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Prediction-based stochastic dynamic programming control for excavator

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ABSTRACT

Because the fuel efficiency of excavators is low and the energy loss is considerable, a prediction-based stochastic dynamic programming (PBSDP) control strategy is proposed in this study to reduce the energy and fuel consumptions. Using the torque prediction method, the optimization control strategy can be used in real time to improve the fuel efficiency. The required torque of the proposed hydraulic hybrid excavator was analyzed. The minimum length of the required torque sample needed to estimate the trend in the required torque change was obtained using approximate mean estimation. The required torque sample was divided into complete cycles using empirical mode decomposition. The required torque of the next period was predicted using a signal superposition technique. The proposed PBSDP control strategy was then applied based on the predicted required torque. The displacement of the auxiliary pump/motor was selected as the control variable whereas the pressure of the accumulator connected to the auxiliary pump/motor was selected as the state variable. The value function was calculated based on the predicted required torque and charging state of the accumulator. The controller was used to minimize the value function by adjusting the displacement of the auxiliary pump/motor. In addition, a numerical experiment was conducted to analyze the rotation torque, energy consumption, and fuel consumption of an internal combustion engine (ICE). The numerical experiment results show that the proposed PBSDP control strategy helps in reducing the maximum torque, energy consumption, and fuel consumption of the ICE by 15, 20, and 26%, respectively.

1. Introduction

In the past few decades, hybrid power technologies have been rapidly developing. Owing to their increasingly prominent role in reducing fuel consumption, improving fuel economy, and lowering emissions in vehicles and the complexity of engineering machineries, using a hybrid power system has become one of the most important methods of reducing environment pollution and energy shortage [1]. Hybrid power systems can be classified into hydraulic hybrid and electric hybrid technologies based on the differences in energy storage elements and auxiliary power sources [2]. The hydraulic hybrid power system is more adaptable for large and heavy engineering machineries because of its high power density, environmental friendliness, and low cost [3]. Hence, the hydraulic hybrid system is widely used in engineering machineries.

To further improve the performance of hydraulic hybrid systems, one of the most important approaches involves optimizing their control strategy, the primary objective of which is to solve the problem associated with energy management. A desirable controller should be capable of simultaneously optimizing the allocation proportion of the required power between the engine and the motor to adapt to complex working conditions, minimizing the fuel consumption, and maintaining the charging state of the battery and energy storage condition of the accumulator. Currently, the control strategies applied to hydraulic hybrid engineering machineries include logical threshold control, fuzzy control, and optimization control.

The logical threshold control strategy helps in determining a series of possible working states based on theoretical analyses and engineering experiences. The working states are then divided into several areas based on a particular rule. An optimal working condition is subsequently recognized based on the critical points and the corresponding control method is then applied. Xiao et al. [4] proposed engine constant-work-point control and double-work-point control strategies using a thermostat control method. This method helped in reducing the fluctuation range of the output power of the engine by 50%; moreover, the energy loss was reduced to some extent. Liu et al. [5] developed a real-time logic threshold control strategy, which helped in reducing the energy consumption by 24.36%. In addition, Xiao [6] proposed a dynamic-work-point control strategy. Sun et al. [7] developed an energy controller using the logic threshold approach to control the dynamic transitions between the various operating modes.

The logical threshold control strategy relies on switching the

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working modes based on the engine efficiency curve and required torque to ensure that the engine works within a high-efficiency range. Although the principle is simple, this approach is quite robust, characterized by the high engine efficiency and low emission. However, a threshold value should be set in advance; thus, the adaptive capability of the working condition changes and the parameter drift becomes poor. Moreover, in the logical threshold control strategy, only the working efficiency of the engine is considered, and the global efficiency of the system is rarely considered. Consequently, the overall energy loss is often considerable and the energy conversion efficiency is low. In fact, the best working efficiency can be hardly obtained in the hydraulic hybrid system.

Lee et al. [8] proposed the first conventional fuzzy control strategy, which was applied to an electric hybrid vehicle. This strategy helped in reducing the nitrogen oxide emission by 20%. Dai et al. [9] developed a fuzzy proportion-integration-differentiation (PID) control strategy for a hydraulic hybrid excavator, which helped in increasing the energy recovery rate from 51.5% to 60.3% compared to conventional PID control approaches. Other reported studies in this area include a control strategy with membership function optimized using a genetic algorithm (Wang et al. [10]), a logical control algorithm based on the on/off state switch of the engine for a hybrid hydraulic excavator (Lai et al. [11]), and a logical control strategy based on the power requirement and system state (Matheson et al. [12]).

The fuzzy control strategy is suitable for nonlinear time-varying systems wherein the mathematical model cannot be accurately obtained. Generally, the input signal of the controller is the energy state of the storage elements, required torque, and rotation speed. The controller is used to calculate the output torque and rotation speed for each energy sources based on a rule library. The main advantage of this strategy lies in its capability of dealing with control rules that cannot be expressed using accurate parameters. However, a rich engineering experience is needed to determine the fuzzy rule, thus making it difficult to obtain directly. Moreover, each involved variable and control rule are invariable, which cannot be adjusted automatically. This limits the dynamic behavior of the system.

The optimization control strategy is commonly applied to the system along with its mathematical model, which is difficult to obtain, such as engineering machineries with complicated structures and significantly variable working conditions. Shen et al. [13] proposed a dynamic programming control strategy for a common-pressure-rail-based hydraulic hybrid excavator. They showed a reduction in the fuel consumption from 44.9 g to 30.1 g under the given working condition. However, the main limitation of their approach is that it is unsuitable for real-time control. Alternatively, Bender et al. [14] reported a predictive control strategy and demonstrated its application using a hydraulic hybrid transportation machinery with a cyclic operating state, which helped in saving 5% more fuel in the experiments. Furthermore, Feng et al. [15] described a predictive control method based on a random model, which improved the fuel economy by 44.2–61.9%. Park et al. [16] reported a control strategy using online learning based on echo state networks. Wu et al. [17] proposed a dynamic programming control strategy applied to a transportation machinery. However, the application of these control strategies in general, and the optimization control approach in particular, to a hydraulic hybrid excavator are rare.

In the optimization control strategy, a value function is used to represent the fuel consumption and emission, the minimum value of which is obtained through power distribution. Consequently, an optimal fuel economy is obtained [1]. The optimization control is the most commonly used strategy in hydraulic hybrid systems, because of its high global efficiency and high adaptation for variable parameters. The simulation on the fuel economy of a hydraulic hybrid bus with different control strategies shows that the fuel economy was optimized using a global optimization control strategy. However, the objective of applying the global optimization control strategy is to obtain the load for the entire working cycle, which is difficult to obtain before the working cycle finishes, particularly for engineering machineries with complicated load and time-varying parameters. Although the dynamic programming control strategy is inferior to the global optimization control strategy in terms of the fuel economy, it is still better than other control strategies, and can be used to obtain approximate optimal fuel economy [18]. Hence, it is feasible to use the dynamic programming control strategy to improve the fuel economy of a hydraulic hybrid excavator.

The dynamic programming control strategy is commonly used in hybrid vehicles, but has rarely been used for the real-time control of hydraulic hybrid systems. The theoretical basis of this strategy is the principle of optimality developed by Bellman. The key idea is to convert a multistage decision process into a single-decision process. For each process, decisions are made based on the state variables and objective functions of the system. Subsequently, the corresponding control variables are obtained to achieve an approximate global optimal state. However, the precondition of using the dynamic programming control strategy to solve the control problem of hydraulic hybrid systems involves obtaining the required power for a given system at any moment. As the power distribution is also determined using the required power, the dynamic programming control strategy is clearly unsuitable for real-time control [19,20].

To apply the dynamic programming control strategy to a hydraulic hybrid excavator, we developed a prediction-based stochastic dynamic programming (PBSDP) control strategy in this study. Our approach is based on the required torque of the hydraulic hybrid excavator in the previous periods to predict the required torque in the next working cycle. The value function is calculated using the required power and charging state of the accumulator. Moreover, the value function is used in the controller to obtain its minimum value by adjusting the displacement of the hydraulic variable pump.

2. System configuration

To recover the potential energy of the hydraulic hybrid excavator, a new drive system is proposed in this study, wherein the mechanical arms are driven using three-chamber cylinders (TCCs) as shown in Fig. 1. Each TCC comprises three chambers, including a chamber with a piston rod, a chamber without any piston rods, and a counterweight chamber, as shown in Fig. 2. The volumes of the three chambers are equal. The counterweight chamber is connected to the accumulator, and the chambers with and without the piston rod are connected to the inlet and outlet of the variable pump, respectively, forming a closed pump control system. The action of the mechanical arms is controlled using the closed-pump control system.

During a normal working cycle of the hydraulic hybrid excavator, the variable pump is used to charge the chamber with piston rod or the one without the piston rod based on the control signal, which drives the TCC to retract or to extend, respectively. The accumulator is used to send high-pressure oil to the counterweight chamber, which provides an average value of the load force. When the piston rod extends, the variable pump charges the chamber without the piston rod, and the accumulator charges the counterweight chamber (see Fig. 3 (a)). In contrast, when the piston rod retracts, the variable pump charges the chamber with the piston rod, and the counterweight chamber charges the accumulator (see Fig. 3 (b)). Accordingly, the potential energy is recovered and stored in the accumulator in the form of pressure energy.

The action of the mechanical arms is controlled using the closed-pump control system. An internal combustion engine (ICE) is used to drive the three variable pumps through the powertrain and maintain a constant rotation speed. When the hydraulic hybrid excavator is in the working condition of walking, the auxiliary pump/motor works as a pump and drives the travel motor to rotate. Under this condition, the excavator driving system is in the form of a series hybrid system. When the hydraulic hybrid excavator is in the working condition of excavating, the auxiliary pump/motor works as a pump or motor based on the required torque of the boom, arm, and bucket pumps. When the