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A NOVEL HYBRID SWING SYSTEM AND ENERGY REGENERATION TIME CONTROL

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Abstract. Facing the energy crisis, energy saving of excavator is important. Hybrid technology is successful in vehicle engineering, which can be used in hydraulic excavator for energy saving. The swing system of hydraulic excavator have large potential to regenerate energy. This paper proposed a novel hybrid hydraulic swing system, in which the hydraulic accumulator is used to regenerate energy. Considering the system performance, the energy regeneration time control is proposed in this paper. The experiment results show that the energy regeneration time affect the system performance. The designer should balance the energy regeneration and performance.

Keywords: Energy regeneration, Energy regeneration time, System performance

1. INTRODUCTION

The hybrid hydraulic excavator has lower fuel consumption than the conventional hydraulic excavator [1-3]. The swing system is a very important part in hydraulic excavator, which has the potential to regenerate the kinetic energy. An electric hybrid swing system could get high energy saving efficiency [4]. However, the system was very costly, because the electric motor, generator and battery or supercapacitor were used in the system. The hydraulic hybrid system uses hydraulic accumulator to store the regeneration energy, which is cheap and easy to arrange in hydraulic circuit.

This paper focuses on research of a swing system of the hydraulic hybrid excavator. During deceleration, the kinetic energy of swing system will be regenerated. A low costs hydraulic hybrid swing system was proposed and the energy regeneration time control is proposed to satisfy the requirement of system performance.

2. STRUCTURE OF THE SYSTEM

This paper focuses on the energy regeneration during deceleration. The hydraulic circuit is shown in Fig.1. A fly wheel is used in the test bench instead of the upper structure of the excavator. It is connected to the hydraulic motor coaxially. The hydraulic accumulator can only store the regenerated energy in the test bench. The mechanical brake isn't setup in the test bench, because this paper only researches the hydraulic brake during deceleration. The parameters of the test bench are shown in table 1.

TABLE 1. Parameters of the test bench

Component	Value	Remark and unit
Fly wheel	8.985	Moment of inertia (kgm2)
Hydraulic pump	12	Displacement of hydraulic pump (mL/r)
Hydraulic motor	28	Displacement of piston hydraulic motor (mL/r)
Accumulator	4*2, 20	Volume (L), Precharge pressure (bar)
Electric motor	7500	Rated power (w)
Relief valve R1 and R2	350	Relief pressure (bar)

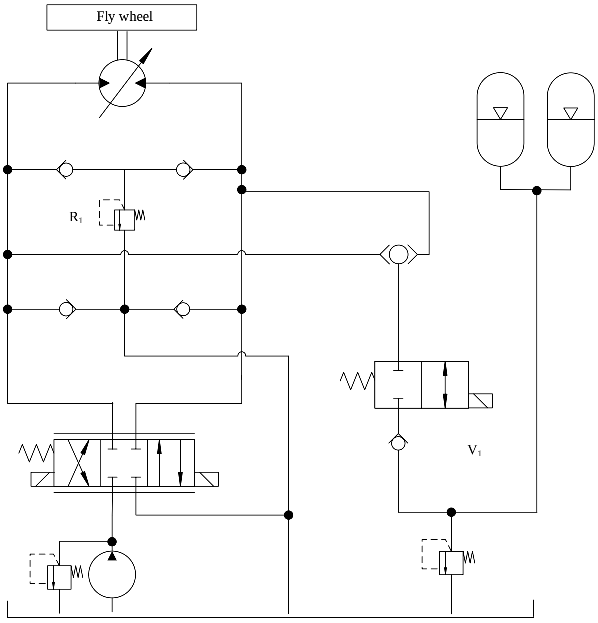

Fig.1 Hydraulic circuit of the test bench

3. CONTROL STRATEGY DESIGN

3.1 Analysis of the proposed system

There are two targets mainly of the control strategy design. Firstly, the energy saving efficiency should be acceptable. Secondly, the performance of the system should not be worse than the conventional system. One experiment was done to analyze the system performance and energy regeneration. Firstly, set the pressure of hydraulic accumulator to 40 bar and accelerated the fly wheel to 400 RPM. Secondly, opened the valve V1 and started to regenerate energy from 18.5 seconds with maximum displacement of hydraulic motor. Finally, when the fly wheel was stopped, closed V1 and stopped energy regeneration. The experiment results are shown in Fig. 2. The diagram of (a) and (b) showed the speed of the flywheel and the pressure of hydraulic accumulator and output side of the hydraulic motor. The flywheel was stopped at 35 seconds approximately. The deceleration time was about 16 seconds. Finally, the pressure of accumulator was charged to 53 bar.

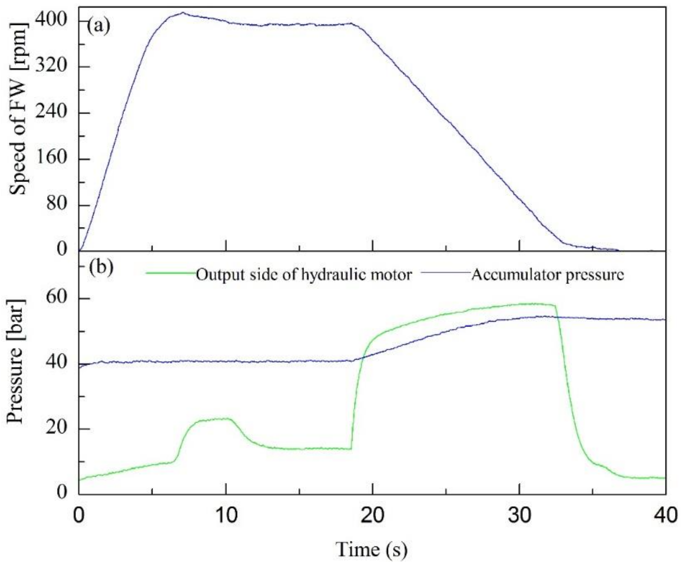

Fig. 2 Experiment results

During deceleration, the fly wheel satisfied the equation 1.

$$J\dot{\omega} = T_{\mathrm{dec}} + T_{\mathrm{f}} + T_{w} \tag{1}$$

where J is the moment of inertia of the flywheel, ω is the speed of the flywheel, T_f is the coulomb friction torque and T_w is the torque due to wind, T_{dec} is the deceleration torque of the hydraulic motor, which is shown in equation 2.

$$T_{\mathrm{dec}} = \frac{p_{out}D}{2\pi}\eta_{\mathrm{m}} \tag{2}$$

where p_{out} is the pressure of output side of the hydraulic motor, D is the displacement of the hydraulic motor and ηm is the torque efficiency of the hydraulic motor. The green line in Fig. 2 (b) is p_{out}. The displacement of hydraulic motor satisfied the following equation:

$$D = \alpha D_{\mathrm{max}} \tag{3}$$

Where, D_{max} is the maximum displacement of the hydraulic motor and α is the variable, which can be used to control the displacement of the hydraulic motor.
During the deceleration, the accumulator was charged and satisfied the equation 4.

$$p_{\mathrm{gi}} V_{\mathrm{gi}}^{\mathrm{n}} = p_{\mathrm{g(i+1)}} V_{\mathrm{g(i+1)}}^{\mathrm{n}} \tag{4}$$

Where p_g and Vg are the pressure and volume of the gas in accumulator, n is the adiabatic exponent (n=1.4) and i and i+1 are the indexes of i state and i+1 state. During charging of accumulator, the volume of gas is decreased and pressure is increased. The gas pressure is equal to the pressure of fluid in the accumulator. During deceleration, the pressure of output side of hydraulic motor was affected by the pressure of accumulator, which can be seen in Fig 2. The pressure drop of the valves existed, otherwise the pressure of accumulator should equal to the pressure of output side of hydraulic motor. According to equation 2, different pressures of accumulator will generate different deceleration torque. To decrease the affection of the varying accumulator pressure and ensure the performance of the system during deceleration, the displacement of hydraulic motor should be controlled.
Even if using the maximum displacement of the hydraulic motor in the experiment, the deceleration time was so long that it was unacceptable in real excavator. Duo to the low pressure of accumulator in the experiment, the deceleration torque was small. If close the valve V_1 during deceleration, the hydraulic accumulator pressure won't affect the deceleration torque. High pressure will be generated at the output side of hydraulic motor to brake the flywheel. However, the system won't regenerate energy. Therefore, the valve V_1 should be controlled to regulate the energy regeneration time and balance the system performance and energy regeneration efficiency. According to above analyses, the displacement of hydraulic motor and energy saving valve should be controlled to ensure the performance of the swing system and improve the system efficiency.

3.2 Energy regeneration time

This paper decides to regenerate energy at the beginning of deceleration, because the flywheel is running at high speed at the beginning of the deceleration. The flow rate is also high, based on the equation 5. Hence, much energy can be regenerated at the beginning of deceleration. The pressure of accumulator in Fig.2 also shows this phenomenon. The pressure of hydraulic accumulator increased fast at the beginning of deceleration. At the end of deceleration, the pressure increase became slowly. The time of energy regeneration is named energy regeneration time. This process is named energy regeneration process. During this process, V1 is open.

$$Q = D\omega\eta_{v} \tag{5}$$

where Q is the flow rate of the output side of the hydraulic motor and η_v is volumetric efficiency of the hydraulic motor.
After the energy regeneration process, the energy regeneration valve V1 will be closed. The pressure of output side of hydraulic motor will increase to decelerate the flywheel. This stage is named normal deceleration process. In this stage, the most crucial point is the relief pressure of valve R1. This paper sets the relief pressure to 350 bar. It is a high pressure to ensure enough deceleration torque to decelerate the flywheel. During deceleration, the deceleration time divided to two parts, which can be seen in equation 6.

$$t_{\mathrm{dec}} = t_{\mathrm{reg\_dec}} + t_{\mathrm{nor\_dec}} \tag{6}$$

where t_{dec} is deceleration time, t_{reg_dec} is energy regeneration time of energy regeneration process and t_{nor_dec} is deceleration time of normal deceleration process. The deceleration time is decided form the joystick signal.

4 EXPERIMENT AND ANALYSIS

According to the theoretical analysis in section 3, the deceleration time, flywheel speed and accumulator pressure affect the energy regeneration time. The experiments will be done to verify the characteristic. Set the initial speed of fly wheel, deceleration time and initial accumulator pressure to 400rpm, 4 seconds and 40 bar. The initial pressure of accumulator is set by manual operation, so there are some errors. Firstly, ran the flywheel at 400 rpm. Secondly, when the speed of flywheel was stable, started to decelerate. Open the valve V1 for 1.5s. Finally, the experiment results were shown in Fig.3. The control command of flywheel speed was the green line in Fig.3 (a). The deceleration time is from 10 seconds to 14 seconds. From 14 seconds to 16 seconds, the contra rotation was happened. However, the speed sensor only output positive value, so the errors were generated. It is assumed that the flywheel is stopped when the speed of flywheel is below 50 rpm and neglect the errors of contra rotation. In the real excavator, the mechanical brake will operate to brake the upper structure of excavator instantaneously when the speed of hydraulic motor is very low such as below 50 rpm. However, a mechanical brake is not setup in the test bench. As shown in Fig. 3, from 10 seconds to 11.5 seconds, the speed decelerated slowly, because the valve V1 was open to regenerate energy and pressure of accumulator was very low. Then the system finished deceleration at 14 seconds. It satisfied the requirement of 4 seconds deceleration. Even if the speed of flywheel did not follow the control command exactly, this performance was acceptable for the hydraulic excavator as a construction machinery. This experiment is named experiment (A). The experiment (B) was done with 1 second of energy regeneration time. Other settings were the same as the experiment (A), with the purpose of comparison. The experiment results were shown in Fig.4. Duo to the short energy regeneration time, the performance of system was improved. However, the accumulator pressure was lower than experiment (A) at the end of energy regeneration process. It means the regenerated energy was decreased. The experiment results of Fig. 2 in section 3 showed more regenerated energy than experiment (A). However, the performance of the system cannot satisfy the requirement. Among these three experiments, the experiment (A) satisfied the requirement of performance, and regenerated more energy than experiment (B), so the energy regeneration time in experiment (A) was the best chose among these three experiments.

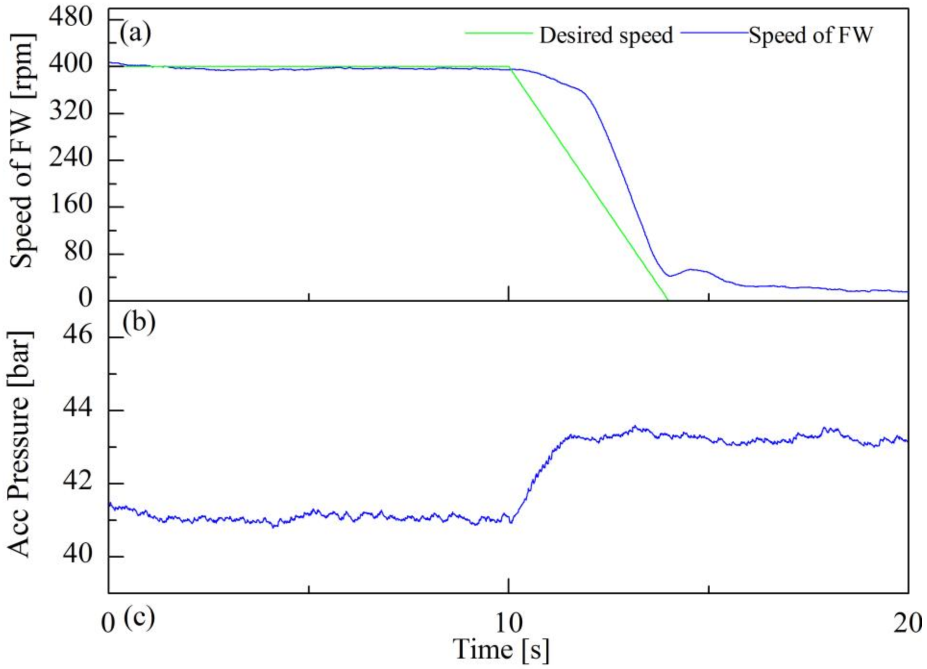

Fig. 3 Results of experiment (A)

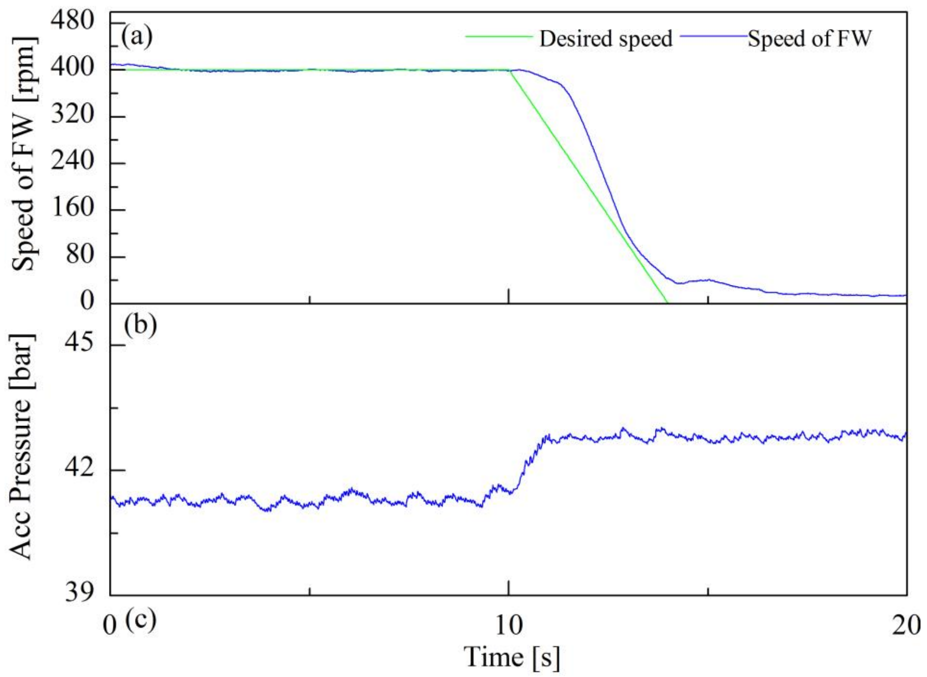

Fig. 4 Results of experiment (B)

5 CONCLUSIONS

This paper designed a new structure of swing system of the hydraulic hybrid excavator. The energy regeneration time control is proposed in this paper. Three experiments were done to show the importance of energy regeneration time control, which affect the energy saving efficiency and system performance. This factor is very useful to guide the future research.

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