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Performance analysis of an automatic idle speed control system with a hydraulic accumulator for pure electric construction machinery

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A B S T R A C T

To reduce the energy consumption and emissions of a hydraulic excavator (HE), an electric motor (EM) is employed to replace the internal combustion engine (ICE) that powers the hydraulic pumps. Owing to the excellent control characteristics and high efficiency of the EM, a two-level idle speed control system with a hydraulic accumulator (HA) for a HE is proposed to reduce energy consumption and improve the control performance of the actuator when the idle speed control (ISC) is switched off. A mathematical model is established and key parameters are analyzed and optimized. A simulation is performed using AMESim, and a control strategy for the two-level idle speed control is developed by using a co-simulation between AMESim and Simulink. A test rig is built based on the optimized parameters and simulation results. Experimental results show that the EM speed can be automatically switched between the first idle speed, second idle speed, and normal operating speed. Although the idle speed of the EM in the novel ISC system can be reduced more than that in a conventional ISC system, the proposed ISC system can still build actuator pressure more quickly in a working mode when the ISC is switched off. Compared to a system without idle speed control, the energy saving of the proposed system is approximately 36.06%. The proposed two-level idle speed control system with a HA can achieve high energy efficiency and excellent control performance, and it can be also applied to engine-driven construction machinery.

1. Introduction

Recently, energy efficiency and a low environmental impact have become the basic requirements for construction machinery to meet increasingly stringent emission regulations. Thus, research on energy saving methods for construction machinery, especially hydraulic excavators (HEs), is necessary and urgent owing to their high energy consumption and emissions. Technologies that aim to reduce energy consumption and emissions, such as positive and negative flow control systems, load sensing controls, hybrid systems, pure electric systems, energy regeneration, and idle speed control (ISC) have been proposed and utilized in various models. Both flow-control systems [1,2] and load-sensing controls [3,4] are to adjust the output of pumps to meet the requirements of a load and avoid extra energy loss. Hybrid systems utilize more than one power train to allow the engine to operate at an ideal output level to reduce fuel consumption and emissions [5–7], but they cannot achieve zero emissions owing to the use of internal combustion engines (ICEs). Energy recovery systems (ERSs) are typically used to regenerate potential energy when the load is down or kinetic energy when the actuator is braking [8–11].

The traditional energy saving methods used in HEs cannot significantly improve energy savings if there are no further technological breakthroughs. The successful application of pure electric systems in vehicles provides a new method for HEs to achieve energy savings. A pure electric system can achieve zero emissions and lower energy losses [12]. Equipping HEs with pure electric systems has become the major trend in energy saving research. There have been only a few studies on pure electric HE systems. Because ISC is considered a good method for fundamentally reducing energy consumption [13], this paper focuses on a new ISC system for a pure electric HE.

The working process of construction machinery is typically periodic. Idle time accounts for approximately 30% of a typical working cycle [14]. ISC is adapted to reduce energy loss and emissions during idle time. Traditional ISC is applied to control the speed switch between two values in ICEs. Generally, idle speed should be as low as possible to improve fuel economy and reduce emissions [15]. He et al. investigated a new engine and reduced the idle speed from the original 800 rpm to 700 rpm [16]. Li et al. set the idle speed in an engine to 611 rpm instead of the normal (production) idle speed of 740 rpm and used a sliding mode control for ISC. Although a low idle speed can reduce fuel

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consumption, it carries an increased risk of misfiring and engine stalling [17,18]. Thus, the transition to and from idle speed must be smooth and carefully controlled [18]. Many researchers have devoted themselves to solving ISC problems with various control strategies [19–21]. Most of the research has focused on ISC for automobiles. However, owing to the intrinsic properties of an ICE, the speed range is narrow and the idle speed remains high, which limits the potential energy savings of ISC.

However, there have been a few studies on construction machinery. Xiong et al. analyzed construction machinery working principles and implemented methods for ISC in a rotary drilling rig [22]. They tested fuel consumption under various speeds and found that the speed with the lowest fuel consumption was the preset idle speed. Liu designed an ISC system based on working conditions, speed sensing, and engine power matching [23]. The adjustment time for the engine between idle speed and the rated speed was approximately two seconds. Hao optimized the duty ratio of pulse wave modulation, minimum ramping time, and idle speed through an adaptive control method and achieved superior energy savings [24]. However, these studies were still based on the ICE and the idle speed could not be set to a low value, causing relatively low energy efficiency. Furthermore, the pump could not build pressure quickly enough to drive the actuator when the working mode of the ISC was switched off.

ISC is adapted to reduce energy loss and emissions during idle time. When ISC is applied to ICEs, it can also reduce fuel consumption and greenhouse gas emissions. However, owing to the intrinsic properties of ICEs, the speed range is narrow and the idle speed remains high, which limits the energy saving potential of ISC and makes it difficult to meet requirements for environmental protection. When ISC is applied to pure electric systems, the control performance of the electric motor (EM) is different from the ICE, particularly the speed range, dynamic response, and efficiency.

Therefore, in this research, a two-ton class pure electric HE was built in our lab for experimentation. A novel ISC with a hydraulic accumulator (HA) for the two-ton HE is the focus of this research. The remainder of this paper is organized as follows: The structure and working principle of the automatic ISC system with a HA is described in Section 2. A mathematical model of the proposed ISC system is described in Section 3. The influence of various parameters on the performance characteristics of the ISC system is discussed in detail in Section 4. The experimental results are analyzed in Section 5. A summary and our final conclusions are provided in Section 6.

2. Structure and working principle of the novel automatic ISC system

Fig. 1 presents a schematic of the proposed automatic ISC system. Compared to traditional ISC systems, the proposed ISC system has the following improvements:

1) Pure electric drive enables zero emissions for the driving system. An EM is used in place of an ICE for driving the hydraulic pumps. The efficiency of the EM is presented in Fig. 2 and can reach 95% when the EM speed is under 500 rpm, and up to 96%–98% when the EM speed is above 800 rpm. The EM has higher efficiency at low speeds, a wider speed range, and a quicker dynamic response than an ICE.

2) A HA is connected to the outlet of the pump via solenoid directional valve 1. The HA can provide auxiliary power to drive the actuator when the working mode of ISC is switched off. The pump can then build pressure quickly enough to drive the actuator. This means that the idle speed can be set to a low value to obtain good energy savings and decrease noise.

3) There is a pressure loading unit at the return port when the multi-way valve is in the middle working position. It can separate the pump from the tank via solenoid directional valve 2 and charge the HA based on the control strategy.

4) All pressures of the key components are detected and used to recognize the working mode of the ISC system.

The working mode recognition process of the ISC system in Fig. 1 is presented in Fig. 3. When the joystick returns to the middle position, the controller detects that the pressure difference between the two pressures on the joystick is under a preset small positive value and sends signals to the multi-way valve to turn it to the middle position. The proposed ISC system is used to control the speed of the EM as it switches between different values, including the switch from high speed to low speed and from low speed to high speed. When reducing the speed of the EM, the main consideration is energy saving. The value of the idle speed is the primary factor that influences energy consumption. When the working mode of the ISC system is switched off, control performance is the main consideration. Therefore, the time required for building pressure in the pump should be smooth and short. By taking the self-suction capacity of the pump into account and referring to Fig. 2, the first level idle speed is set to 800 rpm and the second level idle speed is set to 500 rpm because the HA can help the pump build pressure. During the various processes, the control strategy changes accordingly.

1) First level ISC

When the time that the joystick resides in the middle position is longer than time T_1, the controller reduces the EM speed to the first level idle speed n_1 to reduce energy loss. Meanwhile, the maximum load pressure is used to determine whether the HA should charge the pump. When the pressure difference between the HA and the maximum load pressure is larger than a set value, solenoid directional valves 1 and 2 are powered on. The pump then charges the HA through solenoid directional valve 1. After the HA pressure increases to the set value, solenoid directional valves 1 and 2 are powered off.

2) Second level ISC

The control target is to achieve minimum energy consumption. The output power of the system should outweigh the total energy loss and minimize energy consumption. When the time that the joystick resides in the middle position is longer than time $T_1 + T_2$ and the pressure difference between the maximum actuator pressure and the HA pressure is under a threshold value, the controller switches the EM to the second level idle speed n_2, which is lower than the first level idle speed n_1.

3) ISC is switched off

When the actuator recovers from the idle speed and the EM returns to normal speed, which is approximately 1800 rpm, the global positive flow control is used to make the flow rate supplied by the pump and the HA match the requirement of the load. Solenoid directional valves 1 and 2 are powered on. The stored oil in the HA is released through solenoid directional valve 1 to the inlet of the multi-way valve to help the pump build pressure quickly and drive the actuator. When the HA pressure is lower than the pump pressure, solenoid directional valve 1 is powered off and the actuator is driven by the pump only. The proportion of the flow rate supplied by the HA and the pump is scheduled to achieve smooth and quick movement of the actuator.

3. Mathematical model of the ISC system with a HA

The simplified structure of the proposed ISC system presented in Fig. 4 is used to analyze the control performance of the novel ISC system. The assumptions made are as follows:

1) The influence of the solenoid directional valve on the velocity characteristics of the actuator is not considered.
2) Only the piston-out movement of the actuator is considered. The influence of piston movements on the volume between the non-rod chamber, HA, and the pump is ignored.
3) The actuator and pump have no elastic loads or disturbance torque.
4) The safety valve, which is connected to the pump output port, does not work and overflow during the working process.
5) The pressure of the inlet port of the pump is zero.