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Fuzzy Logic Control Strategy for Parallel Hybrid Excavator

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Abstract

A 20 t parallel hybrid excavator was applied as the research object in the research. To optimize the fuel economy of the engine and maintain the balanced electric quantity of power batteries simultaneously, a fuzzy logic based strategy was proposed to control the power train of the 20t parallel hybrid excavator. The torque required by the system and the state of charge (SOC) of the capacitor were regarded as the input parameters, while the power partition coefficient K was regarded as the output parameter to design the fuzzy logic controller, so as to optimize the power output of the engine and the motor. The simulation and bench test results demonstrated that the proposed fuzzy logic based control strategy can maintain the balanced electric quantity of the capacitor while controlling the engine to be operated at the optimal output power. Meanwhile, after being optimized by the fuzzy logic, the engine reduced the fuel consumption by 8.06%. Therefore, it is concluded that this strategy is applicable to parallel hybrid excavators, accompanying with significant energy saving effect.

Keywords*: hydraulic excavator, parallel hybrid, energy saving, control strategy, fuzzy logic Chinese book classification code: TH137*

1. Introduction

As a kind of articulated construction robots with multi-degree of freedom, hydraulic excavators have been widely applied in the construction operations related to civil engineering due to its multiple functions and strong operating adaptability. Meanwhile, as one of the associated problems, the study on the energy saving of hydraulic excavators has attracted much attention. The violently fluctuated operating load of excavators gives rise to the unstable working points of engines, and thus leads to the high energy consumption, high emission and poor fuel economy of excavators. Hybrid technology has become the research focus for its technical advantages in solving the aforementioned problems. Different from the powertrain of traditional hydraulic excavators, hybrid technology adopts compound drive by using more than one power sources. To be specific, the "peak load shifting" function of the auxiliary power source is utilized to balance the substantial change of the power output of the primary power source (engine) induced by the load fluctuation. In this way, it can stabilize the working points and optimize the fuel economy of engines. In 2004, Komatsu Company in Japan developed the first prototype of the oil-electric hybrid excavator in the world [1], in which the parallel powertrain was adopted. Later, it launched the improved prototypes PC200-8EO and HB215LC successively in 2008 and 2012. In 2006, Kobe Steel Ltd. in Japan developed the prototype of the serial oil-electric hybrid excavator SK70H, which has been put into batch production officially since 2007 [2]. Caterpillar Inc. Company in America launched its own first hybrid excavator CAT336EH in 2012, which adopts the oil hybrid technology and has been put into mass production since 2013. Compared with the tycoons in the international construction machinery industry who have developed increasingly matured technology, the studies regarding

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the hybrid technology of excavators are still in the primary stage in China. In recent years, Sany Heavy Industry Co. Ltd., Sunward Intelligent Machinery Co., Ltd and Zoomlion Heavy Industry Science & Technology Co. Ltd. in China have developed their own prototype of hybrid excavators successively [3-4]. The technology is still immature for realizing the productization. Therefore, it is very necessary to carry out the systematic and special research on the key hybrid technology.

As one of the research hotspots and the key part of the hybrid technology, the energy management of the hybrid powertrain is, directly related to the energy saving effect. In China, Zhejiang University firstly carried out the basic research concerning the hybrid hydraulic excavators. Zhang Yan-ting *et al.* [5-6] put forward a strategy for controlling the invariable working points (including single working point and double working points) of the engine for the 5 t hydraulic excavator. The strategy was proposed based on the parallel hybrid powertrain with the super capacitor applied as the energy storage system. Xiao Qing [7] proposed an improved strategy for controlling the dynamic working points. Wang Dong-yun [8] put forward a strategy for controlling the dynamic mixing degree based on the condition analysis, which was another kind of strategy controlling the dynamic working points. Liu Gang *et al.* [9] from Tongji University developed a strategy which can realize the balanced control over the torque of the parallel hybrid excavator. The aforementioned strategies all can be concluded as the rule based logic threshold control methods, and mainly focus on optimizing engines to have them work in the high efficiency area. However, they present poor optimization effect on the charge-discharge balance of power batteries. He Qing-hua [10] from Central South University proposed a strategy for controlling the quasi-stable working points based on the prediction of working conditions for the parallel hybrid system of the 20 t hydraulic excavator. However, this strategy exhibited poor real-time adaptability to loads.

The powertrain of parallel hybrid excavators belongs to the nonlinear time-varying system. Therefore, to optimize the engine efficiency and maintain the balanced electric quantity of power batteries simultaneously, fuzzy logic based control strategy requires to be utilized to coordinate the power distribution of power components. This research studied the fuzzy logic based strategy for controlling the powertrain of the 20 t parallel hydraulic excavator in which the super capacitor based energy storage system was adopted. Meanwhile, the MATLAB/Simulink software platform was employed to simulate the energy saving effect and optimal performance of the control strategy. Afterwards, the simulated results were verified on the self-developed, integrated test bench for the parallel hybrid powertrain of the excavator.

2. The Fuzzy Logic based Control Strategy

2.1 The System Structure of the Parallel Hybrid Excavator

The structure of the powertrain of the research object, namely, the parallel hybrid hydraulic excavator, is shown in Figure 1.

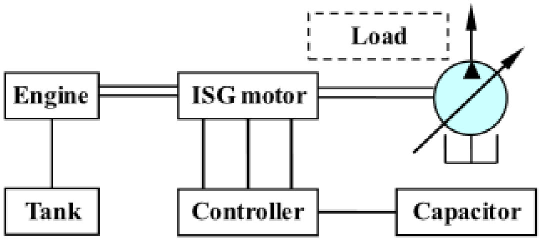


Figure 1. Structure of the Parallel Hybrid Hydraulic eExcavator

The engine of the primary power source and the auxiliary power source—integrated starter generator (ISG) motor are connected using the same axis to drive the hydraulic pump jointly. The power balance among the engine, the ISG motor, and the hydraulic pump is expressed as follows:

$$P_{engine} + P_{motor} = kP_{pump} \tag{1}$$

Where, k and P_{pump} represent the correction factor of efficiency and the absorption power of the hydraulic pump respectively.

Since they have same rotational speeds, the relationship among the torque of three of them is formulated as:

$$T_e + T_m = kT_{pump} \tag{2}$$

Where, T_e and T_m indicate the output torques of the engine and the ISG motor separately.

Electrical connection is established between the super capacitor and the ISG motor and its switch controller. The ISG motor can work by consuming and to generate power, so as to compensate the power according to the variation of the loads. As a kind of energy storage element, the super capacitor is designed to adjust the power to have the engine work in the high efficiency area of specific fuel consumption. By doing so, the authors attempted to offset the influence of the violently fluctuated load on the engine.

2.2 The Optimal Working Curve of the Engine

Both the rotational speed and the power can be utilized to determine the optimal working curve of the engine, and the former is adopted in the research. The map of the fuel consumption of the engine utilized in the research is shown in Figure 2, which is zoned by applying certain a step selected from the workable rotational speeds (within the range from the minimum to the maximum value) of the engine. Taking certain a rotational speed, 1,800 rpm, for an example, the engine efficiency at each torque value T_i within the preset working range (from point B to Point A) of the torque of the engine is calculated in the research according to the map. Then, the point with the maximum efficiency is regarded as the optimal working point of the engine at current rotational speed. Afterwards, the optimal working curve of the engine can be obtained by connecting the optimal working points at various rotational speeds.

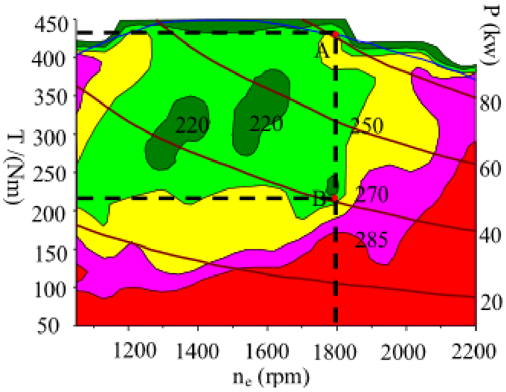


Figure 2. Fuel Consumption Map of the Engine

2.3 The Control Strategy based on Fuzzy Logic

Excavators work in poor environment and bear loads with strong real-time variation. Therefore, they show high requirements on the reliability of components while satisfying the power performance of operation. The hybrid system not only needs to guarantee the fuel economy of the engines during their normal operation, but also to stabilize the SOC of the super capacitor to be within a certain range, so as to avoid the shortened working life of the capacitor caused by overcharging and discharging. Thereby, control strategies are required to have high robustness and adaptability. In this aspect, fuzzy logic control exactly accords with the requirements above. Unlike the control methods based on the logic threshold value, the fuzzy logic based control strategy embeds the knowledge base of expert system into the fuzzy controller in the form of control rules, and describes these control rules using the fuzzy value instead of the accurate value. It presents low dependence on the accurate model of the system, and therefore is endowed with strong robustness and adaptability.

The torque T_{rq} required by the system and the SOC of the super capacitor are input into the fuzzy controller in the research. After the fuzzy logic reasoning, the partition coefficient K of the torque is outputted, which is then defuzzified segmentally to obtain the target output torque T_e of the optimized engine. Then, the target torque T_m of the motor can be obtained by calculating the difference between the required torque T_{rq} and the target output torque T_e of the engine. The principle of the fuzzy logic based control strategy is shown in Figure 3.

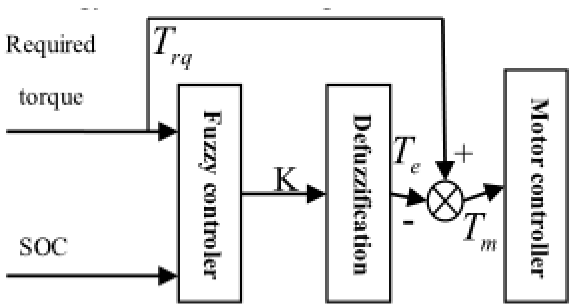


Figure 3. The Principle of the Fuzzy Logic based Control Strategy

The torque required by the system T_{rq} is determined by the absorbed torque of the hydraulic pump, and is formulated as:

$$T_{rq} = T_{pump} = \frac{p.q}{2\pi.\eta_m.\eta_v} \tag{3}$$

Where, p , q and η_v represent the output pressure, the displacement and the volumetric efficiency of the hydraulic pump respectively, while η_m indicates the mechanical efficiency of the system.

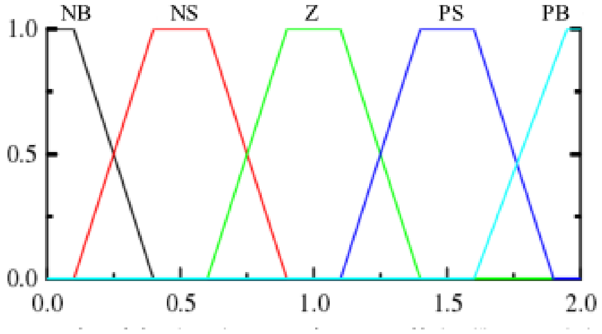
The computational formula of the target output torque T_e of the engine is expressed as:

$$T_e = \begin{cases} K \cdot T_{opt}, & K \le 1 \\ T_{opt} + (K-1)(T_{\max} - T_{opt}), & K > 1 \end{cases} \tag{4}$$

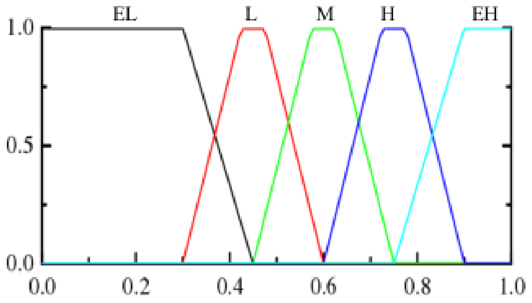
Where, T_{opt} denotes the optimal theoretical torque of the engine at current rotational speed, which is corresponding to the aforementioned optimal working point. $T_{\max}$ represents the maximum output torque of the engine at current rotational speed.

The universe of the input variable T_{rq} is in the range of [0, 2]. Thereinto, 0 indicates that the load torque is basically equal to 0, while 1 indicates that the load torque is equal to the current optimal theoretical torque of the engine. In addition, 2 denotes the maximum value of the load torque. The universe of SOC is in the range of [0, 1], where 0 and 1 represent the theoretical upper and lower limits of the super capacitor respectively. The partition coefficient K of the torque ranges in the universe of [0, 2], in which 0 signifies that the target output torque of the engine is 0, while 1 indicates that the target torque of the engine is the optimal efficiency torque at present. Besides, 2 is the maximum target torque of the engine.

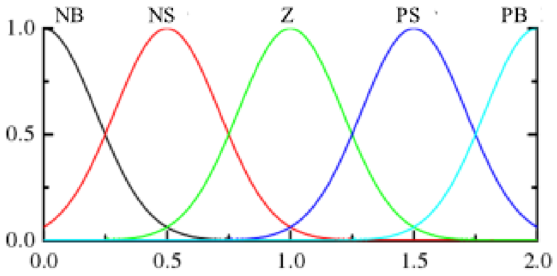
The membership functions of the input and output variables are established to construct the fuzzy rule set. The membership functions of each parameter are demonstrated in Figure 4. The fuzzy rule set utilized in the research is illustrated in Table 1, which is composed of 25 pieces of If-Then rules. Meanwhile, the Mamdani's inference method is adopted [11].



Negative big (NB) Negative Small (NS) zero(Z) Positive Big (PB) Positive Small (PS)
The membership Function of the Input Variable T_{rq}



Excessively Low(EL) Low(L) Moderate(M) High(H) Excessively High(EH)
The Membership Function of the Input Variable SOC



(c) The Membership Function of the Output Variable K

Figure 4. The Membership Functions of Input and Output Variables

Table 1. The Base of Fuzzy Logic Rules

SOC	T_{rq}				
	NB	NS	Zero	PS	PB
Excessively low	M	PS	PB	PB	PB
Low	NS	M	PS	PB	PB
Moderate	NB	NS	M	PS	PB
High	NB	NB	NS	M	PS
Excessively high	NB	NB	NB	NS	M

3. System Modeling

As for the system structure of the parallel hybrid excavator illustrated in Figure 1, the theoretical formula is combined with the experimental data to perform modeling on the main components including the engine, ISG motor, hydraulic pump and super capacitor. Meanwhile, the MATLAB/Simulink software platform is utilized to construct the systematic simulation model shown in Figure 5.

3.1 Engine Model

This research aims to investigate the variation of the working points and the fuel consumption as the engine operates instead of the real-time dynamic performance of the engine. Therefore, the modeling of the experimental data and the theoretical modeling are applied as the main and auxiliary methods respectively to establish the mean model of the engine. After the data measured in the universal characteristic test of the engine are processed by using the interpolation method, the steady output torque of the engine illustrated in formula (5) is obtained.

$$T_e = f(n_e, \alpha) \tag{5}$$

Where, T_e, n_e and α represent the steady output torque, rotational speed, and throttle opening of the engine respectively.

The engine works at the non-steady state in most of the time. Therefore, in order to reflect the dynamic characteristics of the engine, the dynamic output model of the engine is established as follows:

$$T_{ed}(n_e, \alpha) = T_e - J_e \dot{n}_e - C_e n_e \tag{6}$$

Where, $T_{ed}(n_e, \alpha)$ and J_e indicate the dynamic output torque and equivalent rotational inertia of the engine separately, while C_e represents the viscosity damping coefficient.

The fuel consumption model of the engine is illustrated in formula (7):

$$G_e = k \int g_e \cdot T_e \cdot n_e dt \tag{7}$$

Where, G_e denotes the fuel consumption, and g_e indicates the fuel efficiency, which is obtained by processing the expermental data using the interpolation method.

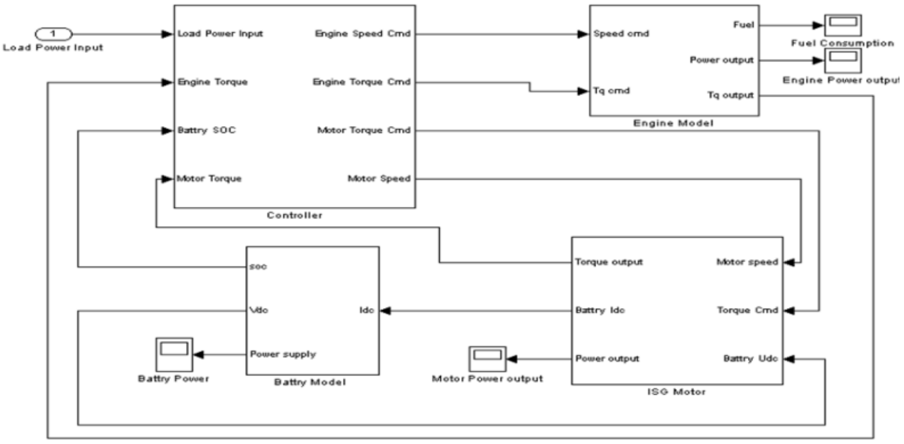


Figure 5. Simulation Model of the Parallel Hybrid System

3.2 The Model of the ISG Motor

As an important element for energy conversion in the powertrain, the ISG motor is intensively studied in the research in terms of the dynamic output characteristics and the energy conversion efficiency. The dynamic output torque of the motor is a first-order inertia link illustrated in formula (8).

$$T_{md} = T_{ms} \cdot \frac{1}{Ts+1} \tag{8}$$

Where, T_{md} and T_{ms} represent the dynamic output torque and the steady output torque of the motor respectivley. Thereinto, the latter can be obtained by looking-up table or performing the interpolation method on the steady data obtained in the experiment. T and s indicate the system time coefficient and the Laplace transform separately.

The efficiency model of the motor can be obtained by performing interpolation on the experimental data using formula (9):

$$\eta_m = \eta_m(n, T_{md}) \tag{9}$$

3.3 The Model of the Super Capacitor

The working voltage of the super capacitor is V. Assume that the capacitor voltage at a moment is $V(n)$, then the working voltage $V(n+1)$ at the next moment is:

$$V(n+1) = V(n) - I\frac{\Delta t}{C} \tag{10}$$

Where, I and C represent the working current and the capacity of the capacitor, while Δt indicates the time step.

The SOC of the super capacitor is formulaed as:

$$SOC = E_C / E_R = 0.5C \cdot V_C^2 / 0.5C \cdot V_R^2 = V_C^2 / V_R^2 \tag{11}$$

Where, E_C and E_R represent the energy of the capacitor at current SOC and full SOC respectively, while V_C and V_R denote the current open circuit voltage and the rated voltage of the capacitor separately.

The output energy E of the capacitor can be calculated using formula (11):

$$E = 0.5C(V_2^2 - V_1^2) \tag{12}$$

Where, V_1 and V_2 signify the working voltage of the capacitor at the initial moment and the final moment respectively.

4. Simulation and Experimental Study

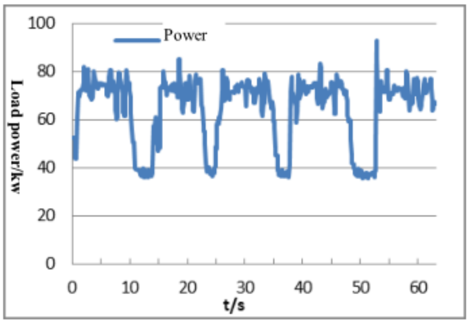


Figure 6. The Load Spectrum Utilized in the Test

In order to enhance the comparabililty between the research results and the real vehicle operation, the load spectrum acquisited by the 20 t excavator of the company under the standard excavation conditon of the testing field was adopted for loading. The data containing five complete working cycles in the load spectrum were applied as the experimental load, whose power spectrum is illustrated in Figure 6. Meanwhile, the condition analysis was combined with the theoretical formula to design parameters for the parallel hybrid power assemby of the excavator according to the operating load. Thereinto, the rated power of the engine was set as 82 kW. Since high power reserve coefficient of the electric elements was required in the experment, the rated power, capacitance and maximum working voltage of the ISG motor were determined to be 60 kW, 40 F and 400 V respectively.

4.1 Simulation Verification

The backward simulation was conducted to verify the optimizition effect of the fuzzy logic based control strategy. By applying the load spectrum illustrated in Figure 6 as the input load, this research carried out the simulation comparison on the fuel consumptions of the hybrid system under the ordinary mode (merely driven by the engine) and the fuzzy control mode. The intial rotational speed of the engine was set as 1,800 rpm, and the initial value of the SOC of the capacitor was 0.6. Figure 7 illustrates the theoretical power outputs of the engine and the motor after being optimized by the fuzzy logic. Compared with the fuel consumption map of the engine in Figure 2, it can be discovered that the real-time servo of the motor to the load power guaranteed that the engine can work in the high efficiency area all the time, and the power output can be basically around the optimal working point, namely, 70 kW. Thus, it was concluded that the fuzzy logic based control strategy showed a favorable optimization effect on the working points of the engine. Figure 8 demonstrates the variation of the SOC of the capacitor controlled by the fuzzy logic, and it can be seen that the SOC of the capacitor decreased from 0.6 to 0.565 after five complete working cycles. Meanwhile, the SOC basically fluctuated around 0.58 during the whole working process, kept operating within modorate range according to the membership function of the SOC. Hence, it can be seen that the proposed strategy presented a favorabel effect on stabilizing the working condition of the capacitor. The simulated curves of the fuel consumption of the engine under the ordinary mode and the fuzzy control mode are compared in Figure 9. It can be seen that under the same load, the fuel consumptions of the engine reduced from 252.5 g under ordinary mode to 226.5 g in the fuzzy logic control, with the rate of fuel saving being 10.32%. Above all, the fuzzy logic based control strategy presented a favorable effect on improving the fuel economy of the engine and maintaining the balanced electric quantity of power batterties simultaneously.

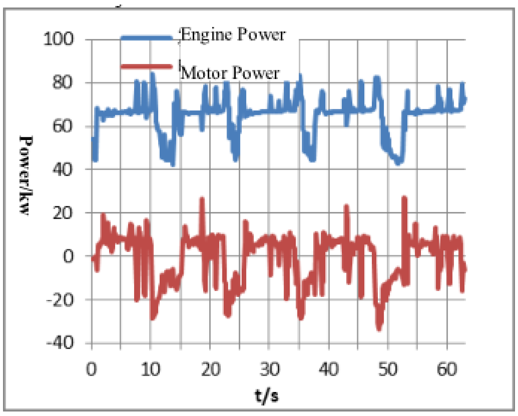


Figure 7. Power Partition of the Power Source under the Control of the Fuzzy Logic

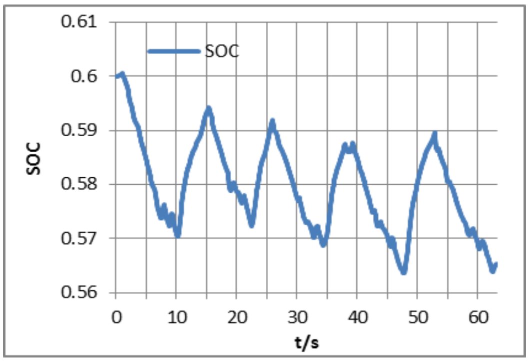


Figure 8. Variation Curve of the SOC of the Capacitor

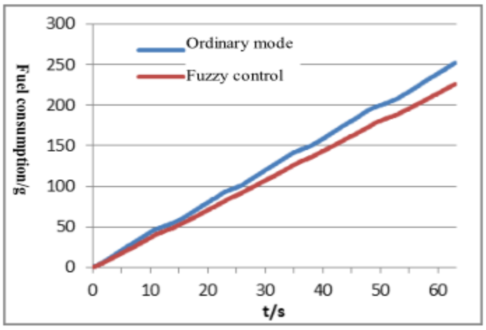
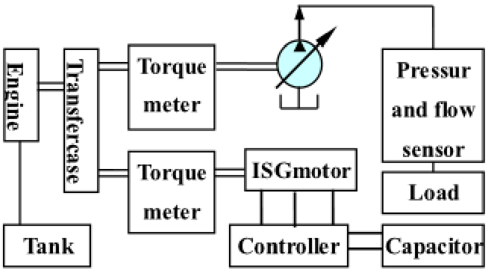


Figure 9. The Simulation Curves of Fuel Consumption

4.2 Experimental Study



(a) Structure of the test bench

(b) Picture of the test bench

Figure 10. The Integrated Test Bench of the Parallel Hybrid Powertrain

In order to verify the validity of the simulation results, the fuel consumptions were compared on the self-developed, integrated test bench for the parallel hybrid powertrain of the middle-sized hydraulic excavator. The structure principle and picture of the test bench are shown in Figures 10 (a) and (b). Meanwhile, the hydraulic system which is same with that of the commercially available 20 t excavators was configured on the test bench. Besides, the electron-hydraulic proportional technology was utilized to design the artificial load system, in which the load spectrum collected above can be used for loading. The initial value of the SOC of the capacitor and the working speed of the engine were 0.85 and 1,800 rpm respectively. Figures 11 and 12 illustrate the power partition of the powertrain and the variation of the SOC of the capacitor under the influence of the fuzzy logic control. It can be discovered that the output power of the engine basically fluctuated up and down slightly near to the optimal working point, that is, 70 kW, and the final value of the SOC of the capacitor was 0.71. Since the value of the SOC of the capacitor was high during the whole experimental process, under the influence of the control strategy, the engine mainly output the power-assisted positive torque instead of the great negative torque—a rapidly electrogeneous state appeared in the simulation process. Figure 13 exhibits the actual fuel consumption curves, and it can be seen that the fuel consumptions of the engine under the ordinary mode and subjected to fuzzy logic optimization were 310 and 285 g, with the actual rate of fuel saving being 8.06%. The reason for the rate of fuel saving in the bench test lower than the simulated one was the lost efficiency of the components. The results of the bench test verified the validity of the simulation results. Therefore, it is concluded that the fuzzy logic based control strategy exhibits a favorabel effect on optimizing the fuel economy of the engine and maintaining the balanced electric quantity of the capacitor, and thus is an effective mehod when applied in parallel hybrid excavators.

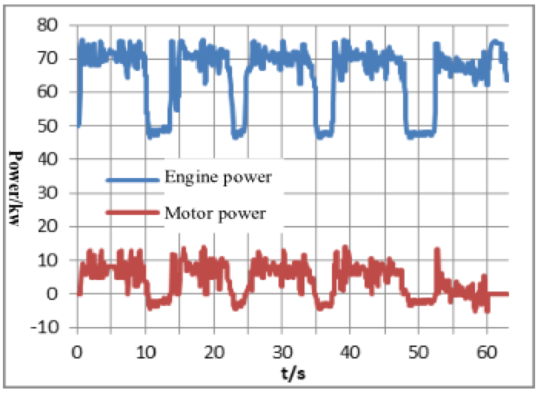


Figure 11. Experimental Curve of Power Output of the Power Source

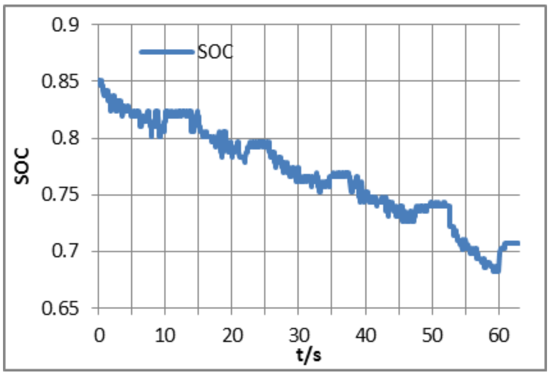


Figure 12. Experimental Curve of the SOC of the Capacitor

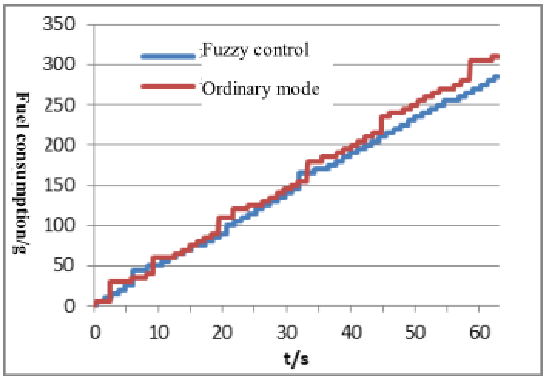


Figure 13. Fuel Consumption Curves

5. Conclusion

This research investigated the fuzzy logic based strategy for controlling the powertrain of the 20 t parallel hybrid excavator. Meanwhile, the MATLAB/Simulink simultion model of the hybrid system was established, with the load spectrum collected by the commercially abvilable 20 t excavator applied as the load model for simulation. The validity of the fuzzy logic based control strategy was verifed through the simulation analysis. Besides, the self-developed, integrated test bench of the parallel hybrid powertrain of the middle-sized hydraulic excavator was adopted to verify the simultion results. As demonstrated in the bench test, the control strategy based on fuzzy logic can stabilize the engine to have it work around the optimal working point while maintaining the balanced electric quantity of the capacitor. Meanwhile, it also enhanced the fuel economy of the engine and thus presented a significant energy saving effect.

Acknowledgment

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