Research on a new energy-recovery system for hybrid hydraulic excavators

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Abstract. Hydraulic excavators, especially medium and large excavators, waste a lot of energy during the frequent lifting-lowering process of its boom. Recovery and regeneration of wasted energy is an important means to achieve energy saving and emission reduction of excavators. In this paper, a potential energy recovery and regeneration system based on a multi-cylinder structure working device is invented. Firstly, the theoretical analysis of the system, and the modeling and simulation research are carried out. Results show that under the same boom-single-action conditions, the energy-saving efficiency of the excavator equipped with energy recovery system can reach 33%, it has important reference significance for evaluating the energy efficiency of the new system.

1. Introduction

Resource shortages and environmental pollution are increasingly urgent global issues that promote the development of energy-saving and emission reduction technologies[1]–[3]. As typical engineering machines, hydraulic excavators (HEs) possess characteristics of large usage, high energy consumption, and poor emissions[4]. HEs generally consume a large amount of energy on inertia movement by which the platform of HEs accelerates and brakes frequently, leading to extremely low energy efficiency in HE power systems[5]-[6]. Energy-saving technology (EST) such as hybrid power and energy recovery/regeneration has thus attracted considerable scholarly attention.

There are three main types of energy recovery systems (ERSs): an electric ERS, hydraulic ERS, and mechanical ERS. An electric ERS adopts a battery, ultra-capacitor, or both as the storage unit. Two electric motors are also adopted; an electric motor replaces the original hydraulic motor as the driving mechanism of the slew platform, and recovery of the platform kinetic energy is realized by regenerative braking of the motor[7]. Another electric motor is coaxially connected to the diesel engine to form an energy regeneration unit to release recovered energy. In a hydraulic ERS, a hydraulic accumulator with compressed nitrogen is used as the storage unit, which absorbs recoverable energy from the hydraulic actuator. It is a simple system consisting of a throttle valve and an accumulator. In the recovery condition,
the pressure oil discharged from the hydraulic cylinder (or hydraulic motor) is directly charged into the hydraulic accumulator[8], [9]. In a mechanical ERS, a hydraulic pump/motor is utilized as an energy transfer device between hydraulic and mechanical energy. Flywheels are the main components of the mechanical ERS. There are two pump/motors: one causes the flywheels to accelerate (recovering energy) when the boom moves downwards; the other is driven by the flywheels (slowing down the flywheels to regenerate energy) during boom-lowering. Most energy losses in mechanical ERSs occur from flywheel friction[10]. The large system structure and inflexible control severely limits the application of mechanical ERSs in mobile machinery.

Compared with the other two methods, hydraulic ERS technology is easier to implement and has greater engineering potential for several reasons[11]. First, it is efficiently compatible with the original hydraulic drive, reducing unnecessary energy conversion while providing high system efficiency. Second, hydraulic power components have higher power density, which is more adaptable to harsh working environments and offers higher system reliability than power electronics. Third, a hydraulic ERS offers cost advantages, a major consideration for owners of such machines given the commercial nature of the mobile machinery market.

The major researches of energy recovery and regeneration focus on boom-lowering potential energy. There are two generalized energy recovery solutions: one is realized by a coaxial electric motor and hydraulic motor, which transfers hydraulic energy of high pressure chamber to electric energy stored in battery or ultra-capacitor. It is an electric ERS. The recovered energy cannot be regenerated by directly. Therefore, Independent regeneration system requirements are installed and the whole energy conversion efficiency is low. The other solution utilizes a hydraulic accumulator as auxiliary power source and links the boom hydraulic cylinder back oil chamber to the hydraulic accumulator directly. To recovery the maximized potential boom-dropping energy, we have to enlarge the volume of hydraulic accumulator since the pressure of oil in hydraulic accumulator is too low, which would result in a difficult installation and application. Besides, this solution propounds a closed system which is independent of the original hydraulic system. Because of the recovery system components’ unstrictly sealing and inevitable leakage, the oil which could be recycled by accumulator will decrease as work time increases, and it will even cause system working improperly.

Different from the above solutions, the authors propose an alternate energy recovery and utilization system based on multi-cylinders (first published in the literature [12]). The simulation model of the energy-recovery system was established and analyzed. Then the energy saving performance test was carried out after we are developing a 33-ton prototype with the potential energy recovery system of multi-cylindered boom.

The remainder of this paper is organized as follows. The working conditions and system configuration of the new energy-recovery system are depicted in Section 2. Section 3 outlines the simulation model and parameters in detail. The simulation results are analyzed in Section 4, and conclusions are drawn in Section 5.

2. Working condition and System configuration

2.1. Working conditions
As typical earth-moving construction machinery, the working conditions of excavators feature high repeatability, many compound actions, and a short duty cycle and power volatility. A standard excavator duty cycle can be roughly classified into five parts: boom descent, mining, boom promotion and slewing, unloading, and slew reset. A schematic diagram of the operation and control time order of HEs is illustrated in Figure 1.

2.2. System configuration and working mode
In general, to ensure force balance, dual hydraulic cylinders are installed in parallel to drive the working device which is a three-degree-of-freedom mechanism composed of a boom, an arm, and a bucket. In this paper, a new energy-recovery system is proposed, as shown in Figure 2.
The proposed system is consisted of a diesel engine, hydraulic pumps, main control valve, energy-saving valve, hydraulic accumulator, mid cylinder, and side cylinders. The hydraulic pumps a two-pump (pump 1 and pump 2) system controlled by negative flow. The middle cylinder is equipped in the mid of the existed side cylinders. The mid cylinder and the side cylinders alternately operate through the oil path direction control of the energy-saving valve, which is determined by the controller. The hydraulic pump and accumulator cooperate to provide time-dependent hydraulic power for the mid cylinder and side cylinders. This energy-recovery system can recovery the equipment potential energy during lowering and regenerate the recovered energy to reduce the engine output power effectively and fuel consumption.

The system works as follows: The controller automatically changes the excavator to work in energy recovery mode when the boom is lowered. The output signal of the operating handle controls the main control valve to work in the right position, and the output pressure oil of the main pump enters the rod chamber of the middle cylinder and the side cylinders through port A of the main valve. At the same time, the pressured oil of the non-rod chambers of the two side cylinders enters the accumulator through the energy-saving valve, which converts the downward potential energy of the boom into the hydraulic energy stored in the accumulator. In this case, the non-rod chamber of the middle cylinder is in an unloaded state.

When the boom is lifted, the controller automatically changes the excavator to work in the energy-regeneration mode. The output signal from the operating handle controls the main control valve to work in the left position. The output pressure oil of the main pump enters the energy-saving valve through port B of the main control valve, and the energy-saving valve connect port P and port S, so that the hydraulic pump can directly drive the side cylinder extending. Meanwhile, the pressure oil of the hydraulic accumulator enters the non-rod cavity of the mid cylinder through the energy-saving valve, so that the accumulator and the hydraulic pump jointly drive the entire working device.

In summary, the energy saving system exhibits the following characteristics:

1. It realizes the energy recovery and regeneration by using the two side-cylinders and the mid cylinder alternately. This will eliminate the flow coupling from complex operations without additional oil charge and second booster devices as for the traditional energy recovery system.

2. It boosts the recovered energy oil pressure automatically by matching the reasonable volume parameters which reduces the volume of energy storage elements. Modeling and simulation
3. Modelling and Simulation

3.1. Modelling
To analyze the energy recovery system, the paper developed a hydraulic system model in AMESim and a dynamic model of working device in ADAMS based on the components’ mathematical model. A co-simulation is carried out through data exchange between the two software.

3.2. Main parameters of simulation model
The simulation is running based on a 33-ton hydraulic excavator SWE330ES and the major parameters of the machine and energy-recovery system are shown in Table 2.

![Figure 3. AMESim-Adams co-simulation model of energy-recovery system for hybrid hydraulic excavators](image1)

![Figure 4. Single action of boom lifting and lowering](image2)
### Table 2. Major parameters of the simulation model

| Item               | Parameter                  | Value    |
|--------------------|----------------------------|----------|
| Vehicle            | Vehicle weight             | 33000 kg |
|                    | Boom weight                | 6500 kg  |
| Hydraulic system   | Maximum pressure           | 35 MPa   |
|                    | Maximum flow               | 400 L/min|
| Power system       | Rated power                | 170 kW   |
|                    | Rated speed                | 2200 rpm |
| Energy-saving valve| Maximum recovery flow      | 200 L/min|
|                    | Maximum pressure           | 30 MPa   |
|                    | Volume                     | 40 L     |
|                    | Pre-pressure               | 8.5 MPa  |

### 4. Simulation analysis

To analyze performance of the boom energy-recovery system, the author compared the new system performance with a traditional excavator during single action of boom lifting and lowering, as is shown in Figure 4. During simulation, the stick and bucket remain in relative position with boom. When the energy-saving valve is close all the time, it is treated as a conventional excavator. Analysis of the pressure and flow of the hydraulic pump (1 and 2) output is carried out. The conventional excavator pumps curve is shown in Figure 5. A complete single action cycle is about 6 seconds, the first 3 seconds is the boom lowering power, the last 3 seconds is the boom lifting action. During the boom lowering process, the pressure of pump 1 is small (close to 3 MPa) and the output flow is maintained at a minimum (about 50 L/min), which means that pump 1 is essentially unloaded. The pump 2 drives the boom alone (the pressure oil enters the rod chamber of the three cylinders), and the flow rate is large (about 265 L/min). However, since the boom cylinder is in a negative-load condition, the pressure is low (close to 2 MPa), which means that the pump 2 mainly used for oil-supply and anti-suction. During the boom-lifting process, pump 1 and pump 2 jointly drive the boom cylinder to lift, both with the same pressure and flow. Stable drive pressure up to 13.5 MPa.

![Figure 5. Flow and pressure of hydraulic pump in original excavator](image1)

![Figure 6. Flow and pressure of hydraulic pump in the energy-recovery excavator](image2)

When the boom moves to the highest position, the system reaches 32MPa due to the overflow pressure. When the energy-saving valve is opened, the corresponding hydraulic pump output data is as shown in Figure 6.
During the boom lowering process, the pressure and flow of pump 1 is small, which means that pump 1 is also unloaded. However, compared to conventional system data, the pressure of pump 2 is significantly increased and is approximately linearly increasing with the lowering process. The reason is that during the lowering process, the hydraulic fluid of the side cylinder non-rod chamber enters the accumulator, which cause a back-pressure, and this back-pressure increases with the continually accumulator oil-charge. During the boom-lifting process, the hydraulic pump 1 is still unloaded (this is the main difference from the conventional system), the pump 2 is driven alone (oil enters the two side cylinders) and the pressure is relatively low. At this time, to ensure the action performance of the boom, the accumulator releases the pressure oil into the middle cylinder, and the pressure and flow characteristic curve of the accumulator is as shown in Figure 7. A negative flow value represents flow into the accumulator.

According to Eq. (1)-(2), and the data of Figure 5 and 6, a comparison of cumulative output energy of hydraulic pumps can be calculated, as is shown in Fig 8. During the first 3 seconds when the boom-lowering, the total output energy of hydraulic pumps in a traditional excavator is 47 kJ, while the energy-recovery excavator exports 84 kJ due to the back pressure of accumulator. The energy-recovery excavator costs more energy than the traditional excavator by 80% at this stage.

Since the working pressure of the accumulator is higher than the back-pressure value of traditional way, it needs hydraulic pump to export extra energy to increase the pressure of the rod chamber. So that the boom can reach a new balance to conduct normal behavior of declining movement. During the boom-lifting stage of the last 3 seconds, the hydraulic pumps in the energy-recovery excavator output less energy (about 124 kJ) compared to the conventional excavator (about 262 kJ). It is because that the former is driven by single pump with low pressure, with the assistance of the charged accumulator. In the whole lowering-and-lifting process, the total energy output by the hydraulic pumps of the recovery-energy excavator is 208 kJ, while it is 309 kJ as for the conventional excavator. The energy-saving efficiency is about 33%.

5. Conclusion
The paper proposed a new alternate energy recovery and regeneration system based on multi-cylinders. A simulation model of energy-recovery system is established, and the simulation analysis is carried out in a single action condition. Results show that the energy saving efficiency of the proposed energy recovery system is 33%. Although this data is not a direct fuel saving indicator, it has important reference significance for evaluating the energy efficiency of the new system.
Acknowledgments
This work was supported by National Natural Science Foundation of China (51809091), Hunan education department scientific research project (B31613), Hunan Science and Technology Association Science and Technology Talents Enhancement Project (2017TJ-Q08) and Open Foundation of the State Key Laboratory of Fluid Power and Mechatronic Systems (GZKF-201813).

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