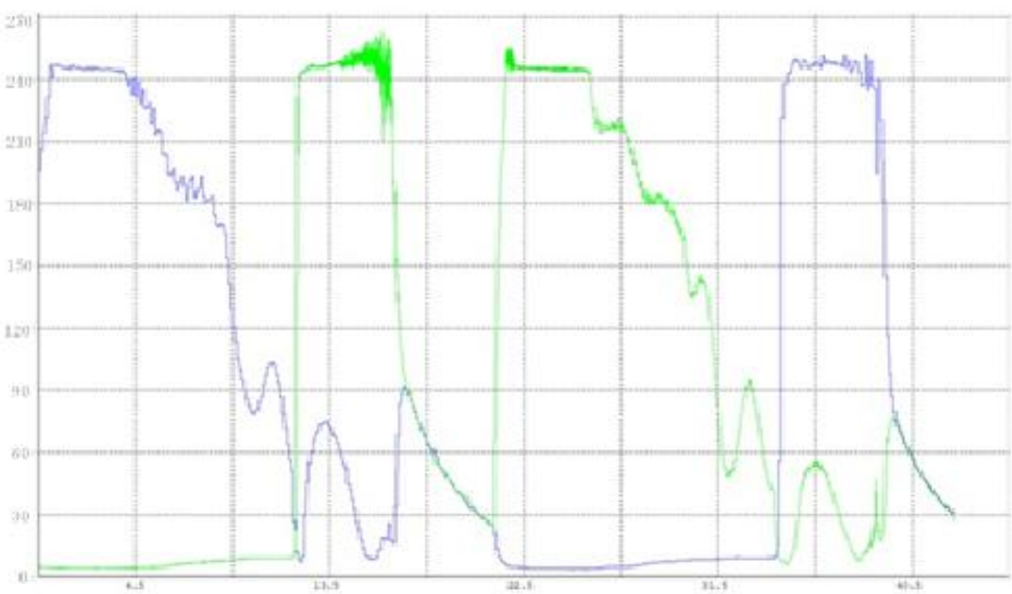

Fig.6 The inlet and outlet oil pressure of motor

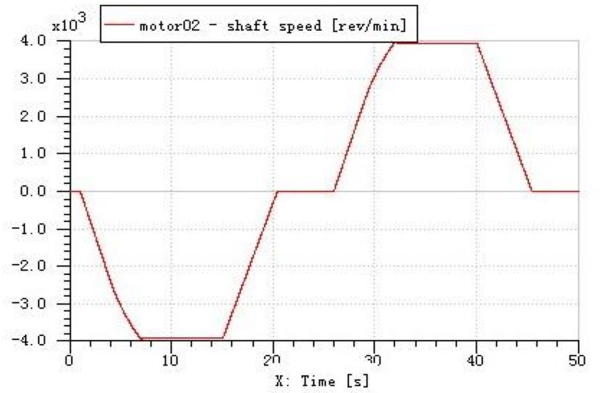

Fig.7 Speed of Motor

3.2 Simulation and Analysis of Swing System based on Secondary Regulation

According to the hydraulic swing system of 100 tons of excavator, the design of the rotary energy saving system is based on the secondary regulation and the model in AMESim is shown in figure 8.

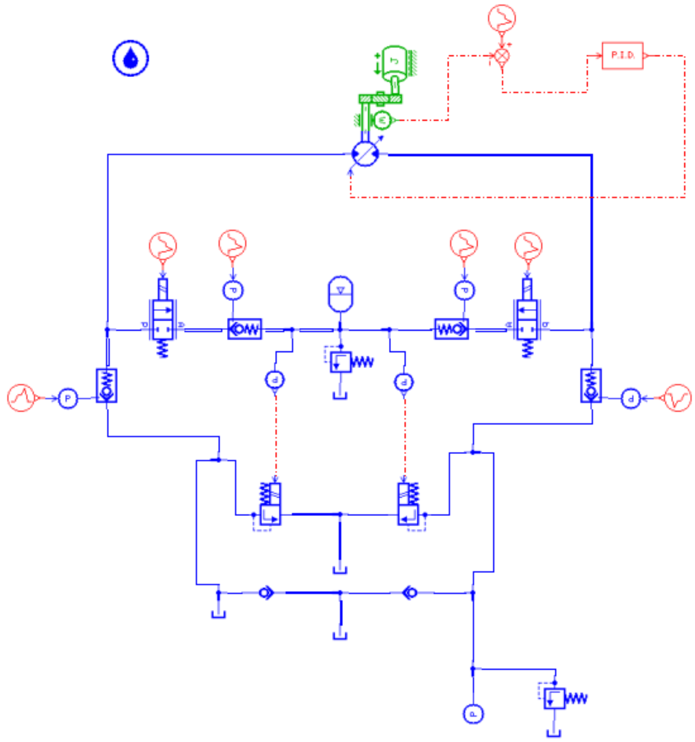

Fig.8 model of a 100-ton excavator rotary energy saving system

The motor rotating speed and the pressure and volume comparison chart of accumulator can be acquired by the AMESim simulation , and as shown in figure 9 and 10. The figure 2 has clearly shown that accumulator collects the overflow energy in the time from 1s to 13s.At this time, accumulator pressure increases from 200 bar to 260 bar and volume is compressed from about 18 L to 13.5 L. In the time from 13s to 26 s, accumulator recycles braking energy and the pressure increase sharply from 260 bar to 400 bar, volume is compressed from 13.5 L to 11.8 L.Starting from the time of 26s, the energy that is released by accumulator will be used for the next turn. As shown in figure 9, motor speed has an obvious acceleration .

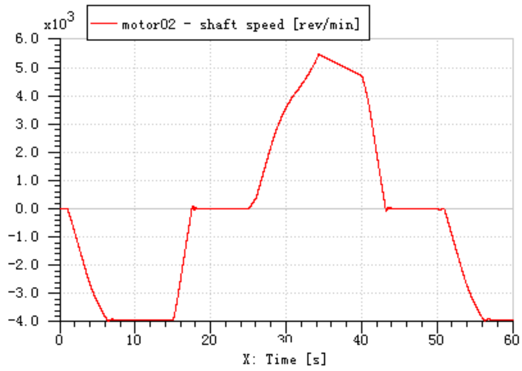

Fig.9 motor rotating speed

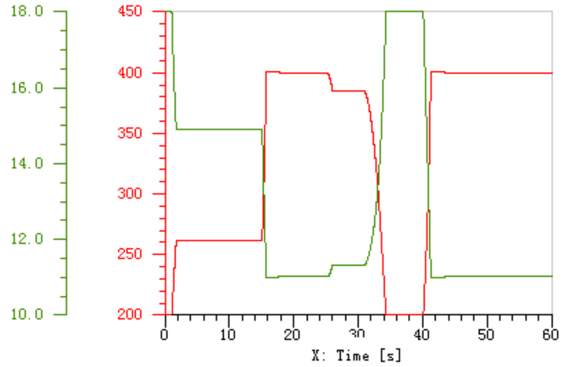

Fig.10 accumulator pressure and volume comparison chart

In the braking stage, the time is form 15s to 25s, all the energy recycled by accumulator is:

$$E_1 = P_B V_B - P_A V_A = 40 \times 11.8 - 26 \times 13.5 = 121(kJ)$$

The braking energy loss in the time form turntable starting braking to the end is:

$$E = 0.5 J \omega_2{}^2 = 0.5 \times 1. \times 10^6 \times (8/60 \times 2\pi)^2 = 350(kJ)$$

The energy absorbed by accumulator in possession of percent of theoretical energy is:

$$\frac{E_1}{E} \times 100\% = \frac{121}{350} \times 100\% = 34.57\%$$

In the time from 25s to 40s, accumulator individually drives motor for a period of time, the energy release of the accumulator is:

$$E_2 = P_{B'} V_{B'} - P_{A'} V_{A'} = 20 \times 18 - 38.4 \times 11.3 = -73.92(kJ)$$

$$P_3 = \frac{|E_2|}{t} = \frac{73.92}{3.73} = 19.82(kJ)$$

Percent of accumulator energy release in possession of absorbing energy is:

$$\frac{E_2}{E_1} \times 100\% = \frac{73.92}{121} \times 100\% = 61.1\%$$

The main components parameters of slewing energy-saving system of excavator in the weight of 7 tons conclude the moment of inertia for 24590 $kg \cdot m^2$ when slewing platform working in full bucket, the moment of inertia for 15112 $kg \cdot m^2$ when platform hollow rotary, motor speed for 2100 rev/min, displacement of variable pump for 30cc/rev, variable pump speed for 2000 rev/min, the motor parameters for 44cc/rev, 1700 rev/min and load for 20000 $kg \cdot m^2$.

The main components parameters of slewing energy-saving system of excavator in the weight of 220 tons conclude the moment of inertia for 5766214 $kg \cdot m^2$ when slewing platform working in full bucket, the moment of inertia for 3543819 $kg \cdot m^2$ when platform hollow rotary, motor speed for 2200 rev/min, displacement of variable pump for 190cc/rev, variable pump speed for 2200 rev/min, the motor parameters for 125cc/rev, 1000 rev/min and load for 3000000 $kg \cdot m^2$.

On the basis of the slewing system schematic diagram of a certain company 7 tons of excavator, using AMESim software to build energy-saving model, which is the same with 100 tons of energy-saving model as shown in figure1. 220 tons of excavator slewing energy-saving model as shown in figure 4.

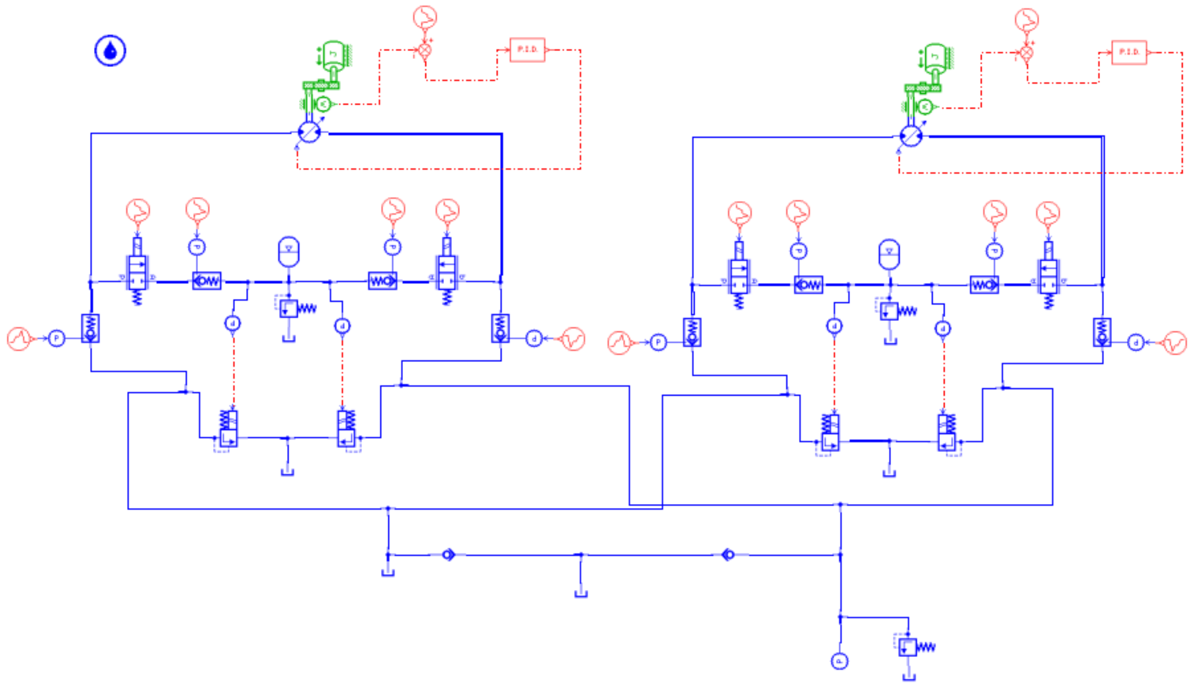

Fig. 11 Model of the 200 tons excavator rotary energy saving system

Based on the simulation model, we can obtain 7 tons and 220 tons of excavator rotary motor speed as shown in figure 12 and figure 13, accumulator recovery and release energy respectively as shown in figure 7 and figure 8.

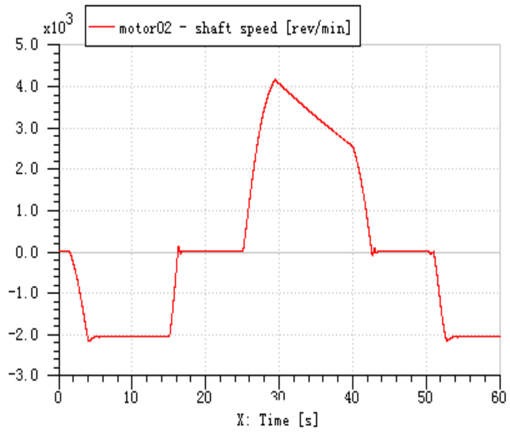

Fig.12 7tons excavator rotating motor speed diagram

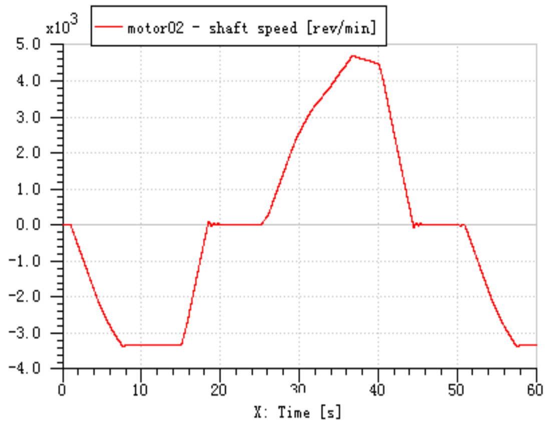

Fig.13 220tons excavator rotating motor speed diagram

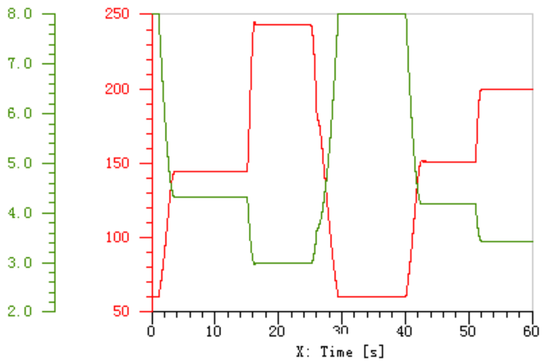

Fig. 14 7tons excavator comparison of the pressure and volume curve

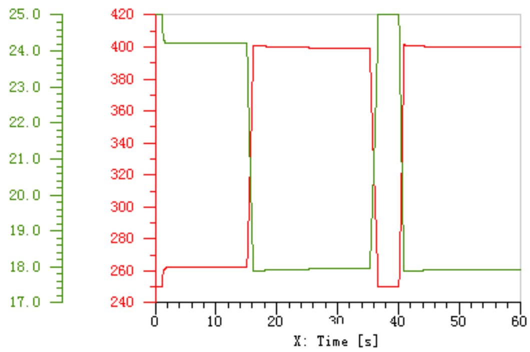

Fig.15 220tons excavator comparison of the pressure and volume curve

The energy analysis method of rotary energy-saving system of the 7tons and 220tons excavator is the same as the 100 tons analysis method. Table 2 is shown as follow by means of calculation and validation.

Table 2 energy-saving in swing motion of 7 tons, 100 tons and 220 ton excavator

Weight of excavator	recovered energy of the accumulator(kJ)	energy absorbed by accumulator in possession of percent of theoretical energy (kJ)	Percent of accumulator energy release in possession of absorbing energy(kJ)
7tons	1.8	57.70%	50.6%
100 tons	76	34.57%	61.1%
220 tons	80.17	19.50%	82.2%

4. Conclusion

1). Based on a company of three types of excavator as the research object, we can find the difference in accumulator energy recovery condition of different tonnage of excavator slewing system through calculation as follow:

a) Accumulator is a common component used in design of energy-saving hydraulic system. It can collect waste hydraulic energy in overflow starting and braking stage when it is applied to excavator slewing system. It can also reclaim gravitational potential energy when accumulator is used to the mobile arm system of excavator.

b) The smaller tonnage of excavator slewing system has, the smaller energy is recycled by accumulator in rotary energy-saving system. At the same time, the rotary platform and the moment of inertia also become smaller. As a result, the recovered energy is accounting for more percentage of the theoretical energy, the energy released by accumulator has a large percentage of absorption energy, so the recovery effect is more ideal. Accumulator in large tonnage of excavator slewing system can recycle more energy and releasing energy has more percentage of absorption energy, however, recycling energy has little percentage of theory energy because of the larger moment of inertia of slewing platform and upper structure.

It can be seen from table 3, the larger tonnage of excavator has, the more energy absorpt by accumulator, releasing energy has more percentage of absorption energy, then the absorption energy by accumulator has little percentage of theory energy.

2). Through simulation analysis in different tonnage excavator rotary energy-saving system, we can concluded that accumulator energy absorption and utilization rate, that is in analysis model, can be used for small tonnage excavator and the recovering effect is better.

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