Coordinated Control of Regenerative Braking System for a Hybrid Electric Bus

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Abstract. This paper presents a design of regenerative braking system (RBS) for a parallel hybrid electric bus using coordinate control algorithm. The coordinate control algorithm is mainly composed of four parts for driver intention identification, brake force distribution, coordinated control with Anti-lock brake system (ABS) and pressure control based on coordinated control. This paper mainly discusses front two parts. As a consequence, a full RBS coordinated control algorithm decomposed four parts is successfully build by C language in Code Warrior. The control strategies are tested and verified on a parallel hybrid electric bus. The result shows that the control strategies can effectively make the pneumatic brake system and motor brake system work harmoniously.

Introduction

With the development of the regenerative brake system and the hybrid electric bus (HEV), making a suitable RBS for the HEV bus is an important target for our independent research and development in automotive industry.

However regenerative braking system is a complicated control system which is related to hybrid power-train structure, characteristic of battery and motor, characteristic of braking system, etc. And it is difficult for controlling [1]. So build an accurate and practical control system is the most important factor for improve the energy efficiency of regenerative RBS. The control methods are discussed by many researchers all over the world. Many strategies and structures are designed for difference type of vehicles [2 3], and so a practical control algorithm for a specific hybrid electric bus is one more step in improving the energy efficiency. For a RBS's performance is mainly dependence on the control strategy of the regenerative braking system [4 5].

By studying the theory of RBS control system, the RBS control problem in HEVs can be mainly divide into four objectives, they are: driver intention identification, brake force distribution, coordinated control with Anti-lock brake system (ABS) and pressure control.

(1) Driver intention identification: estimated driving intention of the driver and calculated the total braking force which the driver wanted.

(2) Brake force distribution: according to the driver braking intention distribute braking force into regenerative braking and frictional braking with considering on the vehicle state and the laws of vehicle.

(3) Coordinated control with Anti-lock brake system (ABS): realized the coordinate control with Anti-lock braking system (ABS) for ensuring the security of vehicle driving.

(4) Pressure control: meet the braking force distribution by accurately controlling the motor torque and pneumatic braking torque for a good drivability and appropriate braking force.

In this paper, part (1) and part (2) are the research contents. Part (3) and part (4) will be researched in another paper.

The basic vehicle configuration

This paper takes a typical parallel hybrid electric bus as the research object. Fig. 1 is the vehicle configuration.

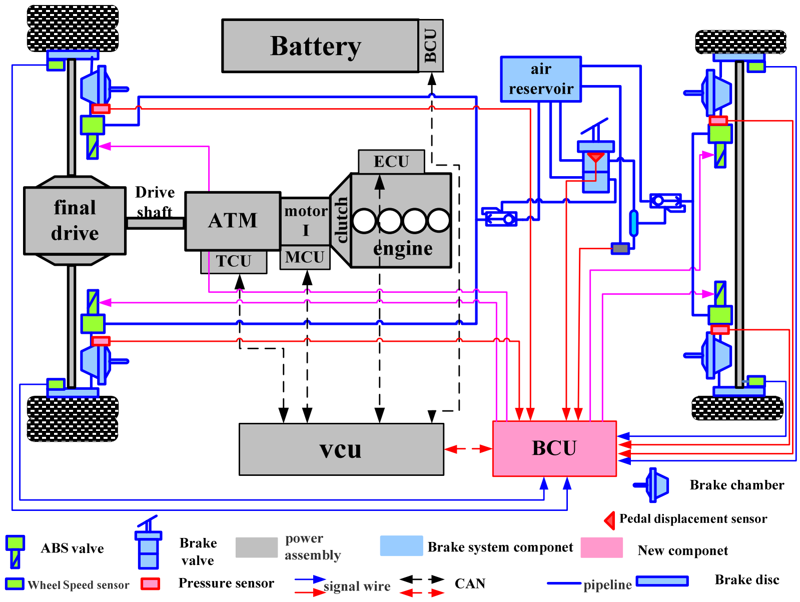

Fig. 1: vehicle configurations

Vehicle's power units are mainly composed of a 6.060L six-in-line diesel engine and a 40/60kw motor. Engine is connected parallel by a Torque synthesizer with the motor. According to control the Torque synthesizer the hybrid bus can be drove only by engine or motor or by engine and motor together. Vehicle control unit (VCU) connected with engine control unit (ECU), motor control unit (MCU), transmission control unit (TCU) and battery management system (BMS) by Control Area Network (CAN) to transmit various state signals and control signals. Vehicle's parameters and power units' parameters are shown in Table 1.

This hybrid bus's regenerative braking system is mainly composed of air reservoir, brake valve, relay valve, three-way valve, switch valve, ABS solenoid valve, brake chamber, drum brake, wheel speed sensor, pressure sensor, brake control unit (BCU), motor and motor control unit (MCU), battery and battery management system (BMS), vehicle control unit (VCU) and pneumatic pipe, etc.

Table 1: Vehicle's parameters and power units' parameters

<table>
<tr><td colspan="2">Maximum Design Total Mass（kg）</td><td>11000</td><td>Axle Base (mm)</td><td>5600</td></tr>
<tr><td colspan="2">Complete Vehicle Shipping Mass（kg）</td><td>12200</td><td>Wheel Base (mm)</td><td>Front/Rear, 2020/1847</td></tr>
<tr><td colspan="3">Distribution of Axle Load (kg)</td><td colspan="2">Front/Rear, 5000/10000kg (Full Load)
Front/Rear, 3500/7000kg (Idle Load)</td></tr>
<tr><td colspan="3">Vehicle Configuration Size (mm)</td><td colspan="2">Length*Width*Height, 11400*2480*2950</td></tr>
<tr><td rowspan="3">Engine</td><td colspan="2">Max Torque (Nm)/Speed (rpm)</td><td colspan="2">577/1400~1600</td></tr>
<tr><td colspan="2">Max Power (kw)/Speed (rpm)</td><td colspan="2">125/2500</td></tr>
<tr><td colspan="2">Max Speed (rpm)</td><td colspan="2">2500</td></tr>
<tr><td rowspan="4">Motor</td><td colspan="2">Rated/Overload Power (kw)</td><td colspan="2">40/80</td></tr>
<tr><td colspan="2">Rated/Overload Torque (Nm)</td><td colspan="2">106/212</td></tr>
<tr><td colspan="2">Base/Max Speed (rpm)</td><td colspan="2">3600/5000</td></tr>
<tr><td colspan="2">Voltage(V) (Voltage Range)</td><td colspan="2">336 (270~450)</td></tr>
<tr><td rowspan="2">Battery</td><td colspan="2">Rated Voltage (V)</td><td colspan="2">336</td></tr>
<tr><td colspan="2">Rated Capacity (Ah)</td><td colspan="2">27</td></tr>
</table>

Regenerative Braking Control Algorithm

Primary Control Algorithm. The primary control algorithm is composed of four objectives. They are: driver intention identification, brake force distribution, coordinated control with Anti-lock brake system (ABS) and pressure control. The structure of primary control algorithm is shown in Fig.

1.

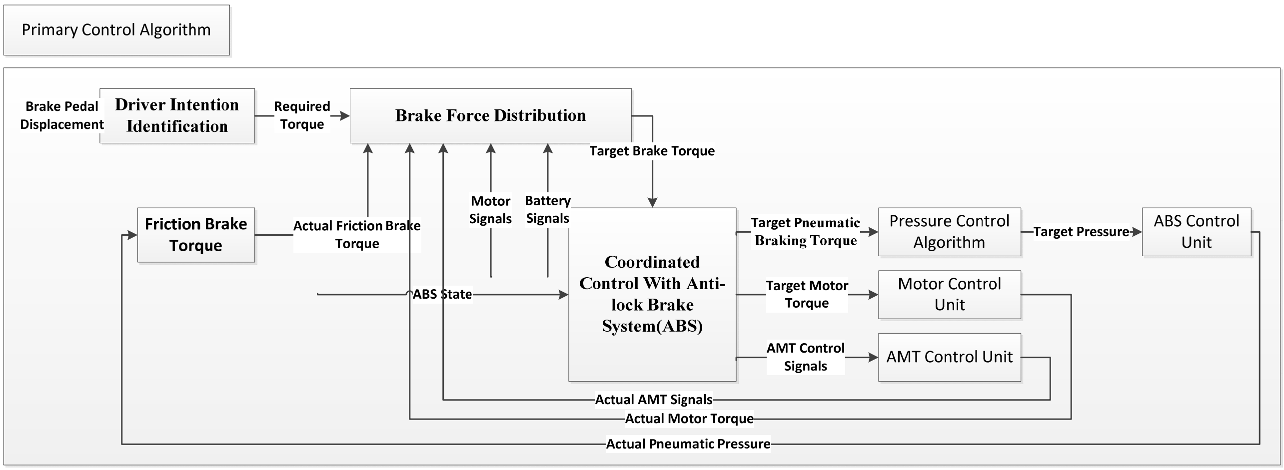

Fig. 1: structure of primary control algorithm

Each part of the primary control algorithm achieved different function with different configuration. And all components coordinate together to a full RBS control program with various signals. Four parts are focused on including driver intention identification, brake force distribution, coordinated control with Anti-lock brake system (ABS) and pressure control. Every part work out objective and transmit particular command to the other parts.

Driver Intention Identification Algorithm. Driver intention identification is designed to estimated driving intention of the driver and calculated the total braking force which the driver wanted. According to the operation of the pedal the driver can realize different states of vehicle. So how to accurately and timely judge the driver intention is an essential problem for ensuring the vehicle safety and vehicle correct control. Especially to RBS, only when the driver intention identification is accurate enough the next brake force distribution algorithm can accurately distribute the brake force dependence on the pedal state.

According to the parameters of the brake pedal and accelerator pedal the driver intention identification algorithm can acquire the driver's driving intention. For example, the pedal position and speed are the most constantly parameters used to judge the driver's intention. In general, the pedal displacement is the most appropriate parameter for RBS driver intention identification [6]. So this paper chooses pedal displacement for the input of the driver intention identification algorithm. The structure of the driver intention identification algorithm is shown in Fig. 3.

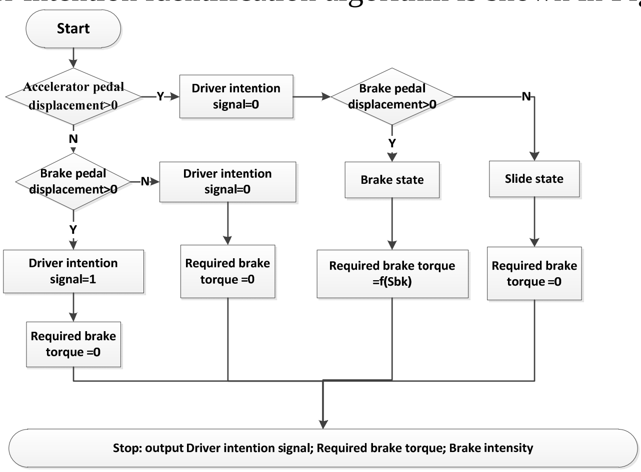

Fig. 3: structure of Driver Intention Identification Algorithm

In this part, according to the different state of brake pedal and accelerator pedal the driver intention signal is endowed with zero or one. Zero represents now the vehicle is acceleration state or slide state. So this mode the required brake torque is zero. Driver intention signal is one represents now the vehicle is brake state. So this mode the required brake torque calculated dependence on the brake pedal displacement. In the end of this algorithm the driver intention signal, required brake torque and the brake intensity are the output signals.

Brake Force Distribution Algorithm. Brake force distribution algorithm is designed to distribute braking force into regenerative braking force and frictional braking force according to the output signals of the driver braking intention algorithm by considering on the vehicle state and the laws of vehicle. After the driver intention identification algorithm, an appropriate brake force distribution algorithm for regenerating most energy without damaging the brake performance of the vehicle. When brake, the motor worked as a generator to transform vehicle kinetic energy to electric energy and then stored in the battery pack for driving the vehicle or used for other auxiliary power unit. The structure of the brake force distribution algorithm is shown in Fig. 4.

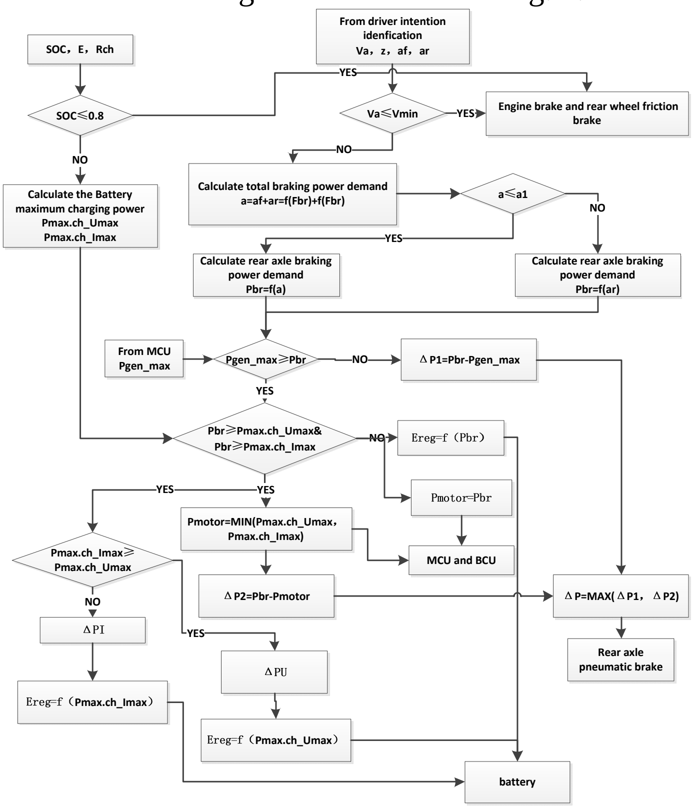

Fig. 4: structure of Brake Force Distribution Algorithm

In this algorithm, according to the result of the driver intention identification algorithm, the control status changed to different status based on different parameters of the vehicle. It mainly considered parameters like as: State of charge(SOC) of battery, Energy (E) of the battery, Charging resistor (Rch) of battery, Max charge power of motor (Pgen_max) which came from motor control unit(MCU), Vehicle speed (Va), Driver braking strength (z), Front axle braking force demand (Fbf), Rear axle braking force demand (Fbr).

In this algorithm, firstly, when SOC is more than SOC1 or Va is less than V1, SOC1and V1 are defined by author, all brake force of the vehicle will come from pure pneumatic brake system. Otherwise when vehicle acceleration demand (a) is less than a1 which is defined by author, rear driver brake force demand (Fbr) will be calculated by a which is calculated from driver braking strength (z), otherwise Fbr will be calculated by rear brake acceleration demand (ar). Then according to the compare result of the Pgen_max and rear brake power demand (Pbr), different motor brake power demand (Pmotor) and pneumatic brake power demand (△P1) will be calculated. After these steps according to the compare result of the Max brake power which is limited by battery charge voltage (Pmax.ch_Umax) or by battery charge current (Pmax.ch_Imax) and Pbr, different motor brake power demand (Pmotor) and pneumatic brake power demand (△P2) will be calculated. And the regenerative energy (Ereg) which can be regenerated by battery will be calculated by the different compare result as △PI, △PU.

Experimental Validation. After simulation of the algorithm, experimental validation has been done with the typical parallel hybrid electric bus. Fig. 5~7 is the RBS experimental result in high adhesion coefficient road with the value of road adhesion coefficient about 0.8. Fig. 8~10 is the RBS experimental result in low adhesion coefficient road with the value of road adhesion coefficient about 0.1.

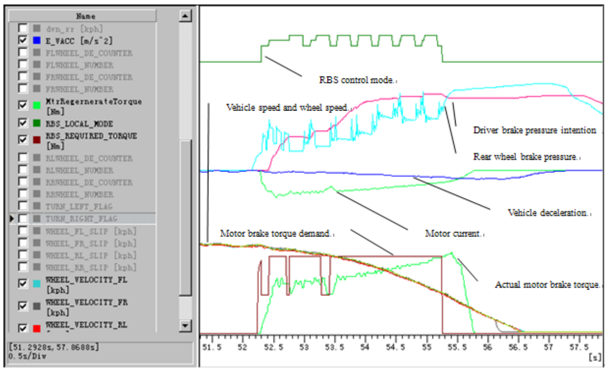

Fig. 5 little brake strength in high adhesion coefficient

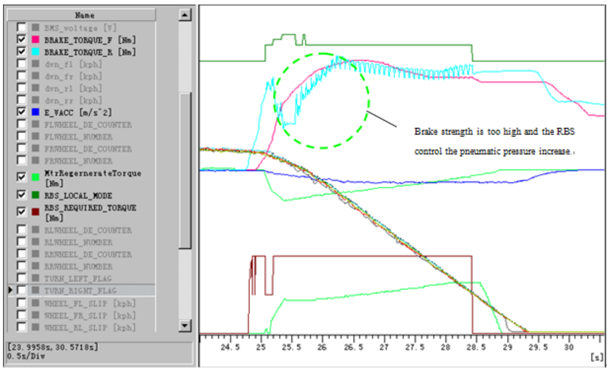

Fig. 6 large brake strength in high adhension coefficient

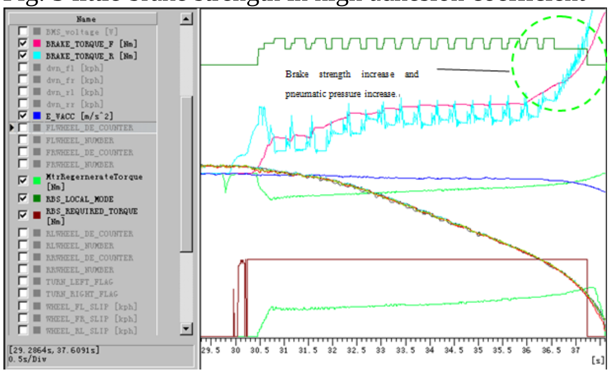

Fig. 7 mutative brake strength in high adhesion coefficient

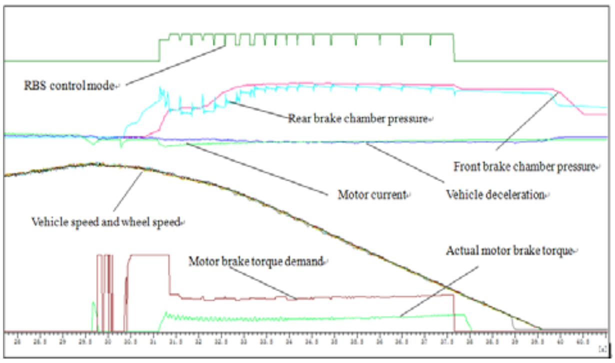

Fig. 8 little brake strength in low adhesion coefficient

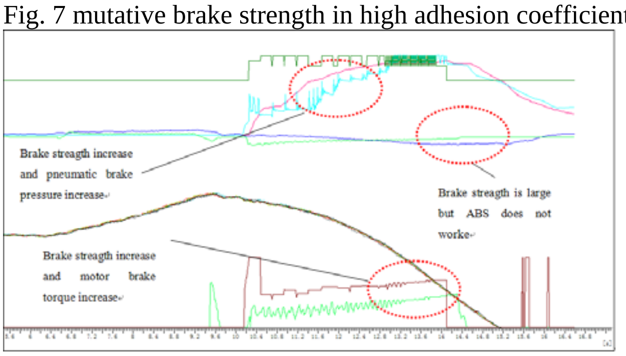

Fig. 9 large brake strength in low adhesion coefficient

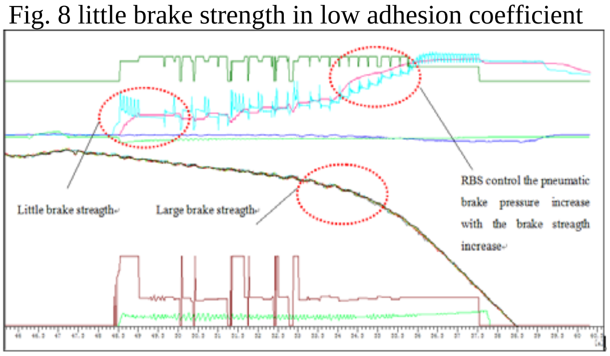

Fig. 10 mutative brake strength in low adhesion coefficient

Fig. 5 and Fig. 8 show the vehicle brake in little brake strength with RBS. Fig. 6 and Fig. 9 show the vehicle brake in large brake strength with RBS. Fig. 7 and Fig. 10 show the vehicle brake in mutative brake strength with RBS.

Fig. 5 shows that the vehicle brake from 51.6s to 56.6s and vehicle brake initial speed is 21.89km/h. In the brake process, rear axle brake with combine brake force which are the pneumatic brake force and motor brake force. The largest motor brake torque is about 2730Nm and the largest pneumatic brake torque is about 23056Nm. The largest brake strength is about 2.16m/s^2. It shows a harmony cooperation work of the pneumatic and motor brake.

Fig. 6 shows that the vehicle brake from 24.7s to 29.4s and vehicle brake initial speed is 44.56km/h. In the brake process, the largest motor brake torque is about 1704Nm and the largest pneumatic brake torque is about 28864Nm. The largest brake strength is about 3.26m/s^2. In the initial brake stage, because of the large brake strength and the motor brake torque can't meet the demand of the driver brake intention so the RBS control the pneumatic brake pressure increase quickly.

Fig. 7 shows that the vehicle brake from 29.8s to 37.8s and vehicle brake initial speed is 41.66km/h. In the initial brake stage, vehicle brake with a relatively little brake strength. In 36.25s the brake strength increases quickly and the motor brake torque and pneumatic brake torque can't meet the driver brake intention. So the RBS control the pneumatic brake torque increase quickly to meet the brake intention.

Fig. 8~Fig. 10 shows that this RBS control algorithm can work well in low adhesion coefficient road.

Conclusions

Coordinate control algorithm of RBS in this paper is tested and verified with a parallel hybrid electric bus in the high adhesion coefficient road and low adhesion coefficient road. The experimental validation result shows that the RBS control algorithm can work very well in conventional braking conditions. The pneumatic brake system and the motor brake system can work harmoniously. More study should be took into account energy management strategy combined braking and driving process during whole drive cycle, and combined the RBS and anti-lock braking system (ABS),traction control system(TCS),etc.

Acknowledgment

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