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# Research on Regenerative Braking Control Strategy and Simulink Simulation for 4WD Electric Vehicle

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**Abstract.** With the reduction of energy and environmental degradation, pure electric vehicles are a breakthrough point to solve the global energy and environmental crisis. However, due to the current battery technology limitations, the mileage cannot meet the use requirements. Regenerative braking is based on the existing structure and components of the electric vehicle. The braking torque is generated simultaneously by controlling the motor to generate electricity, and the braking energy is recovered at the same time. The realization of regenerative braking can compensate for the shortage of continuously driving mileage of pure electric vehicles, and maximize the energy saving advantages and social benefits. The electro hydraulic braking system is the intermediate product of traditional brake system and brake by wire system, electro-hydraulic brake system of pure electric vehicle braking energy recovery can not only improve the effect of energy recovery based on, but also can realize the braking performance. Based on Simulink, a pure electric vehicle model of electro-hydraulic braking system is established. Based on this model, the regenerative braking control strategy of electro-hydraulic braking system of 4WD Electric vehicle is developed.

## 1. Introduction

With the gradual reduction of global available energy and the worsening situation of the environment, mankind needs a safer and low-carbon energy system and environment. Major automobile manufacturers in the world have invested heavily in the development of new energy vehicles, and the government departments have gradually introduced relevant policies to encourage the development of new energy vehicles. Compared with traditional vehicles, electric vehicles have an absolute advantage, you can recover part of the braking energy[1]. Regenerative braking energy recovery, the vehicle is in the process of braking, motor control and power generation, power generation in the process of mechanical energy is used to vehicle performance, at the same time the motor power will produce braking torque through the transmission, transmitted to the wheels by the transmission, braking and charging the battery, to achieve the braking energy recovery however, the inertia energy braking process in traditional vehicle are converted into heat. Braking energy recovery can prolong the vehicle mileage, improve the energy efficiency of the brake friction brake by the bear is reduced, and the regenerative braking can also reduce brake heat load, reduce friction wear, improve the safety of vehicles and use economy. Urban traffic requires frequent parking and deceleration, and braking energy recovery has more important significance and considerable economic and social benefits. The establishment of Simulink electro hydraulic braking system of electric vehicle based on the model, on the basis of the model development of 4WD Electric Vehicle Regenerative Braking Control Strategy



of electro hydraulic braking system, and provide a theoretical basis for the electric vehicle drive and brake type selection, provide control strategy for electric vehicle regenerative braking system development industry[2].

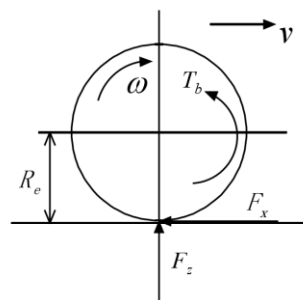
## 2. Related work

A regenerative braking system is an uncertainty system, it has nonlinear parameter and serious disturbances[3]. The braking mode of EV includes hydraulic braking mode, electric braking mode and hybrid braking mode. The traditional friction braking mode is also called hydraulic braking mode, it lets vehicle decelerate or stop with friction plates. The kinetic energy is converted into thermal energy during the braking process, which is very wasteful because the energy cannot be recovered at all[4]. In contrast, energy can be recovered in fully electric braking mode, so it is also called regenerative braking mode[5]. In the braking process, electric braking mode can recover energy, but it needs a relatively long braking time due to the limitation of motor. However, the braking force of the hydraulic braking mode is large and the stability is better. The hybrid braking mode is to combine these two modes and allocate them rationally, so as to recover as much energy as possible. The key question is how to allocate torques between hydraulic braking mode and electric motor braking mode under the premise of baking safety. There are some papers about regenerative braking control system and several control strategies have been presented. Paper[6] presented a nonlinear model predictive controller for regenerative braking system, which improved the recovery efficiency by distributing the braking torque between front and rear axis respectively. However, it did not allocate torques between the hydraulic braking mode and the electric braking mode, which limited the energy recovery efficiency. Paper[7] presented a control strategy based on fuzzy control, which used the displacement of the brake pedal, the variation rate of the brake pedal, the vehicle speed and the wheel slip rate error as input. And the method in paper[8] used the vehicle speed and the achievable force of motor as input. However, the above research did not take the State of Charge (SOC) of energy storage device into consideration, which is a significant point that affects energy recovery efficiency, and it may cause damage to the battery.

## 3. Regenerative Braking Controller Design

### 3.1. Vehicle Dynamics Model

As lateral performance is neglected in this study, considering the vehicle dynamics model adopted here has five degrees of freedom for longitudinal motion and the rotational movement of the four wheels. A single wheel braking model is shown in Figure 1.



**Figure 1.** Single wheel braking model

### 3.2. Braking Torque Allocation of Front and Rear

Wheels Safety is the premise of energy recovery of the whole braking process. Experience has shown that, vehicle would be unstable if rear wheel locks before front wheel. A shock rotation or tail flick might appear while vehicle is driven in high speed on low friction coefficient road. In order to ensure vehicle in a safe state, a large adhesion between tire and road is expected. As the mutative tire load

ratio of front and rear axis have the staple impact on tire-road adhesion, we consider allocating the brake torque based on the mutative tire load ratio of front and rear axis. According to the previously mentioned tire model, we can easily get the mutative tire load ratio of front and rear axis based on normal force equations.

$$\frac{F_{zf}}{F_{zr}} = \frac{l_r g - h a_x}{l_f g + h a_x} \quad (1)$$

Therefore, the brake torque coefficient of front and rear axis  $K$  can be described as

$$K = \frac{F_{zf}}{F_{zr}} = \frac{T_{mf}}{T_{mr}} = \frac{T_{hf}}{T_{hr}} \quad (2)$$

### 3.3. Torque Allocation of Hydraulic Brake and Electric rake Based on MPC

In this section, a model predictive controller is designed for torque allocation of hydraulic brake and electric brake. First, the controller design model is given based on vehicle dynamics equations. Then the cost function is established for the purpose of braking safety and energy Optimization, next the control constraints are introduced. Finally, the approach for solving the cost function is presented. According to the current measurement information obtained, model predictive control method solve the finite horizon open loop optimization problems online at each sampling time, and the first element of the obtained control vectors from optimal solution would be applied to the electric vehicle model. On the basis of the new measurements, this procedure is repeated at next sampling time in optimization process.

**3.1.1 Controller design model.** According to the vehicle dynamics model, the state equation for hydraulic and electric braking distribution can be established. The state and control variables are defined as follows,

$$X = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \omega_{mf} \\ \omega_{mr} \end{bmatrix} \quad (3)$$

$$U = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} T_m \\ T_h \end{bmatrix} \quad (4)$$

Then based on above equation, the state equations can be described as follows,

$$\dot{x}_1 = \frac{g_0}{2J} [\mu_f F_{zf} R_e - \frac{K}{1+K} (g_0 u_1 + u_2)] \quad (5)$$

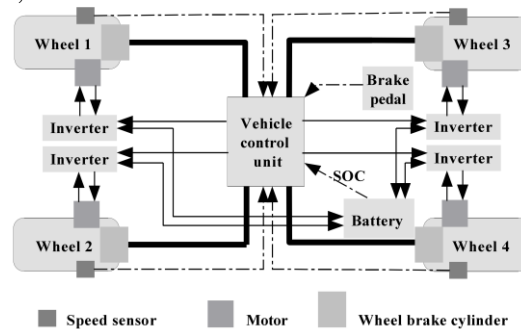
$$\dot{x}_2 = \frac{g_0}{2J} [\mu_r F_{zr} R_e - \frac{1}{1+K} (g_0 u_1 + u_2)] \quad (6)$$

Note that, brake torque  $T_m$  and  $T_h$  are both defined positive.  $K$  is the ratio of front wheel brake torque to rear wheel brake torque, which is defined in the above section.

**3.1.2 Cost function.** Due to the goal that recovering as much energy as possible by distributing the brake torque between hydraulic and electric brake, several cost function terms are need to be established. Actually, the braking mode switching is determined by the characteristics and constraints of the electric motor. First, in order to meeting the demand of total required brake torque and maximizing energy recovery, the electric motor braking mode is implemented as far as possible. If motors have achieved the maximum torque corresponding the current motor speed, then hydraulic braking mode compensate the remaining part of total required braking demand. Secondly, as the vehicle velocity decreases, energy recovery power of electric motors would be lower than its internal copper loss power, then the motors cannot produce regenerative current. Therefore, the electric motor braking mode is completely converted into hydraulic braking mode while the motor speed achieve the certain value.

This section propose a brake torque allocation controller for regenerative braking system of electric vehicle with four in-wheel motors. The regenerative braking system include several modules, brake torque demand calculation module, brake torque distribution module, brake torque tracking module, and battery management unit. The structure of regenerative braking control system is shown in Figure 2. In this article, we focus on the research of brake torque distribution module. This module mainly consists of two parts work, one aspect is to allocate the brake torque on front and rear axis, and the

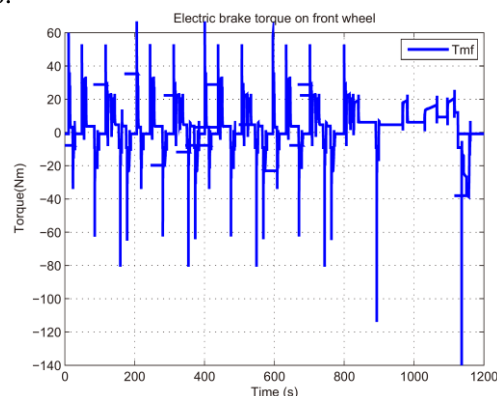
other is distributing the brake torque between hydraulic braking mode and electric braking mode. Note that the brake torque demand calculation and tracking module, and battery management unit are assumed useful and beneficial, we will conduct research on these issues in the future.



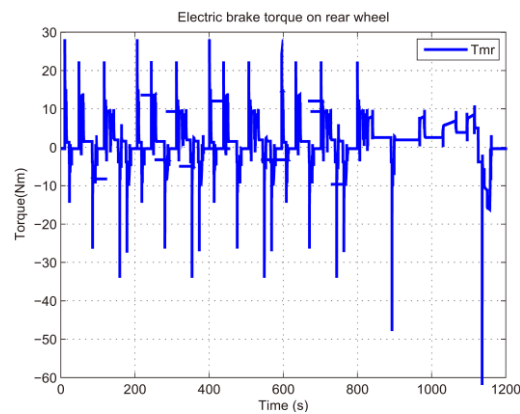
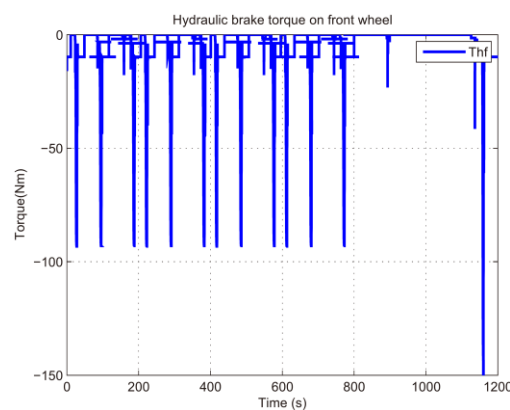
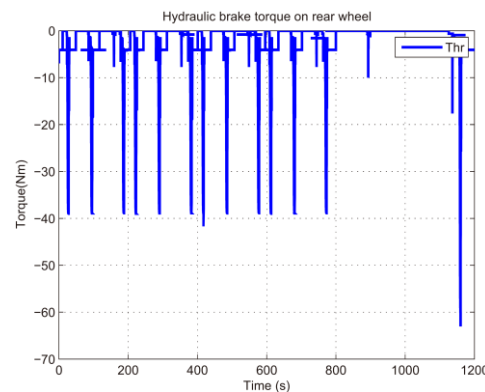
**Figure 2.** Structure of regenerative braking control system

#### 4. Simulations and Analysis

In this paper, the regenerative braking control system is implemented through the combined simulation. The vehicle model with four individually driven in-wheel motors is established in AMESim software, and the fuzzy controller is designed in Simulink software. This paper only study the situation of straight driving, and the motor used is a permanent magnet brushless DC motor. The model is divided into six modules, including vehicle controller, vehicle module, motor module, tire module, driver module and battery module. In the AMESim, the parameters are set as follows: the car quality is 1360 kg, the maximum torque of the motor is 118 N m, the wheel radius is 0.275 m, the peak voltage of the battery is 450V, the rest are all default values. The driver model uses automatic catch and simplifies the transmission, thinking that there is only one gear and that it has a fixed transmission efficiency and that the reversing situation is ignored. The simulation is carried out in NEDC (New European Driving Cycle) and the simulation time is 1200 s. The vehicle braking and acceleration are relatively stable, similar to the actual situation in the city. And the actual vehicle speed can be well tracked the controlled speed, this indicates that the controller can ensure that the vehicle is in a stable state corresponding to the driver expectation. The regenerative braking torques of the motors on front and rear axles are shown in Figure3 and Figure4. The hydraulic braking torques on front and rear axles are shown in Figure5 and Figure6.



**Figure 3.** Electric brake torque on front wheel

**Figure 4.** Electric brake torque on rear wheel**Figure 5.** Hydraulic brake torque on front wheel**Figure 6.** Hydraulic brake torque on rear wheel

## 5. Conclusions

The establishment of Simulink electro hydraulic braking system of electric vehicle based on the model, on the basis of the model development of 4WD Electric Vehicle Regenerative Braking Control Strategy of electro hydraulic braking system, including front and rear axle braking force distribution method and electro-hydraulic hybrid brake coordination control method, control strategy for the development of regenerative braking system. Finally the establishment of the front axle drive and four wheel drive electric vehicle model, selecting basic braking and city driving cycle simulation, braking energy recovery comparison of different drive in the form of pure electric vehicle driving rate and economy. The simulation results show that the four wheel drive electric vehicle with front axle drive electric vehicles are energy, the best braking energy recovery of each control algorithm, the braking

energy recovery rate, and provide a theoretical basis for the electric vehicle drive and brake type selection, control strategy for the development of regenerative braking system.

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