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Novel control algorithm of braking energy regeneration system for an electric vehicle during safety–critical driving maneuvers

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ABSTRACT

This paper mainly focuses on control algorithm of the braking energy regeneration system of an electric bus under safety–critical driving situations. With the aims of guaranteeing vehicle stability in various types of tyre–road adhesion conditions, based on the characteristics of electrified powertrain, a novel control algorithm of regenerative braking system is proposed for electric vehicles during anti-lock braking procedures. First, the models of vehicle dynamics and main components including braking energy regenerative system of the case-study electric bus are built in MATLAB/Simulink. Then, based on the phase-plane method, the optimal brake torque is calculated for ABS control of vehicle. Next, a novel allocation strategy, wherein the target optimal brake torque is divided into two parts that are handled separately by the regenerative and friction brakes, is developed. Simulations of the proposed control strategy are conducted based on system models built using MATLAB/Simulink. The simulation results demonstrate that the developed strategy enables improved control in terms of vehicle stability and braking performance under different emergency driving conditions. To further verify the synthesized control algorithm, hardware-in-the-loop tests are also performed. The experimental results validate the simulation data and verify the feasibility and effectiveness of the developed control algorithm.

1. Introduction

The use of various types of electrified vehicles, including hybrid electric vehicle, pure electric vehicle, and fuel cell electric vehicle, is an effective way to save energy and protect the environment [1]. Therefore, many scholars worldwide have carried out comprehensive and in-depth research on electrified vehicles and electrical systems from different aspects [2–4].

For an electric vehicle, during deceleration process, the electric motor can work as a generator, exerting regenerative braking torque on the axle and charging battery simultaneously. In this way, the kinetic energy of vehicles can be recaptured by regenerative braking system (RBS) during deceleration procedures, thereby efficiently improving vehicle's energy efficiency [5,6]. In an electric vehicle, brake torque can be generated using regenerative and friction brakes, either together or individually. Therefore, for vehicle control in safety–critical driving maneuvers, cooperation between regenerative and frictional braking systems of electrified vehicles is worthwhile studying and has received much attention [7–10].

Among different kinds of safety–critical driving maneuvers, including vehicle longitudinal and lateral dynamics, anti-lock braking is a typical and important emergency situation. Hence, in this paper, we make the anti-lock braking system (ABS) as the study focus of the vehicle safety control.

For the commercialized electric vehicles with regenerative braking, when the vehicle enters an emergency braking situation, the regenerative brake force is removed quickly, and only the friction brake takes over the ABS control [11,12]. This is an easy and mature way to guarantee the brake safety by using the conventional ABS, and practical applications show the effectiveness of this simplification. However, these applications do not fully utilize the potential benefits from the regenerative brake of electric motor for improving vehicle's dynamics control performance. Taking advantage of the rapid response and accurate control of motor torque, researchers worldwide have explored various ways to introduce regenerative braking torque into ABS control, expecting improved control. In [13], a method employing proportional–integral–derivative (PID) control that utilized only regenerative brake force during ABS operation was proposed. The simulation results based on a quarter-vehicle model show that "regenerative ABS" is beneficial during the critical braking process. However, the regeneration capabilities are limited by the operating conditions

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Nomenclature

A	frontal area
A_p	cross-sectional area of the valve opening
B_F	width of the front track
B_R	width of the rear track
C_D	coefficient of the air resistance
C_d	discharge coefficient compensating for the losses during the flow
F_x	longitudinal force of the wheel
F_y	lateral force of the wheel
F_z	vertical force of the wheel
I	wheel's inertia
i_g	transmission ratio of the gearbox
i_0	final drive ratio
J_{pt}	moment of inertia of the powertrain
J_w	moment of inertia of tyre
k	positive gain
L	wheelbase
m	overall mass of the vehicle
$\dot{m}_c$	time rate of change of the air mass in the control volume
m_t	wheel's vertical load
P_b	pneumatic pressure in the brake chamber
ρ	density of air inside the control volume
r	nominal radius of the tyre
R	gas constant for air
γ	ratio of the specific heats
S	slip ratio of the wheel
S^*	ideal value of slip ratio of the wheel
δ	steering angle of the front wheels
τ_m	time constant of the electric motor
T_b	total brake torque of wheel
T_b^*	optimal brake torque of wheel
T_d	driving torque exerted on wheel
T_{b_fric}	friction braking torque on a driven wheel
T_{b_regen}	regenerative braking torque on a driven wheel
T_c	temperature of the control volume
T_{steady}	steady part of the optimal brake torque
T_{dyna}	dynamical part of the optimal brake torque
T_M	real value of motor torque
$T_{M,ref}$	reference value of motor torque
v	velocity along OY
u	longitudinal velocity of vehicle
u_c	velocity of air entering the control volume
V_b	volume of the control volume
ω	rotational speed of the wheel

Subscripts

ij	$ij = 11$ front left wheel; $ij = 12$ front right wheel; $ij = 21$ rear left wheel; $ij = 22$ rear right wheel

of electric motors and batteries. Hence, the friction brake is also required to supplement the overall brake demand. In [14], an electrically-controlled regenerative braking system based on the conventional hydraulic ABS techniques was developed, and a control algorithm coordinating the braking energy regeneration and ABS control functions was designed. In [15], three executive control strategies, namely, the "PQ-method," "frequency selection by filter," and "model following control" strategies were proposed. As the electric motor responds more accurately and rapidly than the friction brake, optimal ABS control is expected. Simulations and road tests validated the control performance of the proposed method.

Nevertheless, all the existing research is mainly based on passenger cars equipped with hydraulic ABS, and the coordinated control of regenerative brake and pneumatic ABS under vehicle's emergency braking conditions has rarely been studied. Since the dynamic behavior of a pneumatic braking system is quite distinguished from a hydraulic one [16,17], the cooperation of regenerative braking system and pneumatic ABS is worthwhile researching for improving advanced control technologies of electric vehicles.

In this paper, a novel control algorithm coordinating the regenerative braking system and pneumatic braking system for an electrified bus under ABS control procedures has been proposed. In Section 2, the system layout of an electrified bus equipped with a regenerative brake system has been introduced. And the models of vehicle dynamics and main components related to the regenerative and the frictional brakes of the case-study electric bus have been built in MATLAB/Simulink. In Section 3, the target brake torque of antilock braking control was obtained based on the phase plane theory. And then, according to the different system characteristics of regenerative and friction brakes, a novel ABS control algorithm was designed wherein the brake torque command is divided into steady and dynamical parts that are handled separately by the pneumatic and regenerative brakes. In Sections 4 and 5, the control strategy was evaluated using simulations and hardware-in-the-loop (HIL) tests and compared with two baseline control strategies. Finally, some concluding remarks are provided.

2. System dynamics modeling

2.1. System layout of the case-study vehicle

Fig. 1 illustrates the diagram of the proposed electric vehicle equipped with regenerative braking system and pneumatic brake system. A brake control unit takes over the control of all the four modulating valves, and communicates with the motor control unit and vehicle control unit via controller area network (CAN) bus. During normal decelerations, the electric motor works as a generator, generating electrical energy and charging the battery [18]. In the meantime, the electric motor provides regenerative braking torque, which is transmitted by the drivetrain, and finally exerted on wheel, decelerating the vehicle.

However, when the vehicle enters a critical driving situation, if the wheel has a locked tendency which is detected by the wheel

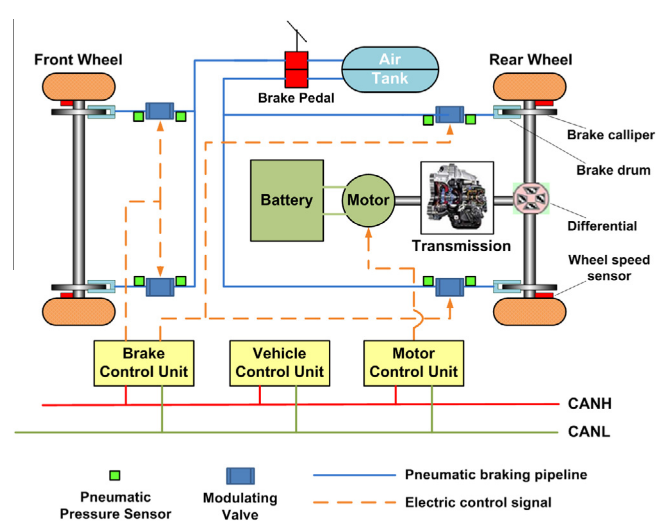

Fig. 1. System layout of the electric vehicle equipped with regenerative braking.