Mechanical Systems and Signal Processing ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

The gravitational potential energy regeneration system with closed-circuit of boom of hydraulic excavator

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ARTICLE INFO

Article history:
Received 6 January 2016
Received in revised form
24 March 2016
Accepted 15 May 2016

Keywords:
Hydraulic excavator
Energy regeneration system
Closed-circuit
Hydraulic accumulator
Energy saving

ABSTRACT

Considering the disadvantage of higher throttling loss for the open-circuit hydrostatic transmission at present, a novel gravitational potential energy regeneration system (GPERS) of the boom of hydraulic excavator, namely the closed-circuit GPERS, is proposed in this paper. The closed-circuit GPERS is based on a closed-circuit hydrostatic transmission and adopts a hydraulic accumulator as main energy storage element fabricated in novel configuration to recover the entire gravitational potential energy of the boom of hydraulic excavator. The matching parameter and control system design are carried out for the proposed system, and the system is modeled based on its physical attributes. Simulation and experiments are performed to validate the employed mathematical models, and then, the velocity and the pressure performance of system are analyzed. It is observed that the closed-circuit GPERS shows better velocity control of the boom and response characteristics. After that, the average working efficiency of the closed-circuit GPERS of boom is estimated under different load conditions. The results indicate that the proposed system is highly effective and that the average working efficiency in different load conditions varied from 60% to 68.2% for the experiment platform.

1. Introduction

In recent years, the hybrid power system has been applied to vehicles successfully [1–3]. With the raising energy consumption in construction machinery, the hybrid power system is paid attention to the construction machinery, especially hydraulic excavators [4–8].

In the process of conventional hydraulic excavator working, the velocity of the boom descending is controlled by the main throttling valve. When the boom of excavator descends, the entire gravitational potential energy of the boom is wasted and converted into fluid heat in the main throttling valve of the hydraulic system. Therefore, the development of boom ERS is an effective method in reducing the further energy consumption in hybrid power system of hydraulic excavators [8].

A lot of researches about the gravitational potential energy regeneration system (GPERS) of the boom of the hydraulic excavator have been reported. In [9], the hydraulic transformer was applied to the boom oil circuit of excavator for Innas Corporation. “Eco-Mate” energy saving system of boom for hydraulic excavator was developed by Lars, which was applied to a 50 t hydraulic excavator [10]. Choi et al. [11] studied the independent metering valve configuration of hydraulic excavator,

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http://dx.doi.org/10.1016/j.ymssp.2016.05.017
0888-3270/

Please cite this article as: M. Chen, D. Zhao, The gravitational potential energy regeneration system with closed-circuit of boom of hydraulic excavator, Mech. Syst. Signal Process. (2016), http://dx.doi.org/10.1016/j.ymssp.2016.05.017

and achieved the rate regeneration of the boom. It is reported that the flow rate of boom system is about 20% of that in the conventional valve configuration. Zhang et al. [12] proposed different the GPERSs of the boom by using the hydraulic generator and motor regeneration to recover energy when the boom of hydraulic excavator descends. It is reported that the recovery efficiency is about 22%. In [13], two different boom energy regeneration configurations were compared. The result showed that 41% of the total potential energy could be regenerated by using the accumulator–motor–generator system. On the basis of Refs. [12,13], Wang et al. [14] studied the boom control performance of hybrid hydraulic excavators with a GPERS of the boom where the super capacitor is selected as the energy storage element, the result of which showed that part of potential energy was dissipated in the directional valve in this energy recovery system and the average efficiency varied from 41.95% to 64.5% in different boom velocity conditions for the test bench. Casoli et al. [15] analyzed the more effective hybrid system layout of the hydraulic excavator used by hybridization methodology. The results showed that the hydraulic energy recovery system (the energy storage element is the accumulator) seems better than the electrical one (the energy storage element is the battery) for this specific application. However, the existing studies on the GPERS of the boom of the hydraulic excavator mainly focus on the open-circuit hydrostatic transmission based on the valve principle, and the throttling loss of system is very big. The closed-circuit GPERS of the boom, which can achieve volumetric speed control without throttling loss, is one of the most effective ways to recover and reuse gravitational potential energy of the boom for hydraulic excavator.

At present, the closed-circuit energy regeneration system is proposed and applied to energy regeneration of rotational loads only, such as the rotational kinetic energy regeneration of construction equipment and electric vehicle [16,17]. The closed-circuit energy regeneration system of linear motion loads such as hydraulic linear actuators of the boom of hydraulic excavators has not been reported. This paper aims to develop a closed-circuit GPERS of the boom of hydraulic excavator. An 8 t hydraulic excavator is the object for this research.

In contrast to the previously published works, the boom velocity of the proposed closed-circuit GPERS is controlled by adjusting the hydraulic pump displacement, namely volumetric speed control of hydraulic system without throttling loss. In addition, the accumulator is selected as the main energy storage element which converts the gravitational potential energy of the boom into hydraulic energy directly. Therefore, it will reduce the energy conversion link between the hydraulic energy and the electric energy, in comparison to the energy storage element of electric energy [15]. In order to achieve the volumetric speed control of the hydraulic system in this paper, the fuzzy PI self-tuning controller is developed to adjust the PMBLDC motor speed. The control performance and the operating efficiency of system are analyzed based on the simulated and experimental results.

The remainder of this paper is organized as follows. Section 2 describes the principle of operation and mathematical modeling in the proposed GPERS of the boom with the hydraulic excavator. The control system design is described in Section 3. Section 4 describes the experiment platform for the proposed GPERS of the boom. Both the simulated and experimental results of the proposed system control performance are analyzed, and the average efficiency of the closed-circuit GPERS of the boom is estimated under different load conditions in Section 5. Finally, the concluding remarks are presented in Section 6.

2. The proposed closed-circuit GPERS of the boom

2.1. System structure

The schematic diagram of the closed-circuit GPERS of the boom is shown in Fig. 1. In this study, the accumulator was selected as an energy storage element due to its high power density and high recovery efficiency [18,19]. Thus, the power source of the system is composed of the permanent magnet brushless DC (PMBLDC) motor and the accumulator. In the process of the system working, the boom velocity is controlled by adjusting the PMBLDC motor speed which can achieve volumetric speed control, and there are not throttling and overflow losses. In the system, the control way of valve 1 and valve 2 is ON/OFF.

The dotted box in Fig. 1 is the hydraulic oil replenishing device which mainly consists of replenishing oil motor, replenishing oil pump, hydraulic oil filter and check valve. If the system pressure drops to a set value or the system flow reduces to a set value due to the hydraulic components, for example, the Pump-Motor, valve, and the boom cylinder in system emerge the external leakage of hydraulic oil, the replenishing oil pump will be driven by replenishing oil motor and pumps the hydraulic oil into main hydraulic circuit from the hydraulic oil tank. The pressure set value of pressure relief valve is the maximum value of replenishing oil pressure.

2.2. Determination of accumulator charging pressure

In the standard working cycle of elevators, the lifting/descending time of the boom of the hydraulic excavator is only 3 s and the regeneration power changes quickly and periodically [13,20]. Hence, the hydraulic accumulator energy recovery system is ideal for those confronted with frequent and short start-stop cycles in enough space.

For the proposed system, the accumulator acts as “the hydraulic counter balance of the boom” and the pressure changes with time during the boom movement of the hydraulic excavator. The set method of charging pressure for accumulator was

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