Study on the Control Strategy of Regenerative Braking for the Hybrid Electric Vehicle under Typical Braking Condition

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\textbf{Abstract.} In this paper, a parallel regenerative braking control strategy and fuzzy PID control algorithm for series-parallel hybrid electric vehicles are developed based on the analysis of the existing regenerative braking control strategy and control algorithm, indicating a reasonable and effective regenerative braking control strategy for series-parallel hybrid vehicles. The simulation model of regenerative braking control system is established by MATLAB/Simulink software, and the parametric model of each component of regenerative braking system is established by AVL CRUISE software. The joint simulation under the typical braking condition of 30, 60 and 90km/h under the moderate braking intensity ($z=0.3$) is conducted. The results show that the braking energy recovery rate is the largest (reaching 24%) and the energy recovery effect is obvious in the initial speed of braking of 60km/h.

\textbf{Keywords:} Hybrid electric vehicle, regenerative brake, control strategy, control algorithm, typical braking condition.

1. Introduction

The recovery of the regenerative braking energy plays an important role in the achieving the goal of low fuel consumption and low emission of hybrid electric vehicles [1], which is also a major way to energy conservation for hybrid electric vehicle.

As the key technology of regenerative braking energy recovery, the rationality of the regenerative braking control for the hybrid electric vehicle determines the fully recover of braking energy while ensuring braking safety and stability, which reveals the advantages of energy conservation and environmental protection [2]. Combined the advantages of the serial and parallel type, series-parallel hybrid electric vehicle possessed the most complex regenerative braking control strategy [3-4]. It is of great significance to develop a regenerative braking control strategy suitable for series-parallel hybrid electric vehicle.

In this paper, the series-parallel hybrid electric vehicle is the research object and the Toyota prius is the reference model. Based on the principle of braking safety and maximum energy recovery, a
regenerative braking control strategy and control algorithm suitable for series-parallel hybrid electric vehicle with high braking energy recovery under the premise of braking safety is determined.

2. Main Evaluation Indexes of the Regenerative Braking Energy Recovery
The main evaluation indexes of the regenerative braking energy recovery mainly include the recovery capacity of braking energy and recovery rate of braking energy. The specific calculation method is as follows:

2.1. The Recovery Capacity of the Braking Energy.
Effective recovery energy of the braking energy Em is calculated by the charging current, voltage and sampling time of power battery. As shown in (1).

\[ E_m = \int U_b I_b dt \text{ (KJ)} \]  

In the equation:
- \( U_b \) —— The voltage at the motor controller while recovering the braking energy, V;
- \( I_b \) —— The current at the motor controller while recovering the braking energy, A;
- \( t \) —— Motor braking time, s.

2.2. The Recovery Rate of Braking Energy.
The recovery rate of braking energy \( \eta_b \) is the ratio between the \( E_m \) and the total consumes energy in braking \( E_b \) is the energy loss calculated according to speed of the braking start and stop, As shown in (2).

\[ E_b = \frac{1}{2} m(v_b^2 - v_0^2) \text{ (J)} \]  

In the equation:
- \( m \) —— The vehicle mass, kg;
- \( v_b \) —— Initial speed of the vehicle braking, m/s;
- \( v_0 \) —— End speed of the vehicle braking, m/s.

\( \eta_b \) is showed by (3).

\[ \eta_b = \frac{E_m}{E_b} = \frac{\int U_b I_b dt}{\frac{1}{2} m(v_b^2 - v_0^2)} \times 100\% \]  

3. The Braking Control Strategy and Control Algorithm for Series-parallel Hybrid Vehicles

3.1. The Braking Control Strategy for Series-parallel Hybrid Vehicles.
The typical braking control strategy include the best brake feeling, the best energy recovery and parallel type braking control strategy [5], in which the former two that firstly consider the regenerative braking, and then to mechanical braking belong to serial braking control strategy. In contrast, the mechanical and regenerative braking are parallel and simultaneously produce braking force in the condition of the parallel braking. The working principle is shown in figure 1.
The mechanical braking of the parallel braking system can distribute the braking force of the front and rear wheels in a fixed proportion and the regenerative braking supplement the braking force insufficient on supplementary driving wheel, which forms the distribution curve of braking force required by the driver.

The mechanical friction braking force applied on the front and rear axle is in direct proportion with the hydraulic pressure in the brake master cylinder. Regenerative braking force is a function of the hydraulic pressure in the main cylinder. Regenerative braking force is a function of the hydraulic pressure in the brake master cylinder, which is also a function of the deceleration speed of vehicles braking.

The basic strategy of the parallel braking control strategy:
(1) When \( z \) is larger
When the braking strength of vehicles is larger (such as \( z = 0.9 \)), the braking energy is less due to the shorter braking time, and the driving motor does not produce regenerative braking force to guarantee the braking safety.

(2) When \( z \) is smaller
During the process of braking, regenerative braking is effective when \( z \) is less than 0.9.

(3) When \( z \) is very small
During the process of braking, when the \( z \) is less than a certain value, such as 0.1, it will just require the regenerative braking.

Figure 1 illustrates the regenerative braking force \( F_{bf\_reg} \) applied on the front wheel and the mechanical braking force applied on the front \( F_{bf\_mech} \) and rear wheels \( F_{br} \).

The series-parallel regenerative braking control strategy of hybrid electric vehicle is designed according to the basic idea of parallel braking control strategy as well the characteristics of regenerative braking system of hybrid electric vehicle and the working characteristics of key components of regenerative braking system such as driving motor and power battery.

Set the \( z \) as the reference, and distribute the mechanical braking force and regenerative braking force to ensure the braking efficiency and recover as much braking energy as possible.
3.2. The Control Algorithm for Series-parallel Hybrid Vehicles.

The control algorithms applied in the regenerative braking process of hybrid electric vehicles mainly include the logic threshold control, PID control and fuzzy control. The logic threshold value is relatively simple, which can be determined by a lot of experiments. PID control is comparative maturity, which is not ideal for the control of nonlinear and time-varying systems. As a kind of non-linear control method that has good stability and adaptability, fuzzy control possess the advantage of transforming the experienced knowledge of technicians or experts into control rules by using fuzzy mathematics method, and realize the automatic control through compilation. However, the control precision of fuzzy control is not high. Combining the advantages of the PID control and fuzzy control, fuzzy PID control can realize the precise control of nonlinear system[6].

In this work, according to the working characteristics of the braking process of hybrid electric vehicle and each key component of regenerative braking system, we adopts the fuzzy PID control algorithm to control the regenerative braking system of hybrid electric vehicle. The overall structure of the fuzzy PID controller is shown in figure 2.

![Fuzzy PID controller structure](image)

Figure 2 shows the control process of the fuzzy PID controller. The input and output control variables are determined according to the characteristics of the braking process of the hybrid electric vehicle, and fuzzy control rules are designed in combination with the requirements of the braking control strategy and the characteristics of the control algorithm to complete the design of the fuzzy controller.

Set the output quantity of fuzzy controller as the input quantity of PID controller, adjust the quantity of control by PID controller, expert the output quantity of the fuzzy PID controller., Controlled by PWM mode, the drive motor is controlled by the Regenerative braking control when the controlled object is the G (s). The error calculation between the actual output values Tu of the regenerative braking torque that can feedback to the input of PID controller and electrical mechanism torque precision value Tm of the fuzzy controller output is calculated to be the input quantity of PID controller, realizing closed loop control.

4. Simulation of Series-parallel Hybrid Electric Vehicles under Typical Braking Condition

4.1. Regenerative Braking Control Model of Series-parallel Hybrid Electric Vehicles.

According to the control strategy and control algorithm of regenerative braking of series-parallel hybrid electric vehicle, we establish the control strategy model of regenerative braking system by using MATLAB/Simulink software, as shown in figure 3.
According to the relevant technical parameters of Toyota prius, AVL CRUISE and MATLAB/Simulink software are applied to build the joint simulation model of regenerative braking control system of series-parallel hybrid electric vehicle, as shown in figure 4.
4.2. Moderate Braking Strength, Braking Simulation at Different Initial Braking Speeds.
In this paper, we choose a typical braking condition that the braking is occurred at a certain initial speed. In the condition of moderate braking strength (\( z = 0.3 \)), the series-parallel hybrid vehicles were carried out braking simulation tests at low, medium and high speed points at 30, 60 and 90km/h respectively, and the fixed step length was set as 0.05s.

According to the simulation model in FIG. 4, the braking simulation was performed at the condition of \( z = 0.3 \) and \( v_b = 30 \text{km/h} \), and the variation curve of each parameter with braking time \( t \) was obtained in figure 5-8.

![Fig.5 Motor speed, braking torque and braking power time-varying curve at 30km/h](image5.jpg)

![Fig.6 Hydraulic braking force, the braking torque and braking power time-varying curve at 30km/h](image6.jpg)

![Fig.7 Battery charging current, charging voltage SOC and capacity time-varying curve at 30km/h](image7.jpg)

![Fig.8 The increased battery capacity and recovered energy time-varying curve at 30km/h](image8.jpg)
As shown in FIG. 5-8, with the increase of t, the electromotive torque of the electric mechanism increases rapidly and then gradually decreases, and the hydraulic braking force and hydraulic braking torque are relatively stable. It is found that the charging current and charging voltage increase first and then decrease gradually. The increased capacity of the battery and the energy recovered by the battery increased at first, then flattened out and stabilized.

During the braking process, the motor is recovering energy all the time, and the hydraulic braking system is involved in the braking with the basically constant hydraulic braking torque. At the end of braking, the battery capacity and SOC increased slightly, achieving recovery of braking energy.

According to the simulation model in fig 4, the braking simulation was constructed at the condition of $z = 0.3$ and $v_p = 60\text{km/h}$, and obtained the variation curve of each parameter vs the changes of t in figure 9-12.

![Motor speed, braking torque and braking power time-varying curve at 60km/h](image)

**Fig.9** Motor speed, braking torque and braking power time-varying curve at 60km/h

![Hydraulic braking force, the braking torque and braking power time-varying curve at 60km/h](image)

**Fig.10** Hydraulic braking force, the braking torque and braking power time-varying curve at 60km/h

![Battery charging current, charging voltage SOC and capacity time-varying curve at 60km/h](image)

**Fig.11** Battery charging current, charging voltage SOC and capacity time-varying curve at 60km/h
As shown in fig 9-12, the braking process is smooth and steady. Compared with braking at $v_b = 30 \text{km/h}$, with the increases of the motor braking torque, the charging current, charging voltage, battery capacity and battery SOC increase, which increase the battery capacity and the braking energy recovered. The hydraulic braking force and hydraulic braking torque are basically kept in a constant state.

According to the simulation model in fig 4, the braking simulation was constructed at the condition of $z = 0.3$ and $v_b = 90 \text{km/h}$, and obtained the variation curve of each parameter vs the changes of $t$ in figure 13-16.
As shown in fig 13-16, the braking process is smooth and steady. Compared with braking at 60km/h, the motor braking torque shows further increase with the increases of the charging current, charging voltage, battery capacity and battery SOC, which further increase the battery capacity and the braking energy recovered. The hydraulic braking force and hydraulic braking torque are basically kept in a constant state.

According to the simulation results in fig 5~16, further treatment was carried out for the results. The maximum braking torque of the motor, the increased battery capacity and the recovered braking energy can be measured by AVL CRUISE post-processing under moderate braking strength, and the values of the total braking energy consumption and the recovery rate of braking energy can be calculated by equations (2) and (3). Under moderate braking intensity, the recovery energy and other parameters at different initial braking speeds are shown in table 1.

| Initial speed of braking (km/h) | Increased battery capacity/Ah | Motor maximum braking torque/Nm | Energy lost of braking/J | Recovery of braking energy/J | Brake energy recovery rate/% |
|--------------------------------|-------------------------------|--------------------------------|--------------------------|-----------------------------|-----------------------------|
| 30                             | 0.006                         | 43                             | 46701                    | 4570                        | 10                          |
| 60                             | 0.051                         | 151                            | 186806                   | 44374                       | 24                          |
| 90                             | 0.102                         | 166                            | 420313                   | 92590                       | 22                          |

As shown in table 1, with the increase of initial braking speed, the increased battery capacity, energy loss of braking, and recycling braking energy increase, which is due to fully recycle of the braking energy under the same braking intensity, along with the increase of the initial speed of the brake and the motor braking time.

When braking speed approach 90km/h, the maximum braking torque of the motor increases monotonically with the initial braking speed, and then is basically stable in 166Nm. It is noted that it can achieve the maximum braking torque of the motor under moderate braking strength, which meets the requirements of the working characteristics of the electromotive torque.

The parabolic shape is exhibited in the integral variation law of brake energy recovery. With the increase of the braking speed, the braking energy recovery increase and reach the maximum value at about 60km/h, then decrease monotonously. The reasons can be explained as follows. When the initial braking speed is low, and the braking energy and the energy available for motor recovery is less. When the initial braking speed is high, the growth of the motor recovered energy is far less than that of the braking energy loss, indicating the gradually decrease according to the definition of its braking energy recovery rate. Therefore, the parabolic shape is exhibited in the recovery of braking energy with increase the initial braking speed.
5. Summary
In this paper, the change rules of the main parameters such as maximum braking torque, braking energy recovery and braking energy recovery of the drive motor were obtained through the simulation verification under the typical braking condition of 30, 60 and 90km/h under the moderate braking intensity of the Toyota prius. In addition, at the initial speed of moderate braking, it is found that 60km/h is the representative speed point, in which the braking energy recovery rate was the largest with the value of 24%. Meanwhile, it is noted that other parameters appear monotonically increasing change rule. Therefore, it is effective to develop the regenerative braking control strategy and control algorithm, which have guiding significance for the research on regenerative braking control of series-parallel hybrid electric vehicles.

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