Novel control strategy for the energy recovery system of a hydraulic excavator

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Abstract: The energy saving of hydraulic excavators is always an essential research. An energy recovery system can effectively recover the boom potential energy and rotational kinetic energy. Based on the standard working cycle of hydraulic excavators, a dynamic programming (DP) control strategy for hybrid hydraulic excavators was proposed to recover the boom potential energy and rotational kinetic energy. The hybrid hydraulic excavator simulation model was built by Simulink software. The simulation results indicated that the fuel consumption of hybrid hydraulic excavators using the DP control strategy was about 21.3% lower than that of the conventional hydraulic excavator. In order to experimentally verify the simulation results, an experimental platform for hybrid hydraulic excavators was built. The experimental results indicated that the fuel consumption of hybrid hydraulic excavators using the DP control strategy was about 18.9% lower than that of the conventional hydraulic excavator. This paper shows that the DP control strategy applied to hybrid hydraulic excavators can recycle the boom potential energy and rotational kinetic energy, and reduce the fuel consumption of hybrid hydraulic excavators.

Keywords: hybrid excavator, energy recovery, control strategy, simulation analysis, test platform
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1 Introduction

In the face of global warming and the continued depletion of fossil energy, there is an increased demand for a more efficient energy-saving method all over the world[1-3]. As typical construction machinery, the hydraulic excavator has a wide range of applications and plays an irreplaceable role in infrastructure construction[4-6]. There are some concerns about using hydraulic excavators due to low energy utilization[6,7]. In the working cycle of hydraulic excavators, the drastic change in load affects the energy utilization rate. The drastic change of load results in low thermal efficiency of the engine[8]. At the same time, in hydraulic energy transfer, the energy loss is excellent due to throttling loss and linear loss[9]. The boom potential energy and rotational kinetic energy are wasted, which is also an essential reason for the low energy utilization rate. Taking a medium or large excavator as an example, during the working cycle, the waste of boom potential energy accounts for 20% of the output power of the hydraulic pump[5]. Therefore, Energy recovery technology to improve the energy efficiency of hydraulic excavators has become an important research direction all over the world.

Hybrid technology and energy recovery technology can effectively reduce fuel consumption, mainly used in the automotive field[10-12]. With the successful application in the automotive field, researchers have begun to study hybrid technology and energy recovery technology to improve the energy utilization rate of hydraulic excavators. Do et al.[13] designed an energy recovery system. The simulation shows that the maximum energy recovery efficiency of the system can reach 44%. Ranjan et al.[14] designed a hybrid system that can improve energy efficiency by 10%. The main components of the system are an accumulator, a hydro-motor, a driving pump, and a loading pump. Yu et al.[15] designed an energy regeneration swing system and proposed a combined control of the flow control valve and hydraulic motor, and a variable accumulator control strategy was also proposed. Experiments indicated that the energy recovery efficiency of the system is between 23%-56%. At the same time, some manufacturers have begun to apply hybrid technology and energy recovery technology to hydraulic excavators. For example, Komatsu, Kobelco, Hitachi, Caterpillar, SANY, Sunward, and LiuGong[3,16]. The above studies and applications indicated that hybrid technology and energy recovery technology can effectively improve the energy utilization efficiency of hydraulic excavators. The application of hybrid technology and energy recovery technology in hydraulic excavators is divided into two categories. One is an electric hybrid excavator, and the other is a hydraulic hybrid excavator[17,18]. The energy storage unit of an electric hybrid excavator is a battery or ultracapacitor. The boom potential energy and rotational kinetic energy are converted into

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electrical energy and stored in the energy storage unit. When the energy is reused, the electrical energy is converted into hydraulic energy, which drives the hydraulic pump to work. The energy storage unit of the hydraulic hybrid excavator is a hydraulic accumulator[18]. The hydraulic accumulator stores the boom potential energy and rotational kinetic energy in the form of hydraulic energy. The hydraulic energy is released by the hydraulic pump to assist the engine work or drive the actuator to work alone. However, the pressure of the hydraulic accumulator is related to the load, so the drastic change in the load affects the energy conversion efficiency of the accumulator. The electric hybrid excavator has unique advantages, such as the small size of the energy storage unit, high peak power, fast charging and discharging, and the ability to recover the rotational kinetic energy of the rotary platform, which are more suitable for energy-saving research[17,19]. The hybrid hydraulic excavator studied in this paper is an electric hybrid excavator, which uses an ultra-capacitor as the energy storage unit.

With further research on hybrid technology and energy recovery technology, many kinds of research focus on energy management strategies of hydraulic excavators, such as rule-based control strategy and optimization-based control strategy[20]. The rule-based control strategy is suitable for real-time control and can switch control modes according to the state of the power system and deal with nonlinear problems. It is divided into deterministic rule-based control strategy and fuzzy rule-based control strategy[21]. The optimization-based control strategy is divided into global optimization control strategy, such as dynamic optimization[22], particle swarm optimization[23], genetic algorithm optimization[24], and real-time optimization control strategy, such as equivalent consumption minimization strategy[25], reinforcement learning control strategy[26], model predictive control strategy[27]. Chen et al.[28] proposed a rule-based control strategy based on the operating efficiency interval of the engine and the SOC of the ultra-capacitor. Truong et al.[29,30] proposed a hydraulic excavator power system consisting of fuel cells, batteries and ultra-capacitors. In order to avoid the shortcomings of the conventional power system, a new mapping fuzzy logic control energy management strategy based on a rule-based algorithm was proposed. Compared with the conventional energy management strategy, it can improve the working efficiency of hydraulic excavators by 47% and improve the fuel economy by 10.919%. Although the conventional rule-based control strategy can realize real-time control, its ability to adapt to the drastic change in load and parameter drift is deficient. The calculation process of the optimization-based control strategy is complex and is not suitable for real-time control. To solve the problem that the rule-based control strategy cannot predict the drastic change of load, and the problem that the optimization-based control strategy is difficult to real-time control. Zhou et al.[24] proposed a fuzzy control strategy based on a genetic algorithm, which estimates the required torque of the engine by predicting the load change while realizing real-time control. Furthermore, an equivalent consumption minimization strategy based on the optimal control problem was established for the hydraulic excavator[31].

At present, the energy management strategy of the hybrid system is mainly applied to the hybrid electric vehicle. Although some studies have begun to apply energy management strategies to hybrid hydraulic excavators, there are more rule-based control strategies and fewer optimization-based control strategies. In order to better recycle the energy, and reduce the fuel consumption of hydraulic excavators, it is necessary to further study the energy management strategy of hydraulic excavators in previous research. In this paper, according to the characteristics of the standard working cycle of hydraulic excavators, a dynamic programming (DP) control strategy was proposed. The control strategy can not only effectively recover the potential energy of the boom potential energy and rotational kinetic energy, but also use the recovered energy to assist the engine in driving the actuator to achieve the optimal goal of global fuel consumption. In order to solve the real-time problem of the DP control strategy, the fuel consumption characteristics of the engine, the characteristic data of the motor/generator, and the pressure and flow loss of the hydraulic system are applied to the DP control strategy. The energy consumption of the DP control strategy applied to the hydraulic excavator and the conventional hydraulic excavator is compared through simulation and experiment, and it is confirmed that the DP control strategy proposed in this paper can effectively reduce the fuel consumption of the hybrid hydraulic excavator.

2 Energy recovery system structure

2.1 Working cycle analysis

The hydraulic excavator working movement has the characteristics of a high repetition rate, a strong periodicity and a power fluctuation during the working cycle. Generally, the working process of excavators is divided into four parts, including digging, rotating, releasing load, and swinging, and it should be noted that the travel portion is not considered in this paper. Under these working conditions, the mechanical components (i.e., boom, arm, bucket and platform) are driven by engine power through hydraulic pumps. The demand for power and energy from hydraulic excavators can be described as

$$P = P_{\text{Boom}} + P_{\text{Arm}} + P_{\text{Bucket}} + P_{\text{Swing}} + P_{\text{Attachment}} \tag{1}$$

$$E = \int_0^t P \mathrm{d}t \tag{2}$$

where, P_{Boom}, P_{Arm}, P_{Bucket} are the driving power of boom, arm and bucket cylinder, respectively, kW; P_{Swing} is the driving power of the swing motor, kW; and $P_{\text{Attachment}}$ is the driving power of the attachment, kW;

The driving power and energy of each hydraulic component are calculated as follows:

$$P_{\text{pi}} = p_{\text{pi}} Q_{\text{pi}} \tag{3}$$

$$E_{\text{pi}} = \int_0^t P_{\text{pi}} \mathrm{d}t = \int_0^t p_{\text{pi}} Q_{\text{pi}} \mathrm{d}t \tag{4}$$

where, p_{pi} is the outlet pressure, MPa; Q_{pi} is the outlet flow for each hydraulic component, L/min;

There is a considerable energy recovery during the boom-lowering and rotation-braking processes compared to the other actions. Therefore, the boom and rotary drive system are the focus of energy-saving research on hydraulic excavators. Furthermore, the engine working points are spread in the broader region and outside the efficient working area when the excavator operates under practical working conditions, resulting in low work efficiency and energy utilization. Through the research of the boom potential energy and rotational kinetic energy, the power matching between the engine and the load is of great significance to energy savings for hydraulic excavators.

2.2 System structure and principles

Traditionally, the diesel engine is the only power unit that drives the hydraulic pump of hydraulic excavators. It is unable to recover the boom potential energy and rotational kinetic energy. Based on the primal system of hydraulic excavators, we import the electric-hybrid driving unit, the boom potential energy recovery unit, the electric rotary driving and braking unit, the energy storage unit, and the energy management unit to compose the energy recovery and recycle system, as shown in Figure 1. A permanent magnet synchronous motor is equipped as the electromotor or generator, and an ultra-capacitor is used as the energy storage unit.

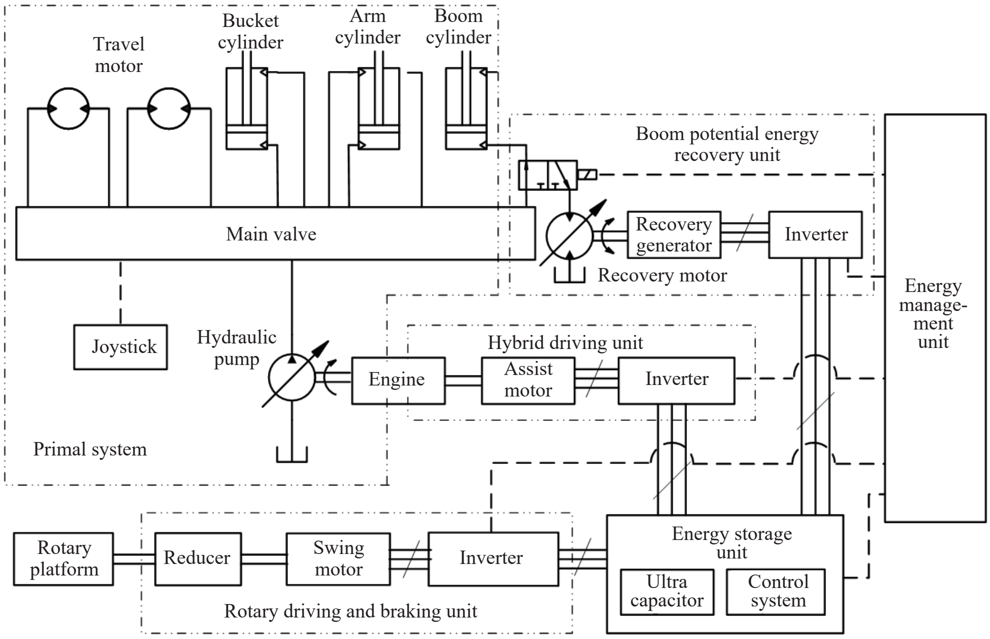


Figure 1 Principle of energy recovery system

According to the main characteristics of the boom and the rotation driving system, the boom potential energy is recovered by a hydraulic motor-generator, and the rotational kinetic energy is recovered by a swing motor (SM). During the rotational braking process, the swing motor (SM) works in generator mode, converting rotational kinetic energy into electrical energy. All recovery energy can be transformed into electrical energy and stored in the ultra-capacitor. Moreover, the assist motor (AM) works as a second power source to drive the hydraulic pump in parallel with the engine. When the power demand of the load exceeds the limit power of the engine, the AM works in the motor mode, driving the hydraulic pump. When the power demand of the load is lower than the output power of the engine, the AM works in the generator mode to absorb the excess power of the engine working in the high-efficiency working area, thereby improving the energy utilization efficiency. When the remaining power of the Ultra Capacitor (UC) reaches the minimum. The recycled motor becomes a load driven by the engine. The mechanical energy of the engine is converted into electrical energy through hydraulic energy, which is used to compensate for the low power state of the Ultra Capacitor (UC). When the energy of the supercapacitor is lower than the minimum energy range. The engine is in a normal working state, and the assist motor (AM) is limited in terms of power output. All recovered power and remaining engine power is used to drive the generator to generate electricity, thus ensuring that the energy of the Ultra Capacitor (UC) is quickly restored to a safe range.

2.3 DP algorithm principles

The dynamic programming algorithm is a branch of operational research and the famous optimal principle proposed by the American mathematician Robert Bellman in 1953. Its core idea is to translate a multi-stage optimal control problem into a series of single-stage problems and then optimize them one by one. If the optimal solution of a problem is at an intermediate state, the optimal solution from the intermediate state to the end of the whole process is a subset of the total optimal decision. Therefore, all the subsets of the optimal solution could accumulate and become the final optimal solution of the multi-step optimal control problem. According to this theory, ranking decisions can be applied to complex systems and by using optimizers at each level to achieve overall optimization goals[32-34].

The DP algorithm is also a reverse calculation of the optimization method. Its goal of achieving control under cyclic conditions can be accomplished in two steps. The first step is to reverse search for the minimum cost function of each layer and record the corresponding optimal control. The second step is to perform a forward search by using the optimal control obtained in the first step.

Under the given working conditions, the energy distribution of the hydraulic excavator could be regarded as a multi-stage optimal decision problem. Therefore, the DP algorithm is applied to solve this problem to obtain the minimum fuel consumption of the excavator.

Based on the above analysis, the excavator working cycle could be divided into N stages by the discretization method with the time step of each stage being Δt. The fuel consumption function of the engine in the energy recovery system is represented as follows:

$$J = \sum_{K=1}^{N} f(x(k), u(k), k)\Delta t \tag{5}$$

where, k is the optimized stage variable, f is the fuel consumption rate function of the engine, $x(k)$ is the stage variable corresponding to the stage k and $u(k)$ is the decision variable of the corresponding state variable at stage k.

The state of charge (SOC) for the energy storage unit is used as the optimized state variable, and the corresponding system state transition equation is as follows:

$$x(k+1) = g_{\mathrm{soc}}(x(k), u(k)) \tag{6}$$

where, g_{soc} is the state transition function.

Then, this system can be represented as follows:

$$\mathrm{SOC}(k+1)=\begin{cases}\mathrm{SOC}(k)-p_m(T_m,\omega_m)/\eta_m\eta_c, & (p_m(T_m,\omega_m)\geq 0)\\ \mathrm{SOC}(k)-p_m(T_m,\omega_m)\eta_m\eta_c, & (p_m(T_m,\omega_m)<0)\end{cases} \tag{7}$$

where, p_m is electric motor power, with the positive value meaning that it is in the motor mode, kW; and the negative value indicating that it is in the generator mode. T_m is the motor torque, Nm; ω_m is the motor speed, r/min; η_m is the electrical efficiency, %; and η_c is the efficiency of energy storage unit, %;

The optimal control trajectories $u(t)$ $(t_0\leq t\leq t_T)$ are tuned to the corresponding optimal control sequence, u_k $(k=1,2,\ldots,N)$, and the constraint condition of its stage and control variables are as follows:

$$\begin{cases}\mathrm{SOC}_{\min}\leq \mathrm{SOC}(k)\leq \mathrm{SOC}_{\max}\\ 0\leq n_{\text{motor}}\leq n_{\text{motor\_max}}\\ -T_{\text{gen\_max}}\leq T_{\text{motor}}\leq T_{\text{motor\_max}}\\ 0\leq T_{\text{engine}}\leq T_{\text{engine\_max}}\\ 0<P_{\text{motor}}<P_{\text{motor\_max}}\end{cases} \tag{8}$$

where, $\mathrm{SOC}_{\min}$ is the minimum value of energy storage unit SOC, $\mathrm{SOC}_{\max}$ is the maximum value of energy storage unit SOC, Ah; $n_{\text{motor\_max}}$ is the motor maximum speed, r/min; $T_{\text{gen\_max}}$ is the maximum torque of the motor in the generator mode, Nm; $T_{\text{motor\_max}}$ is the maximum torque of the motor in the motor mode, Nm; $T_{\text{engine\_max}}$ is the maximum torque of the engine, Nm; and $P_{\text{motor\_max}}$ is the maximum torque of the motor, Nm;

2.4 Programming

The DP algorithm control flow chart is shown in Figure 2. The program can be divided into two loops. The left half of the block diagram is the reverse optimization search process of the DP algorithm, which can calculate and store the state and decision variables and output the optimal value $f_1(x_1)$. The right half is the forward search process for calculating the optimal value at every stage and for obtaining the SOC variation curve and optimal trajectories curve $\{u_1,u_2,\ldots,u_n\}$.

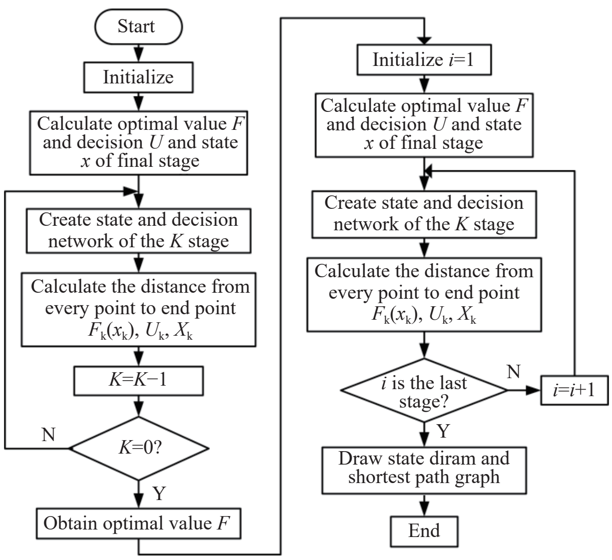


Figure 2 Flow chart of the DP algorithm program

The program shows the DP algorithm control process in detail, and each state is calculated using control variables through dynamic equations. During the calculation process, the control value that exceeds the result of the state domain is eliminated, and the calculation is continued with the next control value. For the accepted control, the fuel consumption data of the engine in this state should be added. By comparing all control value sets in the state, the minimum set is stored.

3 Simulation and analysis

3.1 Simulation model

The simulation model is established based on 23 t of hydraulic excavator, and some parameters of the hydraulic excavator are listed in Table 1. The actual load spectrums of the hydraulic excavator are taken as the input data.

Table 1 Main parameters of the machine and power system

Item	Parameter	Specification
Whole machine	Total weight	22 400 kg
	Bucket capacity	1.05 m³
Hydraulic system	Pump flow	2×220 L·min⁻¹
	Maximize pressure	32.4 MPa
Engine	Output volume	6.494 L
	Rated power/rev. speed	125 kW/2100 r·min⁻¹
	Maximize torque	697 N·m
Assist motor	Rated/peak power	20/40 kW
	Rated speed	1800 r·min⁻¹
Recovery generator	Rated/peak power	30/60 kW
	Rated speed	1800 r·min⁻¹
	Reduction ratio	1.96
Swing motor	Rated/peak power	60/100 kW
	Rated speed	2800 r·min⁻¹
Ultra capacitor	Rated voltage	48.6 V
	Capacity	165 F

To evaluate the energy recovery system and the proposed control strategy for the hydraulic excavator, a simulation model is built in Simulink software based on the mathematical model of the critical system components, as shown in Figure 3. The model takes into account the fuel consumption characteristics of the engine, the efficiency of the AM and SM, the internal resistance of the ultra-capacitor, the pressure and flow losses of the hydraulic unit, and the resistance torque of the swing mechanism.

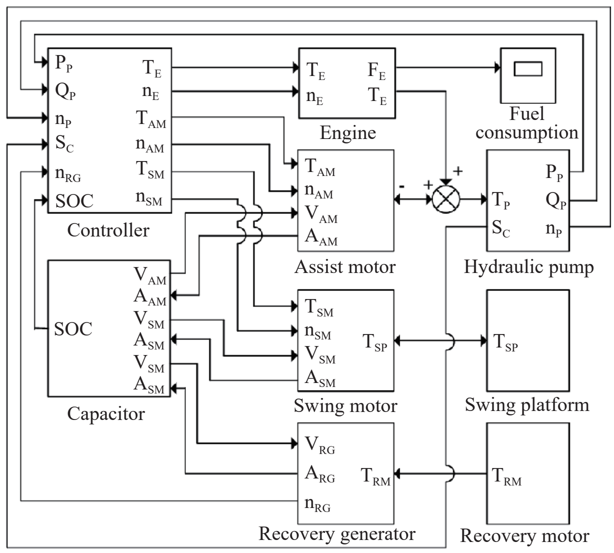
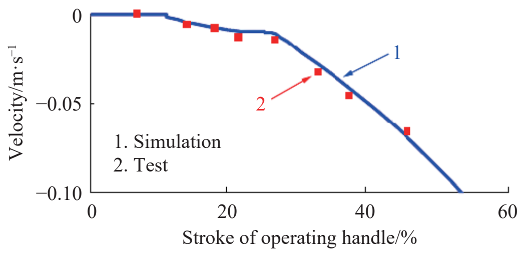


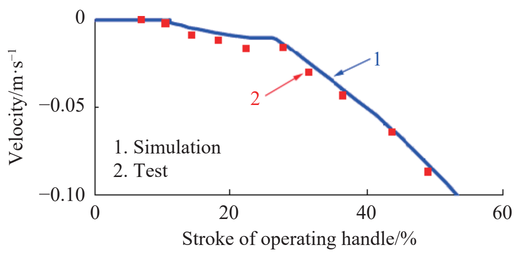
Figure 3 Systematic diagram of the system simulation model

3.2 Result and analyze

Figure 4 shows the movement speed of the hydraulic cylinder during the single-action lowering of the boom under no-load and loaded conditions, respectively. The blue solid line is the movement speed curve of the boom hydraulic cylinder obtained under the simulation model. The red discrete points are the measured movement speed of the hydraulic cylinder under the same operating handle signal as the simulation input. The measured data takes the forward direction of the boom operating handle stroke as positive. At this time, the downward movement speed direction of the boom is negative.



a. Without load



b. With load

Figure 4 Movement speed of boom single action hydraulic cylinder

Figure 5 shows the movement speed of the boom hydraulic cylinder under the operation cycle of the hydraulic excavator. It can be seen from the comparison that the movement velocity of the hydraulic cylinder changes smoothly during the lowering and lifting of the boom and is consistent with the measured curve. The velocity tracking accuracy and error are within the acceptable range of the control system.

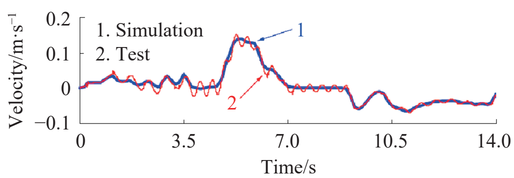
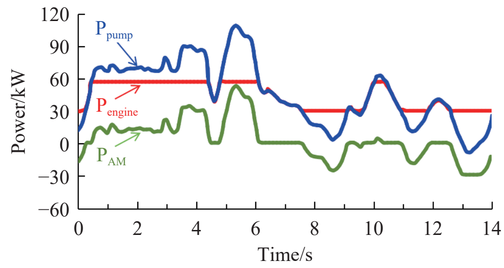
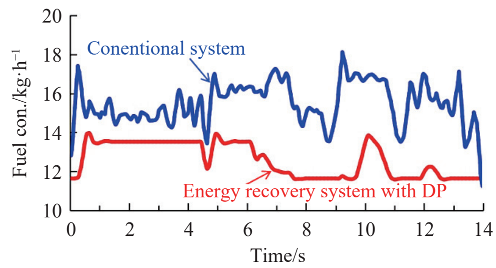


Figure 5 Velocity of boom hydraulic cylinder under operation cycle

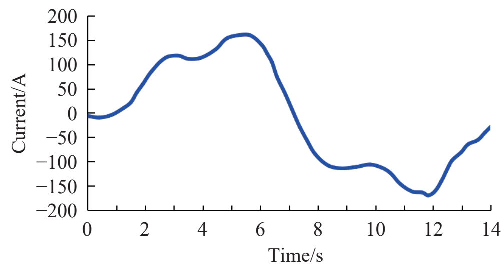
Figure 6a shows the simulation results of the output power distribution among the pump, the engine, and the AM. The comparison between the pump power and the engine power of the hydraulic excavator is evident because the engine shares the load with the ultra-capacitor power through the AM. Therefore, the engine rated power could decrease from 125 kW to 90 kW, and the fuel demand could be lower. The fuel consumption between the conventional system and the energy recovery system with the DP control strategy are shown in Figure 6b. The fuel consumption reduction of approximately 21.3% is obtained with this strategy. The ultra-capacitor current and voltage during one working cycle of the hydraulic excavator are shown in Figures 6c and 6d, respectively. The ultra-capacitor is working efficiently under the DP algorithm, and the SOC of the ultra-capacitor is kept to a certain range during this cycle.



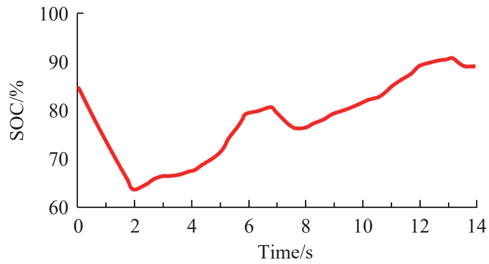
a. Power of the hydraulic pump, the engine and the AM



b. Fuel consumption of two systems



c. Current of ultra-capacitor unit



d. SOC of ultra-capacitor unit

Figure 6 Simulation results of the energy recovery system under the DP algorithm

4 Experiment and analysis

4.1 Experimental method

In order to study the effect of the energy recovery system on hydraulic excavators, a test platform based on the experimental machine was built, as shown in Figure 7. The lower computer adopts the special controller CR0200 of IFM Electronics Company, which is responsible for collecting sensor data and controlling the energy recovery system. The real-time status data is sent to the upper computer through the CAN bus, and the upper computer displays the working status of the energy recovery system and saves the data file. The parameters of CR0200 data acquisition system is described in Table 2.

According to the national standard "Hydraulic excavator test methods" (GB/T 36695-2018)[35], the experimental machine under standard working cycle conditions and operation are shown in Figure 8. The test is performed three times with ten cycles for each test. The experimental data are measured and recorded during the testing process.

1) Preparation

Keeping the digging-ready attitude and the teeth-and-hinge point of the bucket on the same horizontal line, the height between the bucket teeth and the ground is less than 10 cm, and the arm-moving angle is 30° outside of its vertical attitude.

2) Compound digging

The arm moves inside from the ready attitude centered at its hinge point. The moving angle is –30°, and the digging depth D is 1 m.

3) Swinging 90° and boom lifting

The arm swings to the specific location and lifts the boom to ensure that the height H between the bucket teeth and the ground is 2 m.

4) Bucket dumping

When the bucket dumps the soil, the teeth and the hinge point of the bucket should be on the same line as the arm hinge point.

5) Restoration

The arm swings back to the original position and prepares for the next digging cycle.

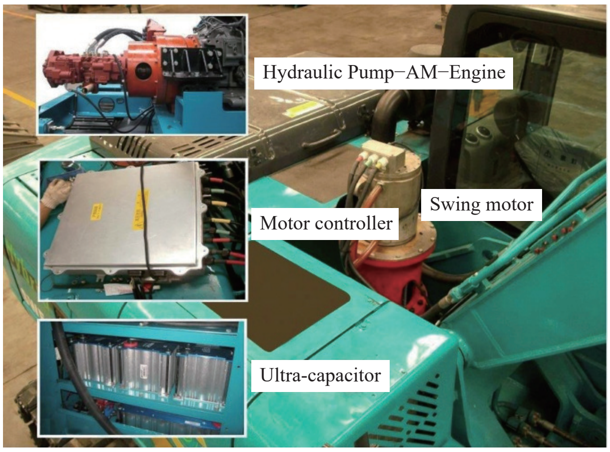


Figure 7 Test platform of the energy recovery system

Table 2 Parameters of CR0200 data acquisition system

Item	Parameters
Supply voltage	5-50 V
Number of channel	24
Distinguishability	16 bit
Precision	0.05%
Measuring voltage range	±100 mV, ±500 mV, ±1 V, ±5 V, ±10 V, ±20 V, ±60 V
Measurement frequency	1 Hz, 2 Hz, 5 Hz, 10 Hz, 50 Hz, 100 Hz, 500 Hz, 1 kHz, 2 kHz
Transmission frequency	125 kBit/s-1 MB/s
CAN BUS channel	2

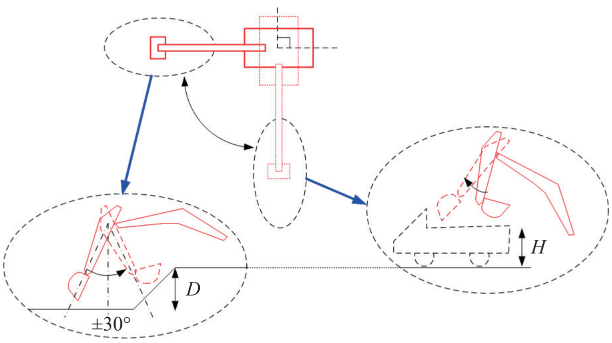


Figure 8 Test method of typical working operations

4.2 Experimental result and analysis

Figure 9 shows the contrast curves of the engine speed under the same working conditions for the conventional system and the energy recovery system using the DP algorithm. It is known that the engine speed of the energy recovery system using the DP algorithm is 300 r/min less than that of the conventional system. This means that with assistance from the energy recovery system, the engine exports less power for the same working load, and therefore, the fuel economy is more efficient.

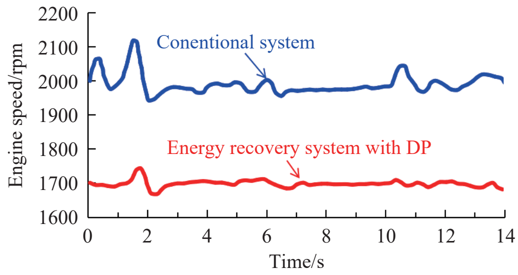


Figure 9 Contrast curve of engine speed

Figure 10 depicts the comparison of engine operating point distribution ratios for different systems. In the conventional excavator system, the output power of the engine is always equal to the power required by the hydraulic pump, and the corresponding operating points are distributed in the broader area, similar to the normal distribution, as shown in Figure 10a. With the DP algorithm, the engine output power of the energy recovery system is centered at the average pump required power, and most of the engine working points are spread in an optimal region with a lower fuel consumption rate, as shown in Figure 10b.

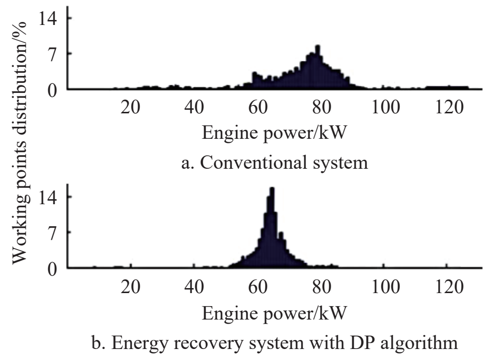


Figure 10 Comparison of the working points distribution rate of engines using the different systems

The energy output curves of the excavator engine for the two systems are shown in Figure 11. The total energy and fuel consumption under the typical operating conditions are listed in Table 3. The fuel consumption is 60.74 g for the conventional system and 49.27 g for the energy recovery system with DP. Therefore, the energy savings for the energy recovery system with the DP algorithm are considerable. The total fuel economy savings

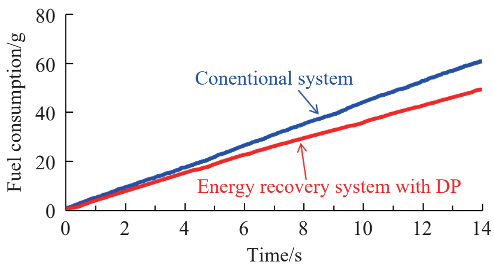


Figure 11 Fuel consumption of the conventional system and energy recovery system with the DP algorithm

of the energy recovery system is equal to 18.88% of the conventional system as calculated from the cumulative fuel consumption over an hour. Therefore, the energy recovery system with the DP algorithm is worth further study because it has a lot of potential in terms of energy savings.

Table 3 Contrast parameters of the two systems

Type	Fuel consumption/g	Fuel saving ratio/%
Conventional hydraulic system	49.27	/
Energy recovery system with DP	60.74	18.88

5 Conclusions

1) An energy recovery scheme based on hybrid hydraulic excavators is proposed, and the ultra-capacitor is used as the energy storage unit of the hybrid system.

2) The simulation model of the hybrid hydraulic excavator is established by using Simulink software, and the DP control algorithm is applied to the energy recovery system of the hybrid hydraulic excavator. Simulation analysis indicated that the energy recovery scheme proposed in this paper can reduce fuel consumption by about 21.3% compared with conventional hydraulic excavators.

3) In order to verify the simulation analysis results, a hybrid hydraulic excavator test platform with an energy recovery system was built. The experimental analysis indicated that the energy recovery scheme proposed in this paper can reduce the fuel consumption by about 18.88% compared with the conventional hydraulic excavator.

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