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Research on Braking Stability of Electro-mechanical Hybrid Braking System in Electric Vehicles

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Abstract

For the electro-mechanical hybrid braking system, which is composed of electric brake and general friction brake, the models of electric braking force, total braking force and the utilization adhesion coefficient for front and rear axles were established based on the analysis of braking torque distribution. The variation relationship between electric braking force and friction braking force in different braking intensity was calculated and analyzed with the paralleled-hybridized braking control strategy. Taking USA urban driving circle UDDS as an example, the utilization adhesion coefficient of front and rear axles was calculated at different braking intensity for a certain Electric Vehicles (EVs), and the braking stability was also analyzed for front-wheel drive EVs. The calculation results indicate that the utilization adhesion coefficient of front axle is always greater than that of rear axle, which means the front axle always locked ahead of the rear axle, thus the braking stability meets the requirement. The calculation results also have certain instructive significance on the anti-lock braking system (ABS) and electric brake-force distribution (EBD) of EVs.

Keywords: electric vehicles, electric brake, electro-mechanical hybrid brake, braking stability, utilization adhesion coefficient.

1 Introduction

Regenerative braking technology for electric vehicles, which also named electric brake technology, is an effective technical measure to improve the driving range by converting kinetic energy into electric energy which then was deposited into accumulator[1]. However, the maximum charging current and charging power of the onboard accumulator in electric vehicles are usually limited, thus the braking ability of electric braking system is also restricted, which can't satisfy the heavy braking intensity. Hence, electric vehicles with electric braking system should also

have the mechanical friction braking system. Namely, the electro-mechanical hybrid braking system should be adopted to meet the need in different braking intensities.

The current research subjects on electric brake mainly focus on the aspects such as the necessity and efficiency of braking energy recycle[2], the control strategy of electric braking[3], the control technique of driving electric motor and power converter[4], and the coordination of the electro-mechanical hybrid braking system[5]. However, the paper on braking stability of electro-mechanical hybrid braking system for electric vehicles is rarely reported. Taking some type of EVs as the research object, the braking stability of electro-mechanical braking system was studied in order to harmonize the electric braking with the mechanical friction braking, thus the braking stability was guaranteed. The research results can establish theoretical basis for research on ABS and EBD of EVs, which have certain engineering application values.

2 Braking torque distribution principle of electro-mechanical hybrid braking system

In order to achieve both the energy recycle and braking stability, a certain braking torque distribution principles must be satisfied for electro-mechanical hybrid braking system[6]. The principles were used to distribute the regenerative braking torque and the frictional braking torque, which were shown in Fig.1.
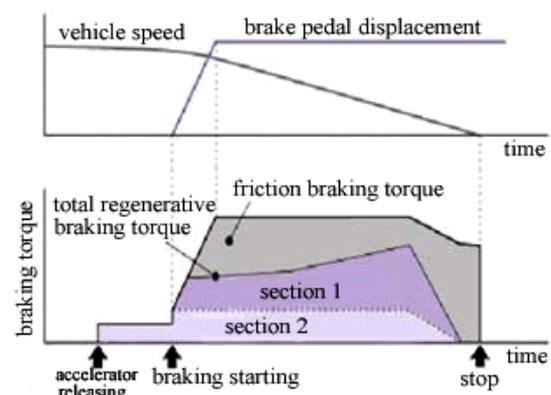

Figure 1: the curves of braking torque of regenerative braking system in HEV

section1: regenerative braking torque in harmonious;

section2: regenerative braking torque equivalent to conventional fuel vehicle

When releasing the accelerator pedal and the EV sliding, the braking intensity is relatively weak (equivalent to the engine braking of conventional fuel vehicle), here, the regenerative braking (electric braking only) could sufficiently meet the demands of braking performance; The driver step on the brake pedal while more braking intensity is required. If the force added to the pedal is less, the braking force effecting on driving wheels is only the regenerative braking force which increasing in direct proportion to pedal force; once the pedal force exceeds a certain value and the braking intensity could not be satisfied by regenerative braking only, the braking torque generated by mechanical friction on both front and rear wheels were needed. With the proceeding of braking, vehicle slows down and regenerative braking torque gradually climbs up and reaches to the maximum at the point which the vehicle speed has reduced to the zone of motor constant torque, while the friction braking torque declines correspondingly. When EV is to stop, the regenerative braking torque promptly fall to zero while the required friction braking torque rapidly rises.

3 Braking force mathematical

model in electro-mechanical hybrid braking system

3.1 Electric braking force mathematical model

According to the analysis mentioned above, the calculation formula of electric braking force is as follows:

$$n < n_e, \quad T_d = T_e$$
$$n \geq n_e, \quad T_d = \frac{9549 P_e}{n} \qquad (1)$$

The electric braking force converted to driving wheels, F_d, is calculated as follows:

$$F_d = \frac{T_d i_g i_0}{r \eta_T} \qquad (2)$$

where, n_e is the rated revolution of the motor, r/min; T_e is the rated torque, Nm; P_e is the rated power, kW; i_g and i_0 are the driving ratio of transmission and main reducing gear, respectively; r is the rolling radius of wheels, m; η_T is the driving efficiency.

As the EVs gearing down, the relationship between vehicle speed and motor speed is as follows:

$$u = 0.377 \frac{rn}{i_g i_0} \qquad (3)$$

In the formula, u is the vehicle speed, km/h; while n is motor speed, r/min.

From formula (1) ~ (3), we can get the calculation formula of electric braking force of driving wheels:

$$n < n_e, \quad F_d = \frac{T_e i_g i_0}{r \eta_T}$$
$$n \geq n_e, \quad F_d = \frac{3600 P_e}{u \eta_T} \qquad (4)$$

It can be seen that the electric braking force is related to vehicle speed, and it decreases gradually with the increasing of vehicle speed. The braking force of electro-mechanical hybrid braking system must be regulated according to the variation of vehicle speed in order to guarantee the braking stability.

3.2 Total braking force mathematical model

It was supposed that the ratio of braking force of front and rear axle arresters is fixed in conventional mechanical friction braking system, and the partition coefficient of braking force is β, then the relationship between braking force of front and rear arresters, F_{b1}、F_{b2}, is as follows[7]:

$$F_{b2} = \frac{1-\beta}{\beta} F_{b1} \qquad (5)$$

It was taken into account that the front wheels are driving wheels. Then the total braking force of rear wheels is F_{b2}, and total braking force of front wheels is as follows:

$$F_{\mu,b1} = F_d + F_{b1} \qquad (6)$$

3.3 Utilization adhesion coefficient of front/rear axles

Utilization adhesion coefficient represents the using condition of ground adhesion coefficient as the EVs braking, That is to say, it is the ground adhesion coefficient that there are no wheels locked at certain degree of braking intensity. It was defined as follows:

$$\varphi_f = \frac{F_{b1}}{F_{z1}}, \varphi_r = \frac{F_{b2}}{F_{z2}} \qquad (7)$$

Where, F_{b1}、F_{b2} represents ground braking force produced by front axle and rear axle respectively when braking intensity is z; F_{z1}、F_{z2} represents the normal ground-reaction which the ground applies to the front axle and rear axle respectively while the braking intensity equals to z; φ_f、φ_r shows the utilization adhesion coefficient of front and rear axle respectively with the braking intensity z.

The utilization adhesion coefficient calculation model can be founded combining with the calculation formulas of ground braking force and normal ground-reaction in references [7], about the rear wheels are going to be locked or both front

and rear wheels are going to be locked under braking intensity z. The model is described as follows:

$$\varphi_f = \frac{[z\beta + (1-\beta)F_d/G]L}{L_2 + zh_g}$$

$$\varphi_r = \frac{L(1-\beta)(z - F_d/G)}{L_1 - zh_g}$$ (8)

In the formula, φ_f、 φ_r are the utilization adhesion coefficient of front axle and rear axle, respectively; L is the axle base, m; L_1 is the distance between the centroid and the front axle, m; L_2 is the distance from the centroid to the rear axle, m; G is the whole gravity of vehicle; h_g is the height of the centroid, m; z is the braking intensity.

The utilization adhesion coefficient of front and rear axles, φ_f、 φ_r, are related to vehicle speed since the electric braking force F_d is related to the vehicle speed. The adhesion utilization curve of driving wheels could go beyond the limit of ECE regulation with the increase of the vehicle speed. It could lead to differences between the braking stability of electro-mechanical hybrid braking system and that of the traditional vehicles.

4 Braking stability of electro-mechanical hybrid braking system

4.1 Braking force of electro-mechanical braking system

In order to ensure the braking stability of electric vehicles, it is not only to be properly distributed for the electric and friction braking torque, but also to be reasonably controlled on the braking torque of the front and rear axle. Theoretically, there are three kinds of control strategies for the braking torque of front and rear axle: ideal front and rear axle braking torque control strategy, optimal energy feedback control strategy, and paralleled-hybridized braking control strategy[6]. The paralleled-hybridized braking control strategy was adopted in this research, which mainly

because the braking controller for whole vehicle is not needed under this control strategy. A motor controller only needs to be added to control the electric braking force in accordance with braking intensity and vehicle speed. In addition, the friction braking system is the same as that in traditional fuel vehicles.

Taking a certain type of electric passenger car as the research object, a mathematical model of electro-mechanical hybrid braking system was established based on the braking torque allocation principle and braking force calculation model mentioned above, with the input parameter as vehicle speed, brake pedal displacement, battery SOC and transmission gear. The electric braking force and friction braking force could be calculate and adjusted timely to satisfy the braking stability of EVS.

The main technical parameters of this EVS are as follows: the total mass (full loaded) is 1615kg; the distance from centroid to front axle is L_1=1060mm; the distance from centroid to rear axle is L_2=1590mm; the height of centroid is h_g=495mm; the wheel radius is r=0.287mm; the transmission gear ratios from 1 to 5 location are respectively 3.181,1.842,1.250,0.864,0.707; the main reducer ratio is i_0=4.266; the driving efficiency is η_T=0.92. The AC asynchronous motor is used in the EVS. The rated power and speed respectively are 20 kW and 3600rpm.

The motor characteristic curves tested were showed in Fig.2. It can be seen that the characteristics of generating and motoring state is similar basically. In regenerative braking condition, the motor brake at rated power as the speed is higher than rated speed; and the motor brake at rated torque as the speed is lower than rated speed. Regenerative braking will be disabled and electric braking force will decrease rapidly to zero if motor speed is quite low.
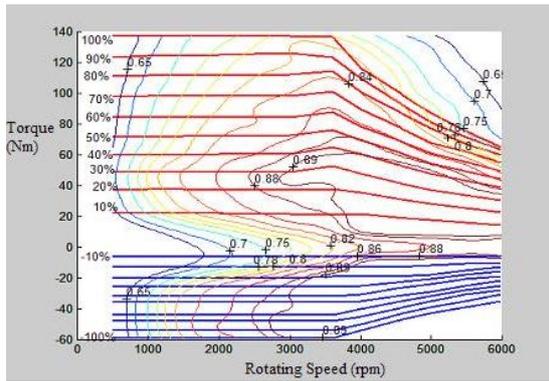
Fig.2: the motor testing curves

Fig.3 showed the braking force distribution curve of the front and rear axles, and the total braking force is borne both by electric braking force and friction braking force under a fixed proportion. There is only electric braking force acting on the whole vehicle when the $z \leq 0.1$; there are both electric braking force and friction braking force bring to bear at a fixed ratio while $0.1 < z \leq 0.7$; the $z > 0.7$ is the state of emergency braking, and there is only friction braking force in this situation.
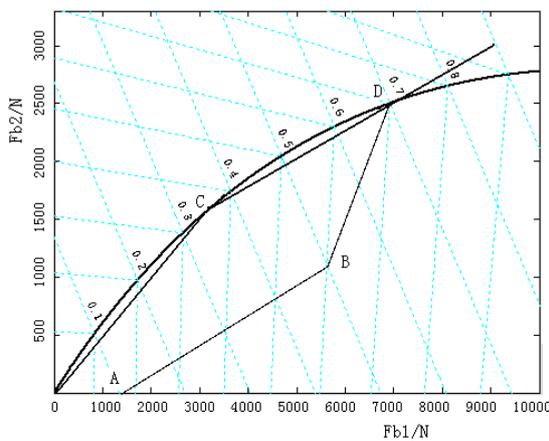

Fig.3: braking force distribution curve of an EVs

## 4.2 Stability of electro-mechanical braking system

Braking stability is the capacity that vehicles do not deviate, sideslip, or lose the steering ability when braking; it is closely related to the distribution and regulation of the braking force of the front and rear arrester. In order to ensure the braking stability of vehicles, firstly, it must make sure that the instances that only the rear wheels locked or rear wheels locked ahead of the front wheels do not happen; Secondly, it should also be avoided that only the front wheels locked or the front and rear wheels locked simultaneity. The ideal instance is that none of the wheels locked when vehicles braking.

In order to analyze the stability of electro-mechanical braking system, the utilization adhesion coefficient was chosen to represent braking conditions of front and rear axle in this study. The simulation on the braking stability of EVs was calculated at the condition of the USA urban driving circle UDDS, in which the maximum velocity is 91.25km/h, while the average velocity is 31.51km/h. The calculation result was shown in Fig.4.
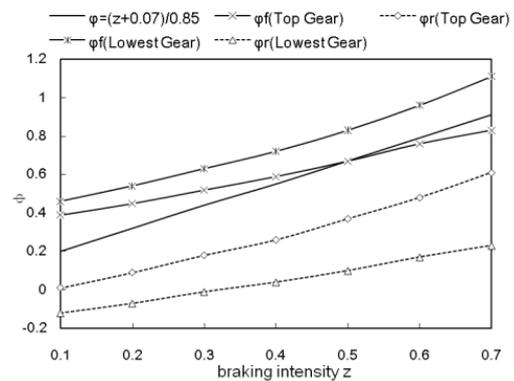
(a) Constant torque braking
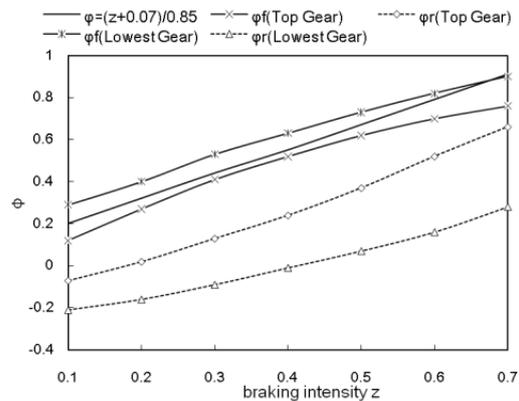
(b) Constant power braking

Fig.4: the relation between utilization adhesion coefficient and braking intensity

Fig.4 illustrated that the curve of utilization adhesion coefficient of front axle φ_f is always above of that of rear axle φ_r no matter what the motor is in constant torque braking area or constant power braking area at the condition of electro-mechanical hybrid braking. That is to say, the front axle is always locked ahead of the rear axle. It indicates that the braking stability of EVs meet the requirements. But the utilization adhesion coefficient curve of the front axle has an intersection with that regulated by ECE regulation when the EVs braked at the top gear, which accounts for that the front axle could be locked in the top gear. Besides, the distance between the curves of φ_f and $\varphi = (z+0.07)/0.85$, in ECE regulation, is growing along with the increasing of electric braking force (low gear), so does the φ_r curve. The braking stability is affected disadvantageously.

5 Conclusion

Electric braking force is related to the vehicle speed, and its braking capacity was limited, which can't meet requirements of heavy braking intensity. Thus the electro-mechanical hybrid braking system should be adopted in the EVs with regenerative braking system. The braking stability is influenced by electric braking force which only acts on driving wheels and changes the distribution portion of braking force of front and rear axles of conventional friction braking system. It can be achieved to meet the requirements of braking stability that the front axle is locked before the rear axle or the two axles are locked simultaneity by allocating electric braking torque and friction braking torque reasonably, choosing proper braking force control strategy of front and rear axles.

However, the utilization adhesion coefficient curve of front axle analyzed in this paper was above the curve regulated by ECE regulation, which might lead to an early locked of the front axle. It can be ensured that the utilization adhesion coefficient curve of front axle be always under the adhesion coefficient curve regulated by ECE regulation at any speed by optimizing or adjusting relevant parameters (such as centroid position, electric braking force controlled by power converter, etc.), which will improve on the utilization ratio of electric braking force.

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