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Analysis of downshift's improvement to energy efficiency of an electric vehicle during regenerative braking

Liang Li [a,b,*], Xujian Li [a], Xiangyu Wang [a], Jian Song [a], Kai He [a], Chenfeng Li [a]

[a] The State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, People's Republic of China
[b] The Collaborative Innovation Center of Electric Vehicles in Beijing, Beijing, People's Republic of China

HIGHLIGHTS

- Downshift is effective in improving the energy efficiency of electric vehicles.
- Energy improvement of downshift varies with vehicle speed and brake strength.
- The designed nonlinear sliding mode observer is accurate in estimating bake torque.
- The proposed resembling PWM method is practical to regulate hydraulic pressure.
- The effect of downshift on braking safety and comfort can be restrained by control.

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ABSTRACT

Downshift during regenerative braking helps to improve the energy efficiency of electric vehicles. Two main problems are involved in the downshift process. One is the determination of optimal downshift point, and the other is the cooperative control of regenerative braking and hydraulic braking. In order to achieve a systemic solution to these problems, a hierarchical control strategy is brought forward for an electric vehicle with a two-speed automated mechanical transmission. For the upper controller, an off-line calculation and on-line look-up table method is adopted to obtain the optimal downshift point, and a series regenerative braking distribution strategy is designed. For the medium controller, a nonlinear sliding mode observer is designed to obtain the actual hydraulic brake torque. For the lower controller, cooperative control of regenerative braking and hydraulic braking is given to ensure brake safety during downshift process, and a resembling pulse width modulation method is proposed to regulated the hydraulic brake torque. Simulation results and hardware-in-loop test show that the proposed algorithm is effective in improving the energy efficiency of electric vehicles.

1. Introduction

Electric vehicles (EVs) provide a promising solution to reduce the energy consumption of transportation [1,2]. In order to improve the mileage, battery life and ultimate costs of EVs, a transmission can be added between the electric machine and driving wheels [3,4]. As the electric motor has a more desirable characteristic compared with internal combustion engine (ICE), a two-speed transmission is more suitable for EVS, considering dynamic performance, energy efficiency and costs [5,6]. Automated mechanical transmission (AMT) has the advantages of low cost, high transmission efficiency and satisfactory fuel economy [7,8], and it is suitable for EV application.

Regenerative braking is an important technology to improve the energy efficiency and driving distance of EVs [9,10]. During braking process, the electric motor of an EV can be acted as an electric generator, converting kinetic energy or potential energy of the vehicle into electric energy, and the recycled energy can be stored in battery for vehicle reacceleration [11,12]. Study shows that up to 50% of the total brake energy can be recycled in the urban driving cycle [13].

Studies about regenerative braking mainly focus the torque distribution between regenerative braking and hydraulic braking and their cooperative control. In [14], a modified control strategy is proposed to obtain higher regenerative efficiency, in which additional braking torque is applied on the rear wheels. In [15], an efficient recovery control strategy is designed based on the modified

* Corresponding author at: The State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, People's Republic of China.
E-mail address: liangl@tsinghua.edu.cn (L. Li).

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nonlinear model predictive control method to optimize the torque distribution between regenerative braking and hydraulic braking.

For an EV equipped with a transmission, downshift during regenerative braking helps to improve energy efficiency of the vehicle. According to the efficiency map of the electric motor, when the electric motor works in constant-torque area, downshift helps to increase the regenerative power, and when the motor works in low-speed area, downshift helps to improve regenerative efficiency [16,17].

However, a gear down shift may lead to torque oscillation due to temporary lack of regenerative braking torque [18]. Thus, cooperative control of regenerative brake torque and hydraulic brake torque is needed to ensure brake safety and comfort. In [19], a downshift strategy during regenerative braking process is proposed considering the reacceleration performance, and a cooperative regenerative braking control algorithm is developed. In [20], a coordinated braking control scheme is constructed based on estimated brake torque and driver's brake torque demand.

These studies didn't cover the determination of the optimal downshift point, which is the key to improving the energy efficiency through downshifting during regenerative braking. Traditional global optimization strategy can obtain the optimal downshift point, but it requires that the brake process can be known in advance [21]. However, there are a lot of uncertainties during braking, making the brake process unpredictable [22]. Besides, traditional global optimization strategy costs a heavy computation, limiting its practical application in real-time [23,24].

Although there are many research articles concerning the cooperative control of regenerative braking and hydraulic braking, the response characteristic of the hydraulic braking system has not been considered. The hydraulic systems are subject to nonlinearities, uncertainties, load disturbances and measurement noise [25], which means precise modeling, is very difficult. For some vehicles that are not equipped with wheel cylinder pressure sensors, the actual hydraulic brake torque is unknown [26]. Thus, accurate estimation of actual hydraulic brake torque is necessary, because the control logic of hydraulic brake system is based on the error between the actual and desired hydraulic brake torque.

In order to give a systemic solution to these problems, a hierarchic control strategy is designed in this paper. For the upper controller, an off-line optimization and on-line look-up table method is proposed to obtain optimal downshift point real-timely. Considering the uncertainty of brake process, the maximum efficiency curve (MEC) is proposed. The distribution of regenerative braking torque and hydraulic braking torque is based on a series distribution strategy. For the medium controller, a nonlinear sliding mode observer (SMO) is designed to obtain the actual hydraulic brake torque of front and rear wheels. For the lower controller, cooperative control of regenerative braking and hydraulic braking is given to ensure brake safety during downshift process, and a resembling pulse width modulation method is proposed to regulated the hydraulic brake torque, whose control logic is based on the error between the desired and estimated hydraulic brake torque.

The arrangement of this paper is given as follows. Section 2 gives a brief introduction to system models. In Section 3, the proposed hierarchic control strategy is described in detail, including upper, medium and lower controllers. In Section 4, the simulation results are discussed. In Section 5, the hardware-in-loop (HIL) tests are given to verify the effectiveness of the proposed scheme. Section 6 is the conclusion.

2. System models

The diagram of the regenerative braking system is shown in Fig. 1. The vehicle is driven by a permanent magnet synchronous motor (PMSM). The powertrain includes a two-speed AMT, a final drive, a differential and half shafts. The regenerative braking is provided by the PMSM, and the hydraulic brake is provided the hydraulic control unit (HCU) which is based on the HCU of electronic stability control (ESC). The two-speed AMT is designed to improve the efficiency of PMSM and climbing capacity of the vehicle.

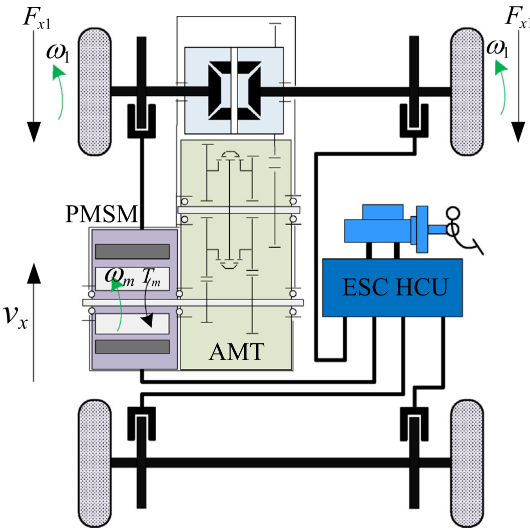

Fig. 1. Structure of the vehicle.

2.1. Vehicle model

A three degree of freedom (DOF) vehicle model is adopted to illustrate the vehicle dynamics, including the longitudinal motion and front/rear wheels' rotations, as shown in Fig. 2.

The equations of the motions are as follows.

The equation of the longitudinal motion can be given as:

$$m\dot{v}_x = 2F_{x1} + 2F_{x2} + F_f + F_w, \tag{1}$$

where

$$\begin{cases} F_w = \frac{C_D A v_x^2}{21.15} \\ F_f = mg(f_0 + f_1 v_x) \end{cases}. \tag{2}$$

Rotation motion of front wheels can be given as

$$I_1\dot{\omega}_1 = F_{x1}R_1 - \overline{T}_m - T_{h1}. \tag{3}$$

Rotation motion of rear wheels can be given as

$$I_2\dot{\omega}_2 = F_{x2}R_2 - T_{h2}, \tag{4}$$

where m is the vehicle mass, v_x is the longitudinal speed of the vehicle, a and b are the distances from the gravity center to front

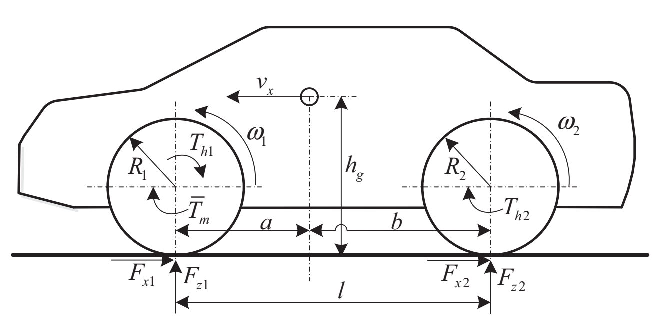

Fig. 2. Vehicle model.