Journal of Zhejiang University SCIENCE A
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Dynamic simulation and optimal control strategy for a parallel hybrid hydraulic excavator*

Xiao LIN†, Shuang-xia PAN, Dong-yun WANG
(*State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, Hangzhou 310027, China*)
†E-mail: linxiao12@163.com

Received Oct. 16, 2007; revision accepted Jan. 28, 2008; published online Apr. 15, 2008

Abstract: The primary focus of this study is to investigate the control strategies of a hybrid system used in hydraulic excavators. First, the structure and evaluation target of hybrid hydraulic excavators are analyzed. Then the dynamic system model including batteries, motor and engine is built as the simulation environment to obtain control results. A so-called multi-work-point dynamic control strategy, which has both closed-loop speed PI (proportion integral) control and direct torque control, is proposed and studied in the simulation model. Simulation results indicate that the hybrid system with this strategy can meet the power demand and achieve better system stability and higher fuel efficiency.

Key words: Hybrid system, Hydraulic excavator, Multi-work-point dynamic control, Direct torque control
doi:10.1631/jzus.A071552 **Document code:** A **CLC number:** TH137

INTRODUCTION

The desire to improve the fuel efficiency and emissions has given rise to the advent of more hybrid electric vehicles (HEVs). Furthermore, a considerable amount of research has been done on hybrid systems during the past five years (Schouten *et al*., 2002; Zhang *et al*., 2004; Zhu *et al*., 2004; 2006; Gao and Ehsani, 2006). However, these studies do not provide much attention to the hybrid construction machinery, especially to hybrid hydraulic excavators.

The real test and literature data (Gao *et al*., 2001) indicate that the required energy of hydraulic excavators varies in short-range periodicity and fluctuates tempestuously, thus the engine cannot be maintained in its high fuel efficiency range. So hydraulic excavators equipped with hybrid systems should be studied in order to save energy and improve emissions.

Usually, a hybrid system is propelled by an internal combustion engine with an electric motor/generator in series or parallel. The engine provides the base power, while the motor offers the fluctuant power, which increases the system's stability and fuel efficiency by regenerating energy and storing excess energy from the engine.

Due to the different load demands between the hydraulic excavator and the vehicle, the popular control strategies used in HEVs cannot be simply applied to hydraulic excavators. It is important to propose new control strategies, which are suitable for hydraulic excavators. Recently, research on the structure, control strategy and energy management of hybrid system in hydraulic excavators has been carried out (Kagoshima *et al*., 2003; Takao *et al*., 2004; Wang *et al*., 2005; Xiao *et al*., 2007). Kagoshima *et al*.(2003) and Takao *et al*.(2004) showed one type of hybrid hydraulic excavators equipped with series configuration, by which the excavators have good fuel consumption, about 40%~51% energy saving at all working conditions. However, they only developed a single-work-point control strategy, which may be suitable for their configurations, but is difficult for obtaining optimal results. Furthermore, the single-work-point control strategy cannot meet the requirements at all kinds of working conditions. Wang

* Project (No. 2006C11148) supported by the Science and Technology Project of Zhejiang Province, China

et al.(2005) and Xiao *et al*.(2007) presented the simulation work and evaluation of energy saving mainly for parallel hybrid hydraulic excavators. The double-work-point control strategy is also analyzed, but with this method an engine only has two output powers that cannot meet the higher requirement for fuel efficiency.

This paper discusses a control strategy, the so-called multi-work-point dynamic control strategy, which introduces four working points, i.e., idle mode, light load mode, medium load mode and heavy load mode, and a switching strategy for the working points. Simulation results indicate that a hybrid system with this method can bring high efficiency and good stability. This paper aims to propose an optimal control strategy and energy distribution methods for hybrid hydraulic excavators. According to the working condition of hydraulic excavators, the closed-loop speed PI (proportion integral) control method is adopted. Since, with this method only, the system response characteristic cannot meet the system requirement during the switching of working points or under unmatched working conditions (so-called "special working conditions"), a direct torque method is added to improve the system performance. In other words, by means of calculating the subsystems' working data, the direct torque method will be implemented until the special working conditions are detected by the central controller. Otherwise, the closed-loop speed PI control method is adopted.

The structure of the paper is as follows. Section 2 describes the system in a general way, including the hybrid system structure, and discusses how to evaluate the system performance. Section 3 devotes to the discussion of the system model using Matlab/Simulink and the analysis of the control system structure. Multi-work-point dynamic control strategy is proposed in Section 4, in which the control effect with this strategy is analyzed and the required improvement especially during the switching of working points is presented. Finally, Section 5 provides a summary and a discussion of some extensions of this paper.

HYBRID SYSTEM STRUCTURE AND EVALUATION TARGET

Considering system efficiency and cost, a parallel hybrid hydraulic excavator is chosen as our system project, as shown in Fig.1. The parallel hybrid hydraulic excavator has not only an engine but also an electric motor coupled to the final drive shaft. This configuration allows the engine and the electric motor to deliver power to the pump in combined mode or engine-alone mode. The electric motor is also used for capturing the excess energy of the engine. A 5-ton hydraulic excavator has been built successfully in our lab several years before. This study aims to build a 5-ton hybrid hydraulic excavator.

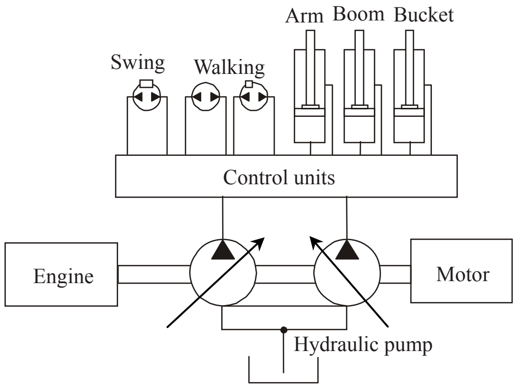


Fig.1 Schematic of a parallel hybrid hydraulic excavator

In the hybrid hydraulic excavator system, we focus on the fuel efficiency and emissions compared with the original hydraulic excavator. Furthermore, the proposed control strategy and the system's dynamic response characteristic are simulated using Matlab/Simulink to show whether the engine stays in the high fuel efficiency range. A parallel hybrid hydraulic excavator has an engine and an electric motor coupled to the same drive shaft to operate at the same speed. On the disregard of system ullage, the torque equation of load torque, motor torque and engine torque is presented in Eq.(1). In other words, the control target is to distribute torque between the engine and the motor, forcing T_e to remain stable and T_m to fluctuate along with T_l.

$$T_l = T_m + T_e, \tag{1}$$

where T_l is the required load torque, T_m the output torque of the motor, and T_e the output torque of the engine.

SYSTEM MODELING

In order to capture the full effects of the hybrid propulsion system on the hydraulic excavator, a hybrid hydraulic excavator model, mainly about the power components, is utilized for simulation (He and Hodgson, 2002; Bogosyan *et al*., 2007). Although the principle of modeling work used in hybrid hydraulic excavators is very much in line with that of HEV, especially for motor modeling and engine modeling, there are following three major differences:

(1) The parameters of motor/engine/batteries are not the same due to the different system requirements.

(2) The load model is different. In hybrid hydraulic excavators, the required torque of the pump, which is obtained from the practical operation, fluctuates periodically and tempestuously.

(3) The control strategies, which are suitable for hybrid hydraulic excavators, are unique according to the working condition of excavators.

The major components of the hybrid hydraulic excavator are listed below:

Excavator operation mass: 4510 kg;

System maximum torque: 152 N·m;

Engine: ZN 485Q, 4-stroke, 4-cylinder maximum output torque 124.8 N·m at 1860 r/min;

Motor: custom-built permanent magnet synchronous motor (PMSM), rating power 15.7 kW, maximum torque 150 N·m, rating speed 2200 r/min, rating voltage 250 V;

Batteries: QNFG 16, maximum power 19.2 kW, 200 1.2-V Ni-H batteries connected in series. The terminal voltage for each cell is 1.2 V, and the nominal battery pack terminal voltage is 240 V.

Fig.2 shows an overview of the model for the parallel hybrid hydraulic excavator system described above. Some elements of this model are taken from previous work while others are developed from the basic principle, as necessary. In addition, this paper mainly focuses on power split between the power source components. Thus, the pump data from the experiment is selected as the load model, which is more authentic than that from the simulation.

Engine modeling

The steady-state efficiency map is selected as the principle to simulate the engine. The torque production and the fuel efficiency map are chosen to deal with the modeling of the engine. The exterior relevant factors, i.e., engine's rotor inertia, have been taken into consideration, but the interior relevant factors in the engine are omitted (Katrasnik, 2007). The relevant curve used to build the engine model is shown in Fig.3.

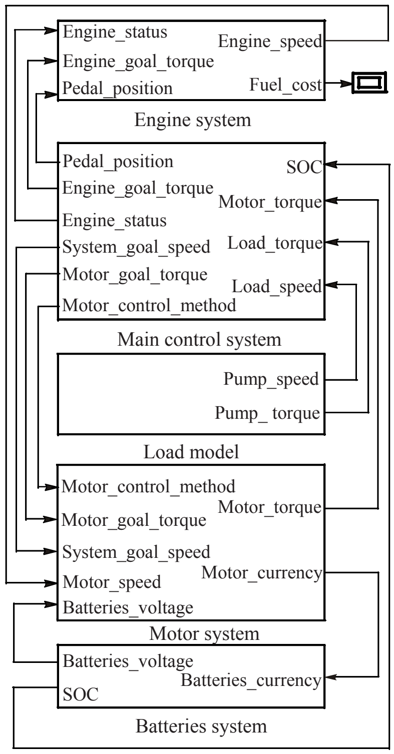


Fig.2 Overview of the model for the parallel hybrid hydraulic excavator system

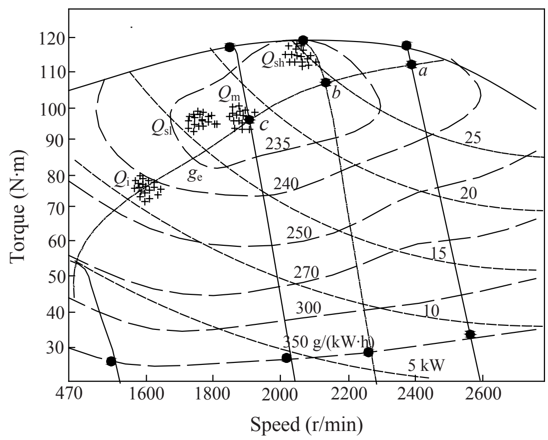


Fig.3 Relevant steady-state curve of the engine. Q_{sh}, Q_m, Q_{sl} and Q_i are respectively heavier load slave, master, lower load slave and idle working points; *a*, *b*, *c* are the optimal working points for different pedal positions; g_e is the engine's optimal efficiency working curve

The engine model is used for the following functions:

(1) Fuel rate. The fuel rate is obtained from a warm engine fuel-rate map as a function of the engine's torque and speed:

$$\dot{m} = \dot{m}_{\text{fuel\_rate}}(T_{\text{e}}, w), \tag{2}$$

where $\dot{m}_{\text{fuel\_rate}}(T_{\text{e}}, w)$ is the fuel-rate map indexed by the engine's torque and speed.

Consequently, the fuel consumption is calculated using the fuel-rate value as follows:

$$m = \int \dot{m} \text{d}t. \tag{3}$$

(2) Torque map. The engine torque is derived from the engine's torque map.

Motor modeling

To simulate the motor system, first the d-q-axes model of PMSM is reviewed by the motor's electrical equation and mechanical equation as follows:

$$\frac{\text{d}}{\text{d}t}i_d = \frac{1}{L_d}v_d - \frac{R}{L_d}i_d + \frac{L_q}{L_d}w_{\text{r}}i_q, \tag{4}$$

$$\frac{\text{d}}{\text{d}t}i_q = \frac{1}{L_q}v_q - \frac{R}{L_q}i_q + \frac{L_d}{L_q}w_{\text{r}}i_d - \frac{\lambda w_d}{L_q}, \tag{5}$$

$$T_{\text{e}} = 1.5p[\lambda i_q + (L_d - L_q)i_d i_q], \tag{6}$$

$$\frac{\text{d}}{\text{d}t}w_{\text{r}} = \frac{1}{J}(T_{\text{e}} - Fw_{\text{r}} - T_{\text{m}}), \quad \frac{\text{d}\theta}{\text{d}t} = w_{\text{r}}, \tag{7}$$

where (L_q, L_d), (i_q, i_d) and (v_q, v_d) are the q- and d-axis inductances, currents and voltages, respectively; R is the resistance of the stator windings; w_{r} is the angular velocity of the rotor; λ is the amplitude of the flux induced by the permanent magnets of the rotor in the stator phases; p is the number of pole pairs; T_{e} is the electromagnetic torque; J is the combined inertia of the rotor and load; F is the combined viscous friction of the rotor and load; θ is the rotor angular position; T_{m} is the shaft mechanical torque.

Next, the efficiency maps of the motor mode and generator mode are chosen for research on the energy losses about the motor (Figs.4a and 4b).

Batteries modeling

Batteries system includes the model of SOC (state of charge) estimation and the model of batteries' working voltage. SOC estimation mainly adopts the energy conservation and four-route method. The model of batteries' working voltage uses the mixed model of Shepherd model, Unnewehr universal model and Nernst model (Plett, 2004):

$$\begin{aligned} y_k = k_0 - R \cdot i_k - k_1 / SOC_k - k_2 \cdot SOC_k \\ + k_3 \cdot \ln(SOC_k) + k_4 \cdot \ln(1 - SOC_k), \end{aligned} \tag{8}$$

where y_k is the batteries' end voltage, R the batteries' interior resistance, and k_0~k_4 the coefficients given by experiments data.

As to the efficiency map of batteries, the average efficiency (80%) is used to value the energy losses during energy transformation in batteries, considering the complicated electrochemistry principle in the batteries system. In summary, the steady-state efficiency maps of the engine, electric motor and batteries are involved to deal with the energy losses. Therefore, the energy conversion phenomena in the hybrid hydraulic excavator have been taken into consideration.

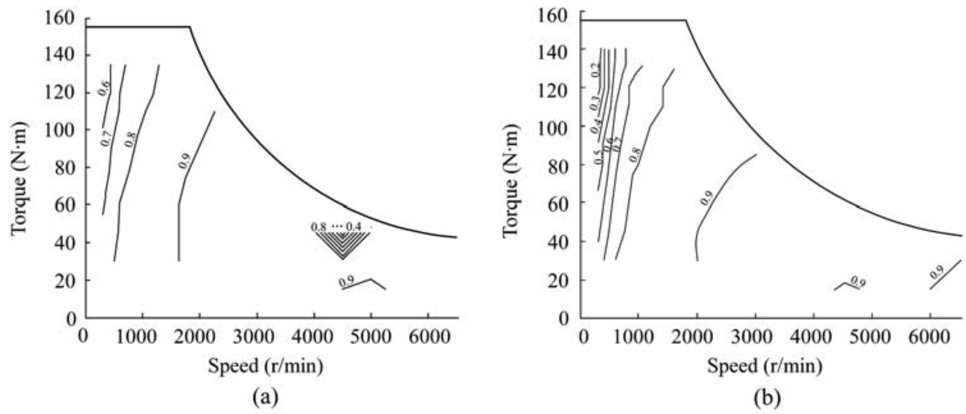


Fig.4 Efficiency map of the motor mode (a) and the generator mode (b) under 230 V power supply/generation voltage

MULTI-WORK-POINT DYNAMIC CONTROL STRATEGY

In this section, the multi-work-point dynamic control strategy is proposed step by step under hybrid hydraulic excavator environment. Firstly, the control system structure is introduced together with the main control target of the engine, motor and batteries. And then, according to the working condition of the hydraulic excavator, the multi-work-point dynamic control strategy is demonstrated in detail. Besides, a group of optimized parameters are given. Finally, the control effect with this strategy is shown in figures.

As shown in Fig.5, the control system structure contains a central control unit (CCU), an engine control unit (ECU), a motor control unit (MCU) and a battery control unit (BCU). CCU is on the top of the control system structure; moreover, it carries out a large amount of commands and control strategies. In short, the CCU's control strategy determines the system efficiency and the control effect. ECU adjusts the engine's pedal when the switching of working points is needed. MCU is of the most importance in subsystems, and the load torque fluctuates tempestuously which leads to the instability of the engine's working points. Besides, MCU is in charge of testing the shaft speed all the while, adjusting the actual speed to the target one in no time, and making the engine remain in the high fuel efficiency range. BCU detects the current and voltage of batteries. And a great deal of work can be done in batteries management, such as SOC, which determines the engine's working point.

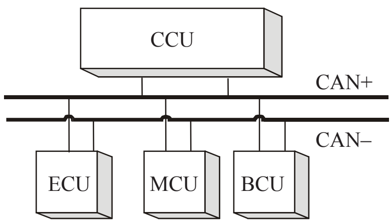


Fig.5 Structure of the control system of the parallel hybrid hydraulic excavator

Hybrid system, in essence, introduces a motor system to fluctuate along with the load power, and thus the engine can remain in high fuel efficiency range. Then the fuel efficiency and emissions of the hydraulic excavator are achieved. Obviously, we first focus on the constant-work-point control strategy, which aims to keep the engine working around a constant working point. For different working conditions, such as low load and heavy load, a constant working point cannot meet the system's requirement and the primary control target. Additionally, the constant working point will cause an unmatched-power control and an ill-suited SOC. So the multi-work-point dynamic control strategy is proposed.

In this control strategy, many efforts are made to keep the engine working stably around one working point, the so-called "master working point" (Q_m). If the engine's output power at the current working point is too much, which causes SOC to exceed the upper limit, the command will be sent to switch the engine's working point to the lower load slave working point (Q_{sl}). The other two working points are the heavier load slave working point (Q_{sh}) and the idle working point (Q_i) which is prepared for the idle working condition. In summary, the chosen Q_m, Q_{sl} and Q_{sh} lie in the highest fuel efficiency range, but Q_i does not locate in that range, as shown in Table 1.

Next, SOC is selected as the signal for switching the working points. When the SOC is too high or too low, the working point will be switched accordingly. Normally, the strategy keeps SOC in a suitable range, and the working point will not change continually. Thus, the arrangement of SOC range should be studied to improve the system's stability and efficiency. Table 2 shows the arrangement of SOC which is optimized in the model above.

It can be seen from Table 2 that the upper limit and lower limit of SOC have been defined. Furthermore, if the value of SOC remains in the normal range, the switching of working points cannot be implemented.

Table 1 Parameters of the chosen working points of the engine

Working point	Pedal	Speed (r/min)	Torque (N·m)	Power (kW)	Fuel-cost (g/(kW·h))
Master working point Q_m	0.7	1910	96.0	19.1	234.7
Lower load slave working point Q_{sl}	0.6	1772	92.5	17.2	233.3
Heavier load slave working point Q_{sh}	0.8	2096	114.8	25.1	233.5
Idle working point Q_i	0.5	1635	74.2	12.7	242.7

Table 2 Setup of the *SOC* range

SOC range	Work-point (pedal position)
SOC<0.5	Q_{sh} (0.8)
0.5<*SOC*<0.7	Q_{m} (0.7)
SOC>0.7	Q_{sl} (0.6)

Finally, the system's response characteristic is introduced in detail. According to Eq.(1), the torque turns to be the control target. But in practice, the engine speed is chosen as the control target. When the load power varies, which leads to the alteration of the engine speed, the PI controller is applied to adjust the speed. Thus, the PI controller determines the system's response characteristic. Fig.6 shows the system's control block diagram.

When the engine's working point is switched, the engine speed cannot return to the normal speed at once, due to the response characteristic of the closed-loop speed PI controller. So the engine's working point, especially the engine's output torque, will fluctuate around the normal range. The narrower the range is, the more efficient the system is. However, the closed-loop speed PI control strategy as shown in Fig.6, especially under the switching of working points, cannot solve this dynamic response problem. So the needed improvement (e.g., direct torque control method) is involved to overcome the limitation of the multi-work-point dynamic control strategy only with the closed-loop speed PI control method.

Fig.7 shows the flowchart of the strategy. The steps of this strategy are presented in detail as follows.

Step 1: System initialization, including the initialization of the parameters of CCU, ECU, MCU and BCU. Especially, the engine's original working point is set up and a suitable SOC range is arranged.

Step 2: The real-time parameters are collected and calculated. In detail, BCU collects information of the charge/discharge currency and working voltage to calculate the current SOC. MCU is in charge of testing the shaft speed at all time. CCU exchanges all necessary messages with subsystem control units and sends control commands to determine the working point and control methods, by the CAN (controller area network) and J1939 protocol (Yang, 2006).

Step 3: The MCU adjusts the engine speed via the closed-loop speed PI controller to keep the engine stable while the SOC remains in the suitable range.

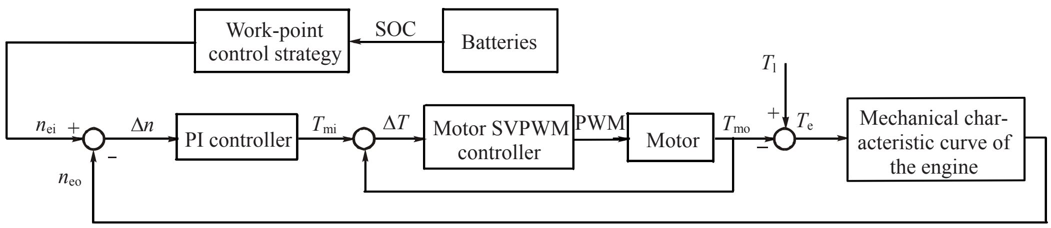
Step 4: While the SOC exceeds the normal limit, the motor direct torque control method is applied via the CCU's torque commands until the engine works steadily around the new working point.

Based on the analysis above, the multi-work-point control strategy is simulated using Matlab/ Simulink. Fig.8a shows the distribution of the required load torque between the motor and the engine. Obviously, while the required load torque varies tempestuously, the engine's output torque still fluctuates smoothly during all the working cycles, and the motor's output torque just follows the alteration of the required load torque in time. It can be indicated that the system response characteristic is determined by the control strategy. Furthermore, much attention should be paid to ease this variable of the engine torque. Therefore the engine will remain at the working point constantly.

Fig.8b shows the engine's actual speed fluctuates around the target speed. The error between these two speeds reflects the performance of the applied control strategy. And the error of this hybrid system with the multi-work-point dynamic control strategy is calculated as follows:

$$error^{+}_{\text{speed}} = \frac{1927-1910}{1910} \times 100\% = 0.89\%,$$

$$error^{-}_{\text{speed}} = \frac{1855-1910}{1910} \times 100\% = -2.88\%.$$



n_{ei}: target speed of the engine; n_{eo}: actual speed of the engine; Δn: speed difference between n_{ei} and n_{eo}; T_{mi}: target torque of the motor; T_{mo}: actual torque of the motor; T_e: actual torque of the engine; T_l: required load torque

Fig.6 Control block diagram of the multi-work-point dynamic control strategy

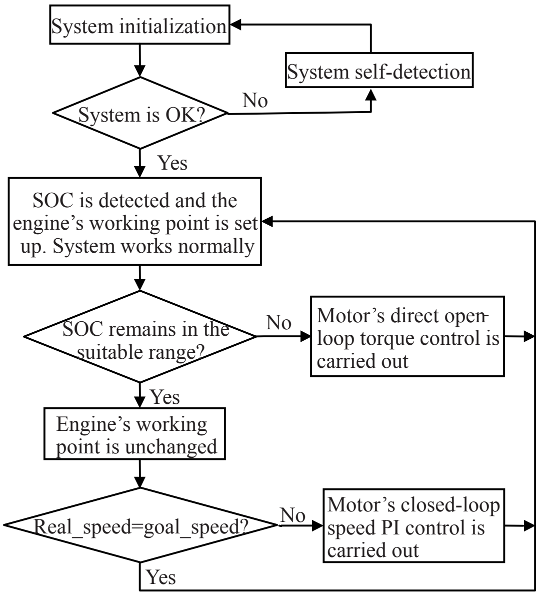


Fig.7 Flowchart of the control strategy of the parallel hybrid hydraulic excavator

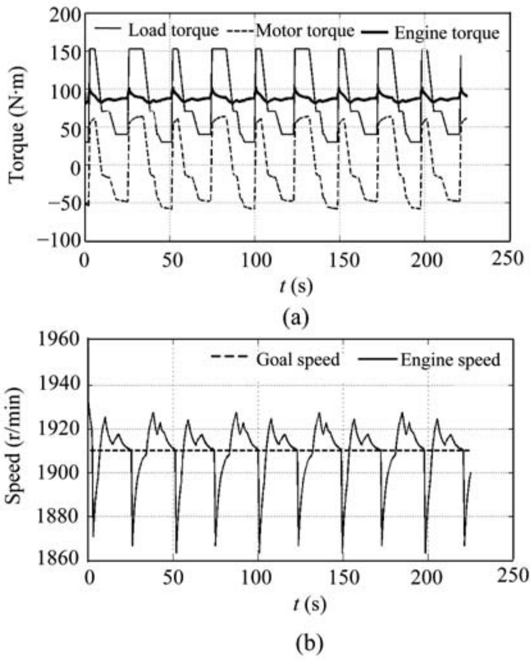


Fig.8 (a) Comparison of load torque, motor torque and engine torque at Q_m; (b) Comparison of goal speed and engine speed at Q_m

According to the calculated results, it can be concluded that the hybrid system with this strategy can lead to high performance and good dynamic response characteristic. However, when the required load torque suddenly increases greatly, the engine speed slows down at once, which causes a disharmonious pulse. Fig.8b shows that the error discussed above is tolerable, but the response time needs to be improved. On this topic, much research should be carried out in the future, which is also our aim to improve the system performance.

Fig.9 shows the fluctuation of SOC during all working cycles. From the very beginning, the value of SOC is set as 0.6. Then it can be seen from the figure that the scope of SOC remains between 0.591 and 0.630 for 225 s. Thus, the batteries' SOC remains in the balanced state; in other words, the discharge level is approximately equal to the charge level. So in the power drive train, the batteries are charged with the task of power transformation, not the role of power supplying.

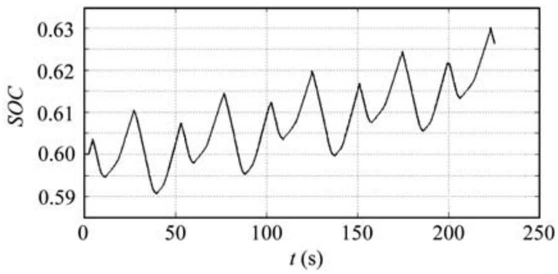


Fig.9 *SOC* value during a working period at Q_m

The target of BCU is to keep the scope of SOC narrow and not need to trigger the switching of working points continually. With the multi-work-point dynamic control strategy, the required control target of SOC is achieved successfully. Still, much attention should be paid to the relevant work such as SOC dynamic detection technology, the life-span of batteries and the discharge/charge characteristic of the batteries.

Figs.10a~10c show the dynamic characteristics of switching the working points. If the unmatched working point is set up, the system with the proposed strategy can switch to a better working point automatically in a certain time. Here, the so-called "certain time" is defined as switch-time. The switch-time should not be too short or too long which will impact the system's response ability. Thus, it is important to determine the switch-time value. From Fig.10a, it can be seen that the engine torque is steady at working points Q_m and Q_{sh}, but when the switching of working points occurs, the performance of the dynamic response characteristic of the engine torque is not perfect with the proposed strategy above. Fig.10b shows the speed comparison at working points Q_m and Q_{sh}, especially, from Q_{sh} to Q_m. Error 1 represents the speed error of an unmatched working condition, which equals 180 r/min; Error 2 is defined as the speed's dynamic characteristic during the fluctuation of the load torque, and it is about 50 r/min. And from 0 to about 160 s, the control system chooses Q_{sh} as its working point. It can be seen from Fig.10c that the value of SOC is increasing up to 0.7, showing that the lower level of the engine's working point should be set up. Suddenly, at approximately the 160th second when the value of SOC reaches to 0.7, the working point is switched and the current working point is changed to Q_m, which has a lower output power.

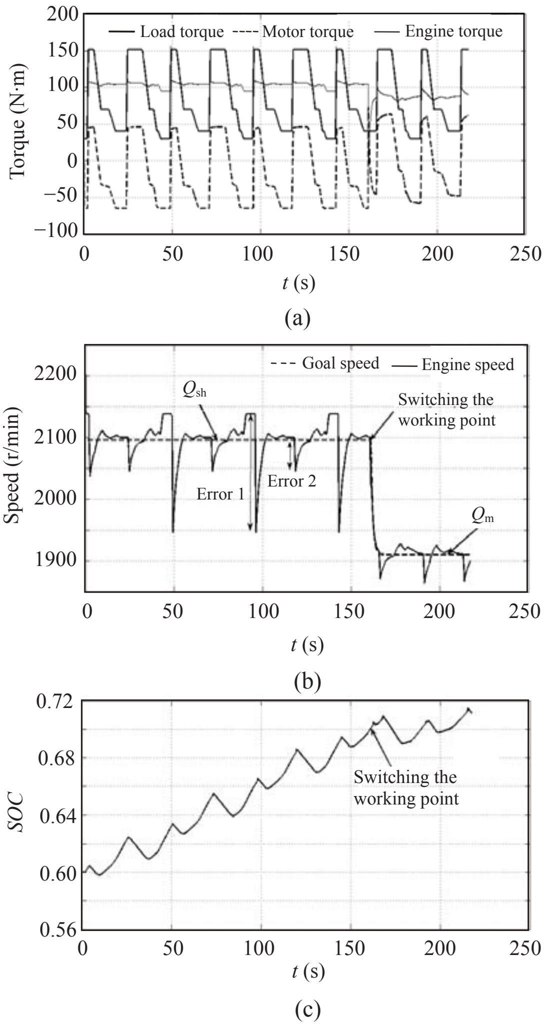


Fig.10 Comparisons of load torque, engine torque and motor torque (a), goal speed and engine speed (b), and *SOC* value (c) during a working period at the working points Q_{sh} and Q_m

The fuel consumption comparisons (Table 3) based on the baseline system, the hybrid system with series configuration and the hybrid system with parallel configuration have been made at different working conditions during 120 working cycles. The results show that the parallel hybrid hydraulic excavator is more efficient than the other two.

Table 3 Comparison of the fuel consumption among three systems

System connection	Fuel consumption*		
	Heavy load	Medium load	Light load
Baseline system	1.000	1.000	1.000
Parallel configuration	0.583	0.632	0.655
Series configuration	0.648	0.670	0.720

* In each case, fuel consumption of the baseline system is set to 1

CONCLUSION

In this paper, a model of the hybrid system is built by Matlab/Simulink for the parallel hybrid hydraulic excavator structure. The multi-work-point dynamic control strategy is proposed and analyzed step by step. The simulation results from the model reveal the advantages and disadvantages of the system with this strategy. If the working point is suitable for the current load condition, the strategy can keep SOC in a narrow range and bring rapid dynamic response of the speed and torque, which leads to the stable system performance and high fuel efficiency. The direct torque method is carried out to improve the system's dynamic response performance for the unmatched working condition and work-point switching. In the future, the response time of the engine speed needs further improvement and the switch-time by other advanced control strategies should be paid more attention to.

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