Simulation and analysis for regenerative braking control strategy of pure electric vehicle driven by double axles with double motors

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Abstract

The regenerative braking control strategy of pure electric vehicle driven by double motors through two axles is different from that by single axle driven. On the basis of braking security, try to recover more braking energy and improve energy recovery efficiency. This paper proposed a control strategy. At low intensity braking, without considering the limit of braking legislation, try to use brake torque of the motor, the inadequate part is supplied by hydraulic; At high intensity braking, the brake force is distributed according to traditional brake force distribution. Under the condition of meeting the request braking torque, the motor braking torque is distributed reasonably through considering the motor efficiency. To validate the control strategy, this paper used AVL Criuse to build the vehilce model and co-simulated with Matlab/Simulink. The result showed that this control strategy can improve the braking energy recovery efficiency and supply theoretical foundation to the regenerative braking control strategy of pure electric vehicle driven by double axles with double motors.

Keywords

Double motors, regenerative braking, control strategy, co-simulated.

1. Introduction

It’s possible to recycle some kinetic energy and transform it into electrical energy for storage during regenerative braking with the aim to improve the economic performance of a vehicle [1-3]. Schematic configuration in this paper is shown in Fig.1.

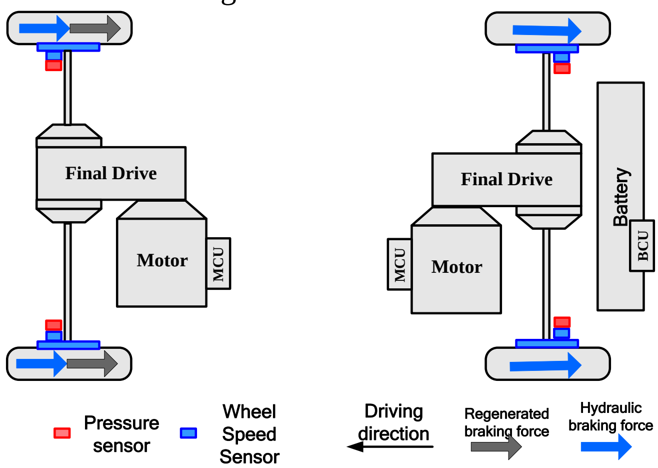


Fig.1 Schematic configuration in this paper

Vehicle parameters and dynamic system parameters of target model are shown in Tables 1.

Table 1 Vehicle parameters and dynamic system parameters of target model

2. Limit to regulations of braking force distribution

About the distribution of braking force, provision of ECE regulations shows [4]: the adhesion coefficient utilization curve of the rear axle should not be located above the front axle, when the brake strength z is between 0.15 and 0.8 in all load conditions. While adhesion coefficient k is between 0.2

and 0.8, and the braking intensity should be z ≥0.1+0.7(k-0.2), braking force distribution are shown in Fig.2.

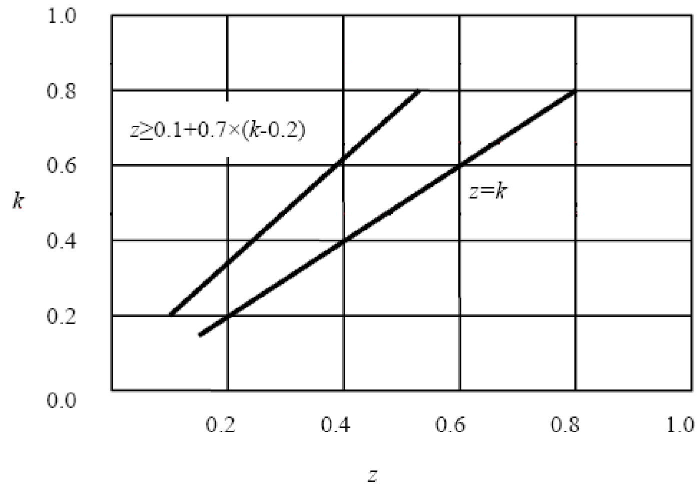


Fig.2 Braking force distribution in ECE Regulations

When the brake intensity z is between 0.15 and 0.80

$$k_f \ge k_r \tag{1}$$

When the brake intensity z between 0.1 and 0.52

$$\begin{cases} k_f \le \dfrac{z-0.1}{0.7}+0.2 \\ k_r \le \dfrac{z-0.1}{0.7}+0.2 \end{cases} \tag{2}$$

According to the definition of adhesion coefficient utilization

$$\begin{cases} k_f = \dfrac{F_{bf}}{F_{zf}} = \dfrac{\beta zL}{b+zhg} \\ k_r = \dfrac{F_{br}}{F_{zr}} = \dfrac{(1-\beta)zL}{a-zhg} \end{cases} \tag{3}$$

Braking force distribution control curve can be obtained by Formula 1, 2, 3, are shown in Formula 4

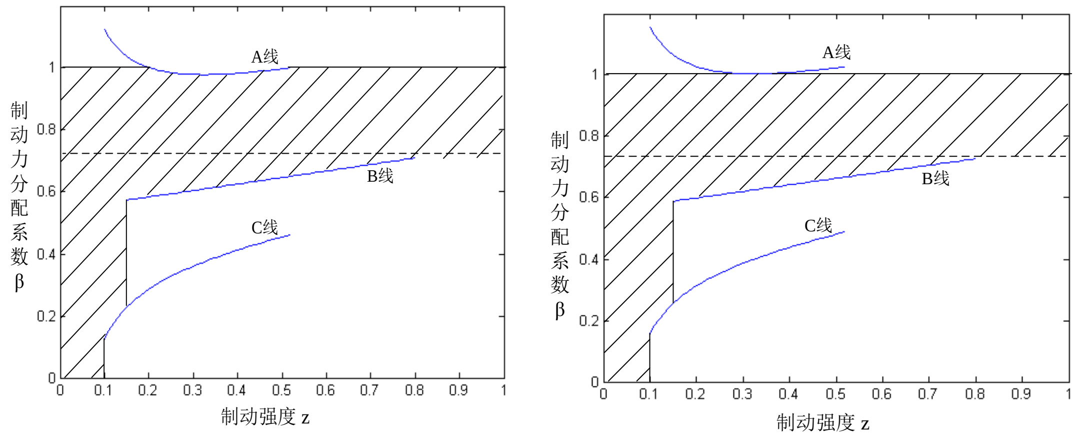
$$\begin{cases} \beta \ge \dfrac{(b+zhg)}{L} & (z = 0.15 \sim 0.8) \\ \beta \le \dfrac{(z+0.04)(b+zhg)}{0.7zL} & (z = 0.1 \sim 0.52) \\ \beta \ge 1-\dfrac{(z+0.04)(a-zhg)}{0.7zL} & (z = 0.1 \sim 0.52) \end{cases} \tag{4}$$

It’s possible to make curve about braking force distribution coefficient β and braking intensity z based on Formula 4, where (a) the curve at full load, (b) for the no-load curve.

As is illustrated in Fig.3, when only the front axle motor involved in braking, the brake threshold z1 should namely be the braking intensity when β = 1 of A line. The threshold is calculated below.

When vehicle is no load or full load, put β = 1 into the equation $\beta = (z+0.04)(b+zhg)/0.7zL$, we can get formula（5）.

$$z = \frac{0.7L - b - 0.04h_g \pm \sqrt{(b + 0.04h_g - 0.7L)^2 - 0.16b \cdot h_g}}{2h_g} \tag{5}$$



(a) (b)

Hydraulic braking β line

β line distributing range under regualtion

Fig.3 Relationship between braking force distribution coefficient β and braking intensity z

In summary, take z1 as the minimum value of above solutions under full load.

When the brake strength is less than this value, the braking force is freely distributed. That is, when there is a certain brake demand, it gives priority to be provided by the motor brake torque, then the hydraulic brake supplement the shortfall, and may be provided by the front axle or rear axle.

When only the rear axle motor provides the braking force, braking threshold z1 is the start point of the C-line, that is 0.1g. In this paper, the four-wheel drive vehicle may apply only front axle brake, only rear axle brake or both apply the brake according to the vehicle state, the state of the motor and the control demand. In order to meet the above requirements, select the braking intensity threshold z1 is 0.1g.

3. Control Strategy of regenerative braking

Electric vehicle braking energy recovery is a measure to improve the comprehensive utilization of energy, and the braking safety is still the most important. Therefore, Energy recovery is not only constrained by itself structural performance, but also by car driving cycle, braking safety and stability, electrical properties, battery charging characteristics, the front and rear axle braking force distribution and electro-hydraulic brake force distribution and other constraints. Based on the above analysis, there are a lot of indicators and factors must be considered in the coordinated control algorithm of braking force. Based on the basic brake force distribution algorithm, we further optimize the control strategy to improve the control performance [5-8].

Software architecture of braking energy recovery system is shown in Fig.4. Before distributing the braking force, we need to divide the braking mode and determine whether the regenerative braking is activated based on the vehicle speed and the battery SOC. According to the motor power and battery charging status, we calculate the maximum regenerative braking torque of motor, and calculate the demanded braking torque and brake intensity according to the brake pedal and the accelerator pedal. Then put them into modules of the brake force distribution to distribute the brake force, outputting target brake torque of motor, the target wheel cylinder pressure and RBS flag.

According to the motor mechanism and external characteristics of the battery, the maximum braking force of motor is calculated in formula (6).

$$F_{reg\_max0} = \frac{\min(T_{mot\max}, \frac{9550 \cdot \min(P_{mot\max}, P_{bat\max})}{n_{motor}}) \cdot i_{final}}{r_{wheel}} \quad (6)$$

If the motor or the battery is fault, or the temperature exceeds the threshold value, then the maximum regenerative braking force F_{reg_max} is taken as 0. Otherwise, judging the battery SOC, if the SOC is greater than the threshold SOC_{max}, the maximum braking force of motor is calculated by formula (7).

$$F_{reg\_max} = \frac{0.8 - SOC}{0.8 - SOC_{max}} F_{reg\_max0} \quad (7)$$

If the SOC is less than SOC_{max}, then the maximum braking force of motor is calculated by formula (8).

$$F_{reg\_max} = F_{reg\_max0} \quad (8)$$

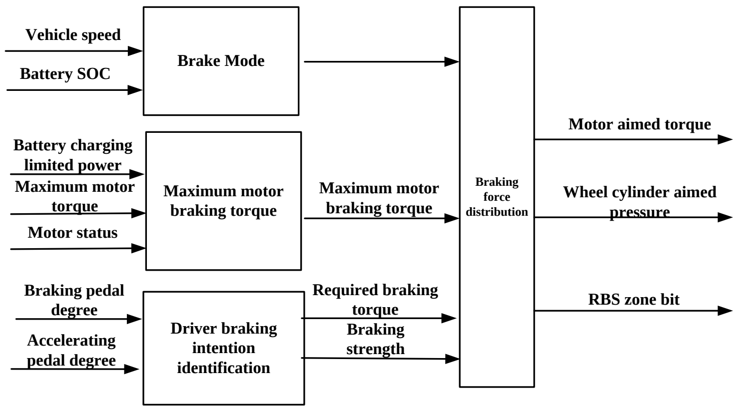


Fig.4 Flow charts of braking energy recovery control algorithm

In this braking force distribution strategy, the front axle braking force includes motor braking force and hydraulic braking force, the rear axle braking force comprises motor braking force and hydraulic braking force. According to each of the front and rear axle braking force distribution strategy, we take the demanded braking force of the front and rear axle as the goal to maximize the regenerative braking force of the motor, making up the shortfall by the front and rear axle hydraulic braking force, to meet the braking regulations requirements, meanwhile increasing energy recovery efficiency [9].

We can get the regulatory restrictions according to the current strength of the vehicle braking force when the vehicle braking with high brake intensity. Then the target brake torque of the front and rear axle motors and the hydraulic brake torque are available based on the maximum brake torque offered by motor and demanded braking torque. This algorithm adjusts the front and rear axle braking force distribution co-factor in time based on the battery and the motor status and vehicle status, with meeting the needs of braking and regulations, gives fully play to the ability of the motor to improve energy recovery.

4. Simulation and analysis

As the strategy is mentioned above, we co-simulate the control strategy in both Matlab / Simulink and Cruise [10-11]. Simulation results are mainly composed of two parts, one is to validate the braking force distribution of a single brake applications, the second is to verify the effect of the energy recovery in driving cycle test, not considering the impact of ABS.

Under the same factors, such as battery SOC and tempeture. Vehicle speed is 120km/h, the braking intensity are 0.1,0.2,0.3,0.4,0.5,0.6g, just take 0.1g, 0.3g and 0.6g as an example, the results are showed in Fig.8, Fig.9, Fig.10.

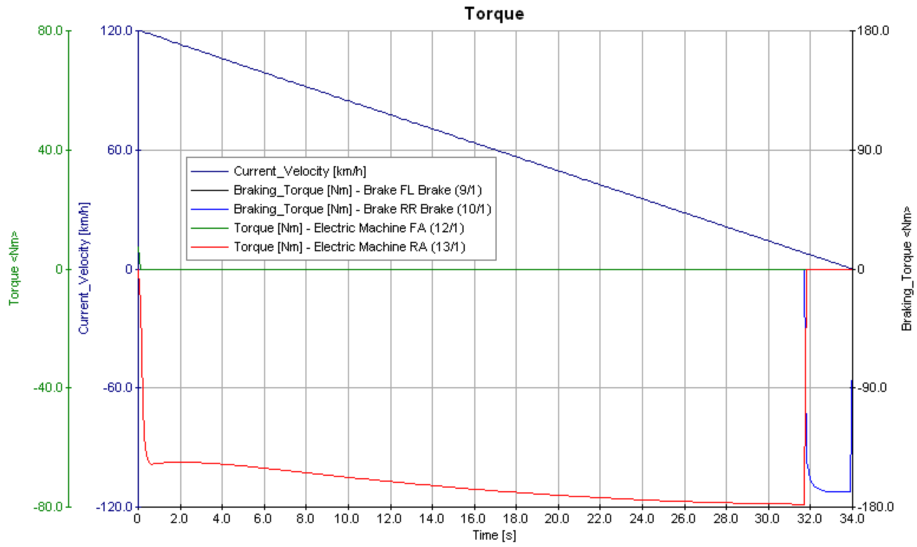


Fig.8 Relationship between vehicle speed and brake torque when the braking intensity is 0.1g

As shown in Fig.8, when braking deceleration is 0.1g and the velocity is more than 8km/h, braking torque is provided only by the rear axle motor, meeting the brake comand of the driver. The maximum braking torque of the rear axle motor is 80Nm. When the vehicle speed is less than 8km/h, the motor quiting braking, the braking torque is only provided by hydraulic braking torque.

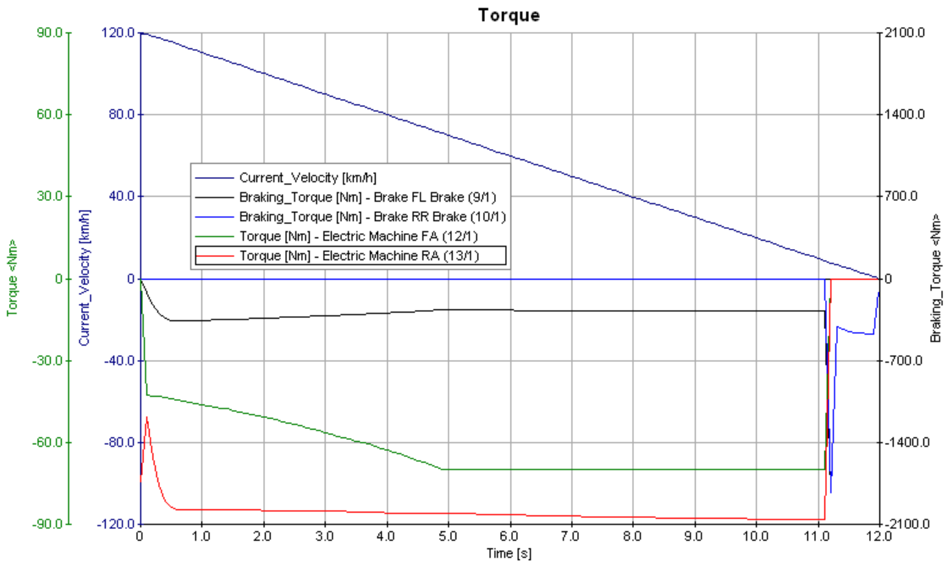


Fig.9 Relationship between vehicle speed and brake torque when the braking intensity is 0.3g

When brake strength is greater than 0.1, front and rear axles both require the braking force, according to the limitations of braking force distribution in ECE legislations. To maximize the capacity of the motor, we select the B line in Fig.3 to distribute braking force. then the rear axle demanded torque is the maximum torque within the regulatory restrictions, while the front axle demanded torque is the minimum regulatory limits. The front axle motor can not fully meet the needs in line B, therefore it needs to be compensated by the hydraulic brake. The rear axle motor is sufficient to meet the needs of the demanded braking torque.

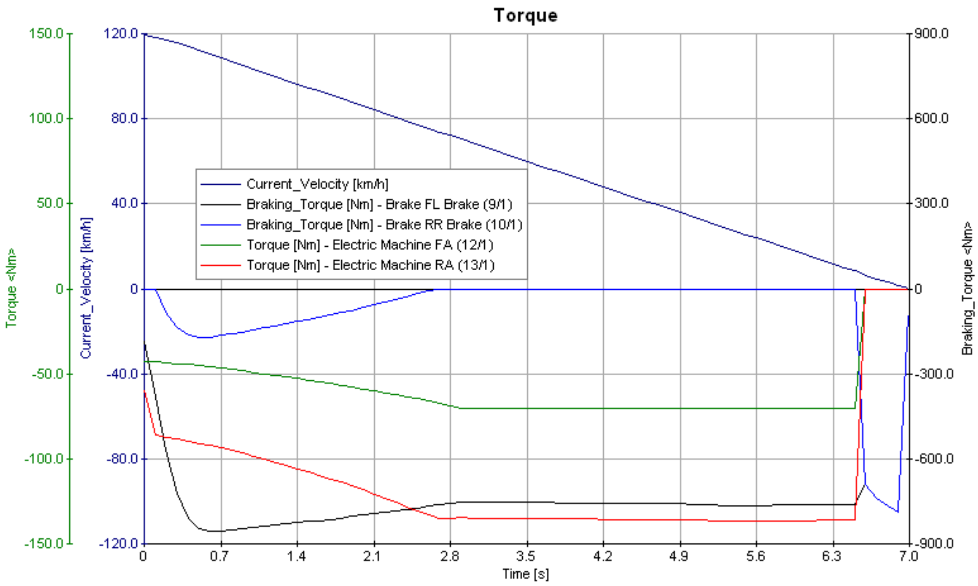


Fig.10 Relationship between vehicle speed and brake torque when the braking intensity is 0.6g

At the initial moment of braking, the front axle motor is not able to meet the demand of front axle, requiring hydraulic supplement. With the participation of the rear axle increasing, hydraulic braking gradually withdraw, completely supplemented by the motor braking force of the rear axle. Since the maximum braking torque of front axle motor is little, the hydraulic braking torque is always involved in.

The experimental results above were analyzed and summarized in table2.

Table 2 statistics of braking energy recovery at the speed of 120km/h

Decelaration/g	0.1	0.2	0.3	0.4	0.5	0.6
Recycled energy/(kWh/100km)	34.75	59.77	72.68	83.4	89.39	90.3
Braking distance/m	566.52	283.27	200.0	150.7	116.81	100.2
Recycled energy /kWh	0.1969	0.1693	0.1454	0.1257	0.1044	0.0905

Meanwhile we carried out experimental verification in different driving cycle, with the same affecting factors, such as battery SOC, temperature. We select typical driving cycles, such as NEDC, UDDS, to simulate and analysis,with the initial battery SOC of 80%, results as follows:

The results of statistical analysis for these five driving cycles are shown in table3, in which energy saving contribution rate is defined as the ratio of energy recovery and energy consumed without energy recovery. It shows the influence of energy recovery on vehicle economic.

Table 3 Energy saving contribution rate in driving cycles

Driving cycle	NEDC	UDDS	ECE
Distance(m)	11005.48	11998.39	1001.93
Energy consumption without energy recovery	10.62	12.91	10.7
Energy consumption with energy recovery	7.58	8.0	6.8
Energy saving contribution rate /%	28.63	38.03	36.45

Note: the unit of energy is kWh / 100km

5. Summary

It's a core technology for braking force distribution control strategy to ensure the overall performance of entire regenerative braking control. Taking into account the state of the vehicle and requirements in braking regulations, we developed a braking force distribution algorithm of front axle, in premise of ensuring the brake safety, to improve the efficiency of energy recovery. We need to consider motor efficiency in order to improve the efficiency of energy recovery, due to the front and rear axle motors participate in regenerative braking at the same time.

As shown in the simulation results, we verify that the proposed braking recovery control strategy for pure electric vehicle driven by double axles with double motors is correct and effective, and braking energy can be effectively recovered, in the case of different braking deceleration. With the increase of the braking intensity, limited to the motor performance and brake force distribution, hydraulic brake participate more in braking and the recovered energy is reduced. It's enough to meet the requirement of 0.2g-0.3g braking deceleration, when considering the size of motor.

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