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Directional-stability-aware brake blending control synthesis for over-actuated electric vehicles during straight-line deceleration

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ABSTRACT

For the purpose of both energy regeneration and directional stability enhancement, regenerative and hydraulic blended braking control of an over-actuated electric vehicle equipped with four individual on-board motors during normal straight-line deceleration is studied. System models which include the vehicle dynamics, tire, electric powertrain, and hydraulic brake models are developed. Mechanisms of directional instability of the electric vehicle during straight-line braking are analyzed. To improve the electric vehicle's safety and performance, novel compensation methods through blended braking are studied. On the basis of half-shaft torque estimation, two new regenerative braking control algorithms are proposed. Simulations of the developed control algorithms are carried out during normal straight-line braking maneuvers. The results and discussions demonstrate that the developed approaches are advantageous when compared with the conventional baseline strategy, with respect to both the directional stability and regeneration efficiency, thus validating the feasibility and effectiveness of the controller synthesis.
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1. Introduction

Increasing global environmental concern requires that automobiles be cleaner and more fuel-efficient. In this context, vehicle electrification is quite promising because of the high-efficiency of powertrain systems and reduced, or zero, emissions [1–5]. Thanks to the actuation flexibility of their systems, over-actuated electric vehicles with individual driving systems, including in-wheel and on-board motors, are a very popular research topic amongst various types of electrified powertrain architectures [6–9]. The introduction of the individual electric powertrain provides great capacity for improvement of the vehicle's energy efficiency and control performance. However, it also poses tremendous challenges concerning vehicle safety, since the system dynamics of the electric powertrain are very different from those of conventional vehicles. Furthermore, cooperation mechanisms between multi-actuators, including motors, brakes, and steering, are quite complex [10–13]. Therefore, the safety factor for various types of driving conditions is of great significance in the design and control of over-actuated electric vehicles.

Existing studies of over-actuated electrified vehicles with individual in-wheel or on-board motors mainly focus on dynamics control during critical driving maneuvers, which can be classified into two categories: anti-slip control of longitudinal dynamics and stability control of lateral dynamics. When considering longitudinal dynamics, current research mainly focuses on regenerative and hydraulic blended braking of electrified vehicles during anti-slip procedures, such as traction control and anti-lock braking. In [14], the integration of friction braking and regenerative braking of an electrified vehicle during anti-lock braking were investigated. A strategy for ABS operation realized through individual in-wheel motors on a full electric vehicle was introduced in [15]. The authors of Fujimoto and Harada [16] optimized the front and rear driving/braking force distribution by considering the slip ratios of the wheels and the motor loss with the assumptions that the road was straight and the steering angle was fixed to zero.

When considering lateral dynamics, important research topics fall into the areas of yaw control and state estimations of electric vehicles undergoing critical handling maneuvers [17]. These include braking, split-μ, straight-line braking, and double lane-changes. In [18], a differential braking-based stability control strategy was developed for an electrified vehicle. A direct yaw moment controller, based on the combination of feed-forward and feedback contributions, for continuous yaw rate control was presented in [6]. The authors of Nam et al. [19] developed a method using lateral tire force sensors to estimate the side-slip angle of the vehicle,

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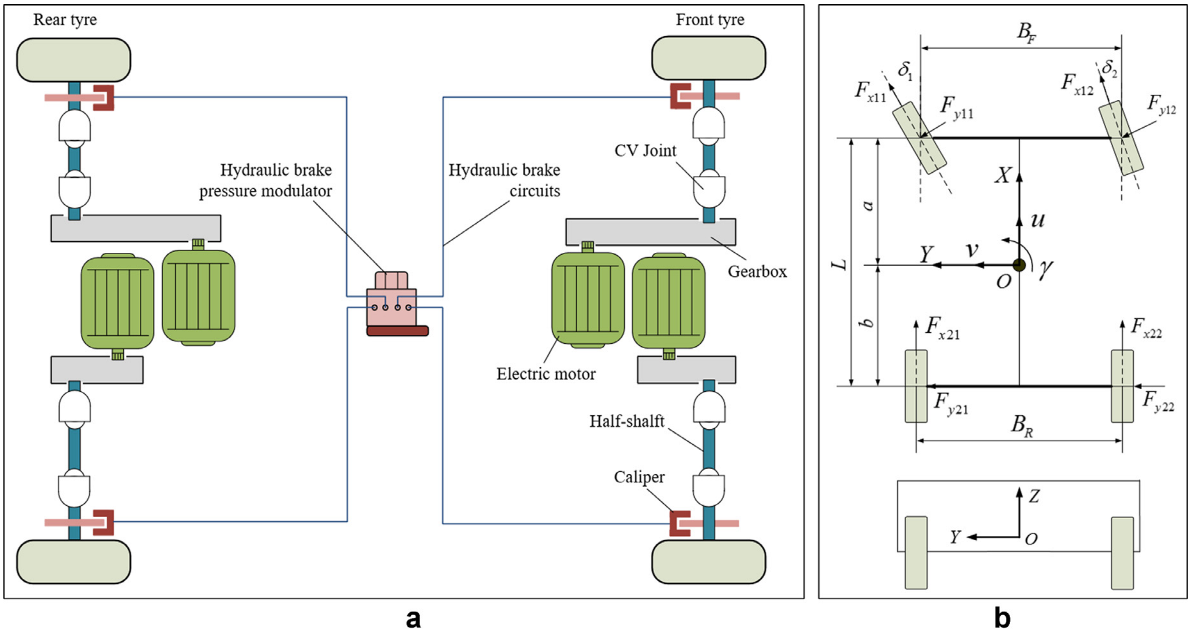

Fig. 1. (a) Structure of the regenerative and hydraulic blended braking system; and (b) vehicle dynamics model.

improving the stability of in-wheel-motor-driven electric vehicles. However, issues of vehicle stability for both longitudinal and lateral dynamics are of interest not only in emergency driving situations, but also during normal driving maneuvers, because they affect vehicle safety and performance. For example, consider the case of directional instability during normal straight-line braking [20,21].

For an electric vehicle with independently controlled motors, because of the design and manufacturing factors, the steady-state error of each motor output torque and the torsional characteristics of left and right drivetrains can be different. This results in asymmetrical output characteristics of electric powertrain systems on the same axle [11,22–24]. Therefore, during a normal straight-line deceleration, an unexpected yaw moment would be generated, affecting the directional stability of the vehicle. If not corrected by the driver, the vehicle may pull towards one side of the road. This phenomenon is referred to as brake pull. To eliminate the unexpected brake pull, approaches have been investigated through optimization of drivetrain layout and active steering control for conventional vehicles [5,25]. However, directional stability enhancement during regenerative deceleration for an electric vehicle with individually controlled motors can be even more difficult, because of the complex cooperation mechanisms between multi-actuators, which include motors and hydraulic brakes.

In this study, the directional stability problem of an over-actuated electric vehicle during normal straight-line blended braking is addressed. The main contributions of this work are three-fold: (1) the mechanism of the directional instability of an electric vehicle during straight-line regenerative deceleration is analyzed; (2) two novel brake blending control methods, namely the hydraulic brake compensation based method, and the regenerative brake robust control-based method are proposed, ensuring vehicle's handling and directional stability during normal straight-line braking; (3) under the proposed regenerative brake robust control-based approach, the regeneration efficiency is increased as well, improving vehicle's energy efficiency.

The rest of the paper is organized as follows. System models, including the vehicle dynamics, tire, electric powertrain, and hydraulic brake models, are developed in Section 2. The impact of torque imbalance on electric vehicle directional stability is analyzed in Section 3. To further improve the electric vehicle's safety and performance, two blended braking control algorithms are developed based on half-shaft regenerative torque estimation in Section 4. Simulations of the proposed control algorithms are carried out during normal straight-line braking processes in Section 5, which is followed by the concluding remarks in Section 6.

2. System modeling

Fig. 1(a) presents the overall structure of the regenerative and hydraulic blended braking system considered in this study. Four on-board electric motors are installed individually on the left and right sides of the two axles of the vehicle. During deceleration, regenerative braking torques, which are transmitted by the drivelines, are exerted onto the axle. In the meantime, hydraulic braking torque of each wheel is modulated by the hydraulic modulator. Blended braking torque governs the overall braking operation.

2.1. Vehicle dynamics

A model for vehicle dynamics with eight degrees of freedom was built in MATLAB/Simulink. The *OXYZ* coordinate system and the vehicle model, shown in Fig. 1(b), originate at the center of gravity of the vehicle. The eight degrees of freedom of the vehicle model are as follows: the displacements of the vehicle along *OX* and *OY*; the yaw angle of the vehicle around *OZ*, which is represented by γ; the rotations of the four wheels and the steering angle δ of the front wheels. The equations for vehicle motions are as follows [3].

The longitudinal motion of the vehicle can be represented as:

$$m(\dot{u} - v\gamma) = (F_{x11} + F_{x12})\cos\delta - (F_{y11} + F_{y12})\sin\delta + F_{x21} + F_{x22} - \frac{C_D A}{21.15}(3.6u)^2 \tag{1}$$

The lateral motion of the vehicle can be described as:

$$m(\dot{v} + u\gamma) = (F_{x11} + F_{x12})\sin\delta + (F_{y11} + F_{y12})\cos\delta + F_{y21} + F_{y22} \tag{2}$$

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