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Efficiency analysis and evaluation of energy-saving pressure-compensated circuit for hybrid hydraulic excavator

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ABSTRACT

A hydraulic cylinder driven scheme combining a pressure compensator and an energy recovery device together has been proposed to achieve good control operation and energy-saving capability simultaneously. In this paper, its efficiency characteristics are further investigated in order to provide analytical and experimental references to practical applications. Since an excavator owns multiple actuators, a general schematic configuration including hydraulic cylinders with and without energy recovery is developed and analyzed. Based on the analysis of energy losses in every conversion, component selections and possible improvements are discussed, and then the design flowchart and criteria of key parameters are also presented. Finally, experiments under different load and velocity conditions are implemented on a test bench. Energy distributions, recovery efficiencies and component efficiencies are all evaluated.

1. Introduction

Hydraulic excavators are widely applied in construction. However, one remarkable drawback in their applications is the low energy efficiency [1], which mainly comes from the energy conversions in power systems and hydraulic systems. In individual engine driven power systems, the fuel economy is usually decreased due to the variation of working points [2]. Therefore, as a highly efficient driving method, the hybrid power technology is extended from traditional vehicles to excavators, which mainly involves system design, hybridization structure, modeling and control strategy [1–7,17,18].

The commonly used hydraulic systems in excavators include positive flow control systems, negative flow control systems and load sensing control systems. All of them are capable of matching the pump flow with the operation requirement so as to reduce the output energy of power systems. However, in these hydraulic systems, a large number of energy losses are still existing. Some of them are produced when cylinders are lowering down, and some come from the pressure difference between two actuators driven by the same pump [8]. The energy losses are dissipated in throttles and converted to heat which leads to the negative effects on the cooling of hydraulic oil [9]. Besides the aforementioned open-circuit hydraulic systems, the applications of closed-circuit hydraulic systems in excavators are also investigated, for they totally eliminate the throttling losses and have good energy-saving potential. But the controller design is quite challenging because pump-controlled systems usually have low damping ratios and stability margins in comparison to throttle-controlled systems [10,11].

Energy recovery is an effective approach to reduce the energy losses in hydraulic systems. In hydraulic cylinder driven circuits, energy can be recovered through cross connection [12], hydraulic accumulator [13,14] and electrical storage [15,16]. There are two indexes to evaluate the performance of an energy recovery system. Firstly, the energy recovery efficiency should be acceptable, otherwise the energy saving is insignificant and the system is meaningless. Secondly, the actuator controllability in the system with energy recovery should not be worse than traditional systems so that various required operations can still be performed normally.

The electrical recovery is suitable for hybrid hydraulic excavators where the electrical storages such as batteries or super capacitors are equipped [17,18]. In an electrical recovery system, the cylinder velocity is usually governed by controlling the rotational speed of a hydraulic motor coaxially connected with an electrical generator. To improve the cylinder controllability, some compensation is also used in controller design [19]. However, this volumetric control is difficult to match the traditional throttling control in practice, because excavators usually have high requirements on control performance.

An energy-saving pressure-compensated scheme, which combines a pressure compensator and an energy recovery device together, can realize effective energy recovery and guarantee good operation of hydraulic cylinders simultaneously [20]. In this paper, its general configuration in excavators, efficiency analysis and evaluation, and relevant parameter

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design are further investigated, aiming to provide analytical and experimental guidelines for practical applications.

The paper is organized as follows. In Section 2, the configuration of the proposed system is presented and analyzed by the comparison to the load sensing system. Section 3 studies the energy losses, efficiency and possible improvement in each energy conversion. Section 4 discusses the quantitative relations and design criteria of key parameters. In Section 5, experiments with different loads and motion velocities are implemented to evaluate the energy distributions and efficiencies of the proposed circuit. Finally, the conclusions of this paper are drawn in Section 6.

2. System configuration

The energy-saving pressure-compensated scheme is to replace the pressure compensator in a conventional load sensing control system with an energy recovery device consisting of a hydraulic motor and a coaxially coupled generator. And the compensation part is installed in the meter-out oil line in order to counterbalance overrunning load. By using this scheme, we can design a more efficient load sensing control system, where energy losses due to overrunning load or multi-actuator effect can be recovered in electrical form. The configurations of the two load sensing control systems are presented and analyzed as follows.

2.1. Load sensing system

An advanced load sensing control technology called load independent flow distribution or LUDV is introduced for comparison at first. This commercially available system is proposed by Bosch Rexroth. It has the advantage that actuators with lower loads can automatically slow down in order to maintain the flow to the actuator with the highest load when there is no sufficient pump flow. In this system, each control valve operates with a pressure compensator downstream as shown in Fig. 1. The highest load pressure is used as the load sensing pilot line to control the pressure compensators so that when the pump flow corresponding to actuator commands is insufficient, the flow to every actuator will be reduced proportionally.

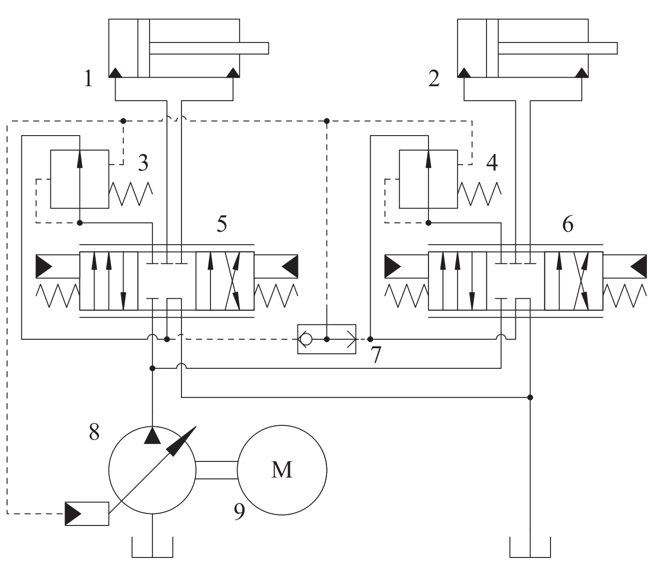
It can be observed that the pressure compensators operate with energy consumptions which are related to the pressure differences between actuators. Moreover, there will be a large amount of energy dissipated when the loads are overrunning. Therefore, although the pump outlet pressure is adaptive to the highest load in the load sensing system, the energy losses are still considerable.

2.2. Developed system

A hydraulic system with the energy-saving pressure-compensated scheme is developed for hybrid hydraulic excavators in order to realize energy recovery while maintaining an equivalent controllability of the load sensing system. Fig. 2 shows the schematic diagram, where both of the cylinder circuits with and without energy recovery are included in one system, for there are only a part of actuators having enough energy-saving potential in an excavator. Considering the amount of recoverable energy, it is reasonable to apply the energy recovery scheme to the boom cylinder and the arm cylinder. As shown in the figure, the load sensing pilot line adopts the highest inlet pressure of operated actuators through shuttle valves and governs the pump outlet pressure to the sum of the dominant load pressure and a constant margin. In the cylinder circuit with energy recovery, when its load condition is overrunning or its operated pressure is not the highest, the hydraulic motor and the generator convert the outlet energy of the cylinder to electrical form and provide compensated pressure. The recovered energy can be stored in electrical energy storage devices or directly supplied to electrical energy consumption devices. With the energy-saving compensator, the flow to each actuator in the developed system can also be reduced proportionally when the pump flow is insufficient as in the load independent flow distribution system.

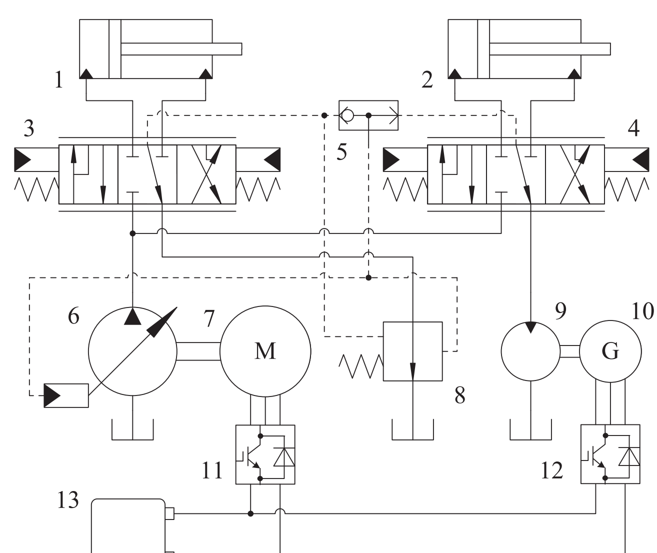
3. Energy losses and efficiency

Based on the developed system configuration, energy losses of the main components can be analyzed to select appropriate types and make possible improvements. Fig. 3 shows the energy distribution in the cylinder circuit with energy recovery, where a super capacitor is employed as the electrical energy storage device. It should be noticed that the figure only presents the cylinder movement in one direction,



1, 2-cylinder; 3, 4-compensator; 5, 6-control valve; 7-shuttle valve; 8-variable displacement pump; 9-electric motor.

Fig. 1. Schematic diagram of the load independent flow distribution system.



1-cylinder (without energy recovery); 2-cylinder (with energy recovery); 3, 4-control valve; 5-shuttle valve; 6-variable displacement pump; 7-electric motor; 8-compensator; 9-hydraulic motor; 10-generator; 11, 12-converter; 13-super capacitor/battery.

Fig. 2. Schematic diagram of the developed hydraulic system.