

Use of Electric Driveline for a Cooperative Braking Strategy

Mustafa Ali Arat, Hans-Martin Duringhof, Johan Hagnander, and Eduardo L. Simoes
 NEVS

ABSTRACT

This paper presents a brake control strategy with a novel approach to the allocation of actuator effort in an electric vehicle. The proposed strategy relies on a combination of the conventional hydraulic braking system and the electric machine in order to improve braking performance. The higher response frequency of the electric machine is paired with the additional braking torque employed by the hydraulic brakes using an integrated control allocation strategy, which allows for a constant availability of a faster and more accurate modulation of both wheel torque and wheel speed. Therefore, the availability of an electric machine as a fast longitudinal actuator yields to an improved tracking of the desired wheel slip, especially when compared to the hydraulic actuators used in traditional braking applications. As a result, this strategy leads to a clear and considerable reduction of the braking distance, removes the need for a hydraulic modulator and thereby also removes the disturbing feedback on the brake pedal in hard braking maneuvers. The control algorithm is implemented and tested with numerical analysis using a plant model identified and validated with experimental data from a NEVS electric vehicle.

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INTRODUCTION

The powertrain in electric vehicles (EVs) provides an additional mechanism for braking. It has been successfully utilized for the so-called regenerative braking in various designs, which is one of the key technologies to improve efficiency as a result of energy recuperation when braking [1]. Nevertheless, the current EVs are also equipped with a frictional braking system employing conventional actuators without exception, therefore the participation of braking with the electric powertrain requires a specific strategy to be developed. This issue has been studied widely, mainly considering solutions for regenerative braking, and currently there are two general approaches. First approach is based on utilizing the electric motor output to produce brake torque until it satisfies a deceleration requirement, and employs frictional brake when this torque cannot fulfil the requirement. Second mode uses electric motor and frictional brake forces synchronously to increase or decrease resulting brakes when the pedal is pressed. Based on these two solutions, a large number of scenarios have been proposed, not only to enhance efficiency of energy regeneration but also to satisfy the regulations.

This study focuses on the synthesis of a cooperative electric powertrain braking strategy with conventional friction brakes, especially for anti-lock braking system (ABS) controls. In the relative literature so far, the issue has been categorized regarding hardware and software requirements. The synthesis of the required hardware has already been realized in several successful electrified vehicles. For instance, the regenerative strategy employed in Toyota Prius is based on an electro-hydraulic braking system (EHB) [2]. On the other hand, Honda adopts a new brake chamber configuration to realize this

combination [3]. As for the software synthesis, the original equipment manufacturers (OEMs) has taken a more simplified approach. The common practice dictates that the friction brake controller takes over and disables any brake force applied by the electric powertrain [4, 5]. Although this simplification works in practice, research has been carried on as the potential for improvement has been known.

Tur and Ustun have proposed a scenario employing pure regenerative brake force with proportional–integral–derivative (PID) control when the ABS works [6]. Their simulation results with a quarter car model show that such a ‘regenerative ABS’ has benefits in a panic stop, however, the limited regenerative capacity on modern EVs does not allow any massive application. Another scenario based on a similar idea was proposed by Okano et al. [7]. They have embedded three executive modes inside the controller, namely ‘PQ method’, ‘frequency selection by filter’, and ‘model following control’. The electric motor works more accurately and swiftly than the hydraulic braking system, which is used to approach the optimum ABS control. The performance of the algorithm has been validated through simulation and road testing. Peng et al. [8] proposes a logic-threshold ABS strategy to regulate hydraulic brake force and a fuzzy logic strategy to regulate regenerative brake force. The strategy has also been proved to be stable and effective through simulation and road testing.

As such, more numbers of similar studies can be listed from literature, which are generally focusing on the regenerative mechanism. The regenerative mechanism provides clear advantages for energy efficiency however it needs to be limited regarding the battery capacity, current state of charge (SoC), etc. On the other hand, the electric powertrain braking has additional advantages such as

considerably faster response time and closed-loop feedback of applied torque that can improve braking performance significantly. In this study, the authors propose a strategy to optimally integrate electric powertrain and friction braking to utilize these advantages and investigate possible improvements of braking performance.

The rest of this document is structured as follows. Section 2 summarizes the mathematical models considered for the vehicle and actuators. In Section 3, the control strategy developed for the integration of the two actuation mechanisms is described. Section 4 lists the results of the test scenarios conducted numerically using a simplified vehicle model. Finally, Section 5 includes the conclusions from this investigation.

MATHEMATICAL BACKGROUND

In this section, a simplified model of the quarter car undergoing a braking manoeuvre is developed (Fig. 1). This model is then used for system analysis and design of the control laws. The model assumes zero steering input and ignores lateral and vertical dynamics related to the vehicle motion. Then the dynamic equation for the wheel rotation is given as:

$$J\dot{\omega} = F_t R_w + (T_e - T_b) \quad (1)$$

where T_e and T_b represent the engine/driving torque and the braking torque respectively. Applying a net torque due to the sum of the driving and braking to a pneumatic tire produces a tractive force F_t at the tire-road contact patch [9]. The driving torque produces compression at the tire tread in front and within the contact patch. Consequently, the tire travels less distance than it would if it were free rolling. Similarly, when a braking torque is applied, it produces a tension at the tire tread within the contact patch and at the front. Because of this tension, the tire travels more distance than it would during free rolling. This phenomenon is called the deformation slip or wheel slip (λ) [10], and mathematically, the wheel slip is defined as [11]:

$$\lambda = \frac{V - R_w \omega_w}{\max(V, R_w \omega_w)} \quad (2)$$

where R_w is the wheel radius, ω_w is the angular velocity of the wheel and V is the linear velocity of the vehicle. The tractive force in eq. 1 can be approximated by the load applied on the wheel F_z and the friction coefficient between the tire and the road:

$$F_t = F_z \mu(\lambda) \quad (3)$$

and the friction coefficient is typically represented as a function of the wheel slip. In this study a Burckhardt model [12] is used for this representation:

$$\mu(\lambda) = c_1(1 - e^{-c_2\lambda}) - c_3\lambda \quad (4)$$

The coefficients c_1 , c_2 and c_3 are used to modify the model for different road conditions such as dry asphalt or gravel.

Actuator Dynamics

The control strategy proposed in this study uses the conventional hydraulic actuators typically available on vehicles today that provides friction braking, and the electric machine as the general source of motion in EVs. The following sections summarize experimental results to obtain the step response of these actuators and the approximate transfer function yielded out of these results.

The hydraulic actuators are tested using a brake-by-wire set-up that is implemented over an existing commercial ABS. Given a brake request of 80kPa in a step function, the actuator response was measured and used to compute a first order transfer function approximation with the cut-off frequency of $f_{ch} = 8\text{Hz}$.

$$f_h = \frac{\omega_{ch}}{s + \omega_{ch}} \quad (5)$$

Figure 1 indicate the input, the measurements and the transfer functions responses.

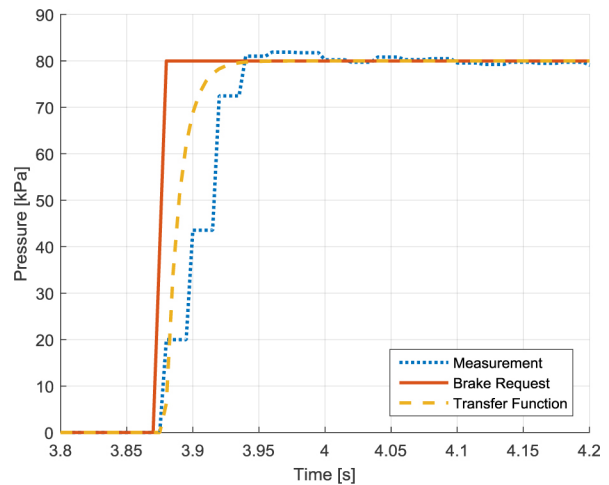


Figure 1. Step response for the hydraulic actuators

The electric machine was modelled using a similar approach, according to experimental data, a first order transfer function with the cut-off frequency of $f_{ce} = 36\text{Hz}$ was found to be a good approximation to model the torque response. As the response dynamics depend on the rotational speed at which the torque request is executed, the cut-off frequency here presented is considered as the average between the results obtained for a variety of rotational speeds.

CONTROL STRATEGY

The conventional algorithms for ABSs today utilize varying sensor information regarding the state of the vehicle and the individual wheels to respond accordingly. Typical states include the velocity for the wheel and the vehicle to observe the slip (eq. 2) and the acceleration/deceleration of each wheel to have an indirect measure of the contact forces. The modern ABSs undoubtedly provide a strong

basis for safety, however their performance can be improved as indicated in a number of studies so far [15, 16, 17]. A common conclusion in these studies is that the performance of such control systems can be improved utilizing available means for providing feedback of the forces acting on the system. The electric machine in the modern EVs is a very promising platform for such an improvement as the control structure for the electric motor motion intrinsically uses the torque measurements acting its output shaft. As a result, the control strategy proposed here focuses on the use of this torque feedback and introduces a hybrid structure to define an overall torque request to be implemented by the available actuators. In what follows, an optimal control allocation method is utilized to divide the workload between the hydraulic (Figure 1) and electric systems based on their response frequencies.

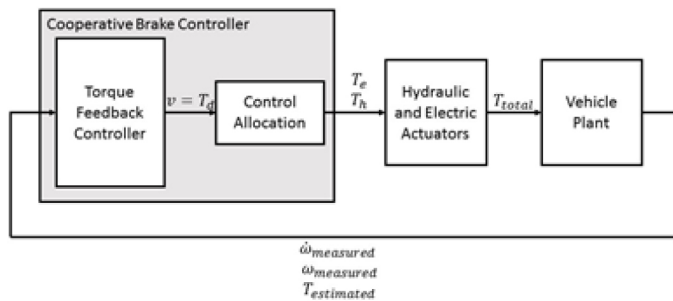


Figure 2. Complete system block diagram.

Torque Feedback Controller

State Flow

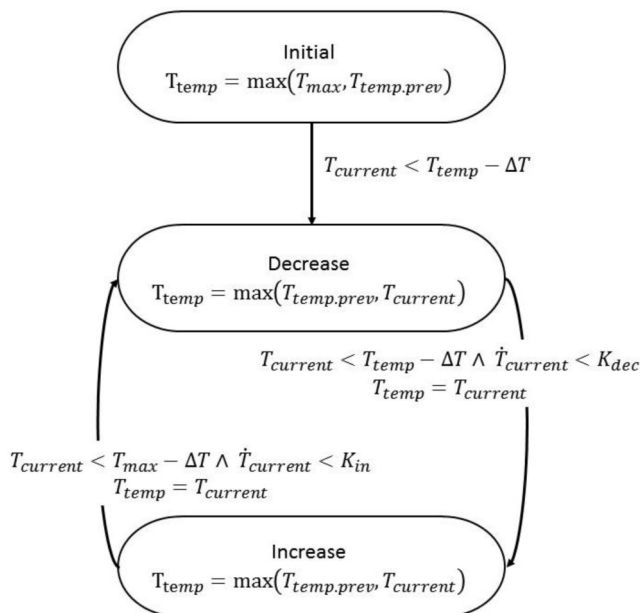


Figure 3. Torque feedback controller state-machine

The higher level of the torque feedback controller as seen in Figure 2 is the state machine that is described in flow chart in Figure 3. The conditions for transitioning between states and actions taken within a state can be visualized inside each state block and mainly consist in the update of the variable T_{temp} that is a reference for the transitioning decision process. Additionally, when inside the Increase and Decrease

States (referring to the increase and decrease of the applied torque) a continuous controller is activated, providing the hybrid nature of the controller implemented.

For the purpose of simulations, the initial state has been taken as constant ramp on the brake pressure that is emulating driver input in a hard brake maneuver.

The previously presented flow chart can be formally described as a discrete system, as seen in eq. (6). There T_{max} refers to the maximum detected torque, T_{temp} is a temporary torque reference, $T_{temp,prev}$ is the T_{temp} defined in the previous sampling time, $T_{current}$ refers to the currently estimated torque measurement and $\dot{T}_{current}$ to its derivative.

$$T_{desired}(t) = \begin{cases} T_{initial} & \text{if } T_{current} > T_{temp} - \Delta T \\ T_{increase} & \text{if } T_{current} > T_{temp} - \Delta T \text{ and } \dot{T}_{current} > K_{in} \\ T_{decrease} & \text{if } T_{current} > T_{temp} - \Delta T \text{ and } \dot{T}_{current} > K_{dec} \end{cases} \quad (6)$$

In this state-machine there are three parameters that can be changed according to the vehicle and operating state: ΔT , K_{in} and K_{dec} . The first parameter, ΔT , changes the sensitivity of the controller to change between the different states, a small value leads to fast changes between the states that might result in false triggering, while a value too big leads to slow permutation between states and might lead to instability and wheel lock. The second parameter, K_{in} , defines the boundary condition for the current torque derivative to allow a change between the Increase to the Decrease state. The third parameter, K_{dec} , similarly to the second, defines the boundary condition for a change between the Decrease to the Increase state.

Continuous Controller

The continuous P-controller used during the increase and the decrease stage share the same architecture, which can be visualized in Figure 4.

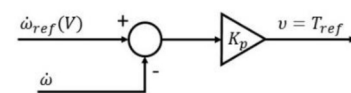


Figure 4. Continuous controller block diagram

Given a wheel acceleration dependent on the current speed, a wheel acceleration error is determined and the virtual control (Total torque desired) is calculated with a proportional gain.

$$T_{initial} = K_{ramp} t \quad (7a)$$

$$T_{increase} = K_{p_{increase}} (\dot{\omega}_{ref}(V) - \dot{\omega}) \quad (7b)$$

$$T_{decrease} = K_{p_{decrease}} (\dot{\omega}_{ref}(V) - \dot{\omega}) \quad (7c)$$