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New compound energy regeneration system and control strategy for hybrid hydraulic excavators

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ABSTRACT

Energy regeneration systems (ERSs) that use the same energy storage device as hybrid power systems can improve the fuel economies of hybrid hydraulic excavators (HHEs). However, conventional ERSs have worse dynamic actuator performance than traditional orifice control systems. In addition, the capacities of both the hydraulic motor and the generator should be large enough to avoid overload. Based on comprehensive considerations, a compound ERS that combines the advantages of an electric accumulator and a hydraulic accumulator was proposed. Then control strategies that guarantee the minimum and maximum recovery times and methods for controlling the boom velocity and improving the recovery efficiency were discussed. A test bench was constructed and described here. An estimated 39% of the total potential energy could be regenerated under the standard operating conditions in the proposed system, while the recovery efficiency of the conventional ERS is approximately 36%. In addition, the recovery efficiency can be improved under extreme operating conditions. It was also shown that the proposed ERS had better control performance than the conventional ERS, while the capacity of the regenerator could be reduced by more than 65%.

1. Introduction

In recent years, energy crisis and environmental pollution have become increasingly serious problems that the world has to face. It is meaningful to investigate the energy saving of construction machinery, especially for hydraulic excavators (HEs) due to their wide application and extremely low efficiency. Hybrid power system, which has been successfully applied to vehicles, is also paid much attention in the field of construction machinery [1–5].

Commonly, when the boom of a HE comes down, the gravitational potential energy of the boom dissipates as heat in the throttle valves of the hydraulic system. In general, the regenerated energy of the boom cylinder comprises 51% of the total regenerated energy [6]. Hence, ERS that can be realised when booms are lowered down is an attractive way to further reduce the energy losses in hydraulic systems. There are two types of ER systems in HHEs, including the hydraulic ERS and the electrical ERS. The former stores the regenerated energy in a hydraulic accumulator, while the electrical ERS converts the recoverable energy to electricity. This system is more suitable for HHEs because the hybrid power systems provide electrical energy storage devices, such as batteries or super capacitors, and the recovered energy can be delivered directly to the electric actuators.

In hydraulic ERS, Virvalo et al. [7–11] studied an ERS with a hydraulic accumulator that can save and restore the hydraulic energy in a crane's hydraulic system. The hydraulic approach is to convert the recoverable energy to hydraulic form, store it in a hydraulic accumulator, and release it when there are requirements.

Andersen et al. [12] studied an electrical ERS in hydraulic forklift trucks. The ERS, which had an electric motor and batteries in the main lift system, was discussed. Different systems and control strategies were compared. The results showed improved energy efficiency but shorter component lifetimes because of the system's oscillatory response. Minav et al. [13,14] also studied storage of energy recovered from an electro-hydraulic forklift truck. The lifting system was controlled directly by an electric servo motor and a hydraulic pump that was capable of operating as a hydraulic motor for potential energy recovery at the lowering of the boom. Some of the available energy storage devices were described, and their energy efficiencies of the proposed system were compared with other traditional systems. The maximum energy saving is 54%.

However, only a few ERSs have been developed for HEs. Bruun [15] presented an application called ‘Eco Mate’ based on the hydraulic ERS and installed it on a 50-t HE [16,17]. The ‘Eco Mate’ system was said to be one of the most successful inventions to recover energy in a hydraulic boom control system in recent years. However, hydraulic ERSs required additional components, such as hydraulic pumps/motors or hydraulic transformers, to reuse the recovered energy. In addition, the major

Abbreviations: ERS, energy regeneration system; HE, hydraulic excavator; HHE, hybrid hydraulic excavator; MGERS, motor-generator energy regeneration system; AMGERS, accumulator-hydraulic motor-generator energy regeneration system; BU, boom up; BS, boom stop; BD, boom down; PDV, proportional valve; PI, proportional integral.

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Nomenclature

p_{a1}	the minimum pressure of the hydraulic accumulator
p_{a2}	the maximum pressure of the hydraulic accumulator
p_{a0}	the initial pressure of the accumulator
V_0	the rated volume of the hydraulic accumulator.
n	a polytropic exponent
ΔV_w	the minimum change in volume of the hydraulic accumulator
n_{ge}	the rated rotational speed of the generator
q_m	the displacement of the hydraulic motor.
p_{c1}	the high-pressure threshold
p_{c2}	the low-pressure threshold
p_{ctr1}, p_{ctr2}	the pilot pressures of the joystick.
Δp_c	pressure differential
ξ	a small positive value
Q_{bt}	the target flow rate of the boom
Q_b	the actual flow rate
k_{Qc}	a proportionality factor between the pilot-control signal and the target flow rate of the boom.
Q_{mt}	the target flow rate of the hydraulic motor
p_x	the pressure of the hydraulic accumulator
n_{gt}	the target rotational speed of the generator
n_{eff}	the high-efficiency rotational speed of the generator
n_{gmin}	the minimum rotational speed of the generator
t_{max}	the maximum recovery time
t_{min}	the minimum recovery time
C_1	the control signal of the PDV
p_{b1}	the pressure of port A of the PDV
p_{b2}	the pressure of port T of the PDV
k	the transfer coefficient.

disadvantage of a hydraulic accumulator is that the energy density is severely limited compared with other competing technologies.

Recently, a compound potential ERS with a regeneration device and a throttle valve was demonstrated [18]. The regenerative torque was adaptive to the load to keep the pressure drop over the throttle valve almost constant. Thus, the actuator can be governed by adjusting the opening of the throttle valve. The proposed ERS was analysed and evaluated using the frequency domain method and nonlinear simulation.

However, both the time for lowering the boom in the hydraulic forklift and the crane is approximately 10 s, whereas it is only 2 s–4 s in HEs. Hence, the ERSs used in the hydraulic forklifts and cranes cannot be directly used for HHEs. Although the ERS shown in reference [18] can regenerate some of the energy and features good control performance, the rated power of the motor and the generator should be larger to fulfil the needs of this application.

This paper aims to design a novel ERS for HHEs based on improving the recovery time, recovery efficiency, and economy. The remainder of this paper is organised as follows. Section 2 demonstrates the energy regeneration methods for HHEs. Section 3 describes the control strategies in detail. The comparison and analysis of experimental results are described in Section 4. Concluding remarks are presented in Section 5.

2. Energy regeneration methods for HHEs

There are various types of ERSs in construction machinery. When an ERS is used in an HHE, the whole system has to be considered for the ERS to fit its special working style.

2.1. Working style

Fig. 1 shows that the time required to regenerate the potential energy of the boom is approximately 3 s, while a typical working period is

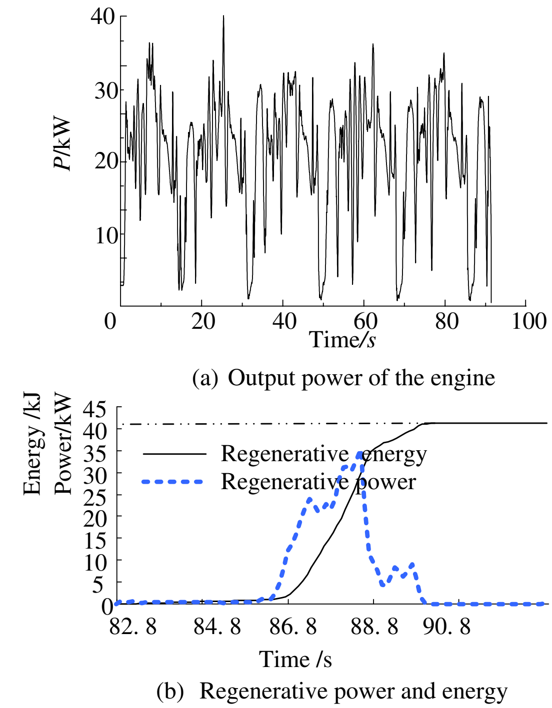

Fig. 1. Output power of the engine, regenerative power and energy of the boom of a 7-t HE in digging working condition.

about 20 s. Moreover, the regeneration power changes quickly and periodically. The peak power is approximately 35 kW, while the average power is 15 kW. The total regeneration energy in one working cycle is approximately 42.5 kJ.

2.2. Configurations of the ERS

In our prior research, the motor-generator ERS (MGERS) shown in Fig. 2 was proposed. A hydraulic motor and a generator connected to

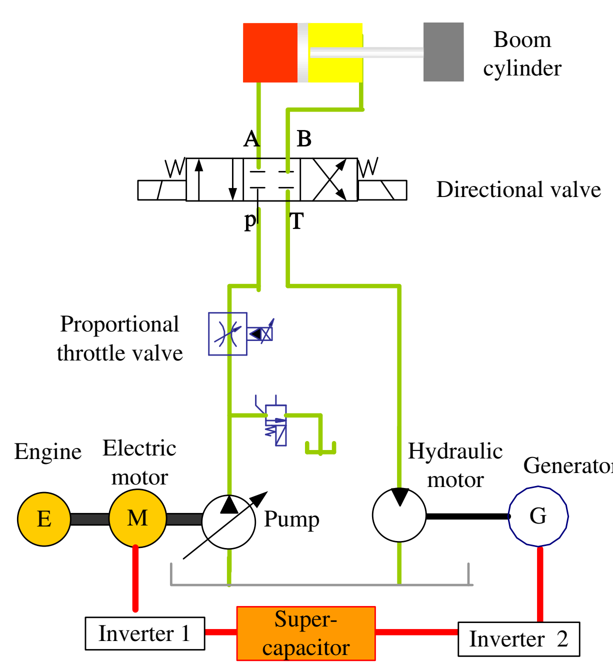

Fig. 2. Schematic of MGERS.