

Experimental Study on Continuous ABS Operation in Pure Regenerative Mode for Full Electric Vehicle

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ABSTRACT

Anti-lock braking functions of electric vehicles with individual wheel drive can be effectively realized through the operation of in-wheel or on-board motors in the pure regenerative mode or in the blending mode with conventional electro-hydraulic anti-lock braking system (ABS). The regenerative ABS has an advantage in simultaneous improvement of active safety, energy efficiency, and driving comfort. In scope of this topic, the presented work introduces results of experimental investigations on a pure electric ABS installed on an electric powered sport utility vehicle (SUV) test platform with individual switch reluctance on-board electric motors transferring torque to the each wheel through the single-speed gearbox and half-shaft. The study presents test results of the vehicle braking on inhomogeneous low-friction surface for the case of ABS operation with front electric motors. The performed tests confirm considerable reduction of braking distance and accurate tracking of the reference slip as compared with the vehicle braking without ABS. Hence the pure electric ABS can be considered as an efficient alternative to anti-lock braking systems with friction brakes only.

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INTRODUCTION

The Beneficial beneficial effect of electric powertrain on reduction of power consumption and emissions is confirmed both by numerous studies and results of electric vehicles (EV) operation available on the market. However, the use of electric motors in vehicle architecture has also an added value for vehicle safety and driving comfort and can provide functions of ride comfort control. In particular, Murata [1] and Akaho et al. [2] reported that (i) a purely electric brakes can shorten the braking distance up to 7 % on the ice road as compared with a conventional hydraulic brake system and (ii) can reduce the level of heave and roll acceleration of the EV body. These results were obtained for Toyota's all-wheel drive electric vehicle with in-wheel motors.

The use of individual electric motors, as on the vehicle configuration from [1, 2], opens also the way to fundamentally new methods of anti-lock braking, where the wheel slip control can be realized through the operation of electric motors applying negative torques. Such approach extends the operational ABS frequency due to higher dynamics of electric motors compared to the hydraulic brake systems. With brake system architecture utilizing electric and hydraulic brake systems, the ABS operation can be realized either by share of the

generated brake torque demand between them or by pure operation of each subsystem. The combined operation of both variants of anti-lock brake systems is adequately covered in different studies proposing various approaches to the ABS blending [3, 4, 5]. However, the specific methods of the pure electric ABS actuation are still rarely discovered in the research and technical publications. Within this context, in particular, Zhou et al. [6] have investigated the method of pulse width modulation of in-wheel brushless direct current motors with its subsequent implementation in the ABS controller. Other relevant study has been introduced by Mi et al. in [7], where the iterative learning control method is proposed for an electric ABS.

The validation of developed ABS control tools is limited by model- or hardware-in-the-loop tests in the most of mentioned and other related publications. The experimental investigation of electric vehicle braking with a pure electric ABS is insufficiently addressed in the analyzed literature. To partially narrow this gap, next sections of the work present tests results of the aforementioned test platform equipped with electric ABS in the pure regenerative mode. The tests were performed at Ford Lommel Proving Ground (Belgium) in low-friction road conditions. The following parts of the paper outline



Documents

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the architecture of experimental vehicle, overall ABS control structure and working principles, specifications of the testing track and test procedure, and analysis of obtained results.

SPECIFICATION OF THE TEST VEHICLE

The test vehicle used in the presented study is built on the basis of sport utility vehicle (SUV) Range Rover Evoque within the framework of the European project E-VECTOORC [8]. The powertrain architecture includes individually controlled switched reluctance on-board electric motors connected to the wheels through the single-speed gearbox and the half-shaft. The left and right motors are arranged in pairs for each axle as depicted on Fig. 1.

Motor characteristics of each motor are: peak torque / power 200 Nm / 100 kW (for maximum 30 s); nominal torque / power 80 Nm / 35 kW; maximum speed 15000 rpm. The single-speed gearbox has a crawl ratio of 1:10.5 through a 2-stage reduction by helical gears. The powertrain elements installed on the vehicle demonstrator are represented on Fig. 2 and 3.

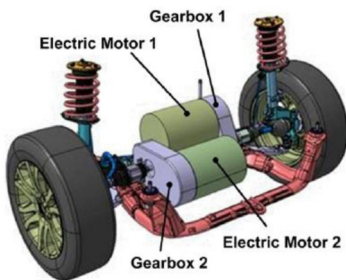


Figure 1. Axial components of electric powertrain [9]



Figure 2. Front wheel drive elements



Figure 3. Rear axle drive elements

The vehicle has both the decoupled electro-hydraulic brake system [10] actuating the friction brakes and the regenerative brake system represented by the electric motors. The electric motors produce negative torques in a braking mode.

ABS DESIGN

The anti-lock braking control is developed in accordance with the system architecture presented on Fig. 4.

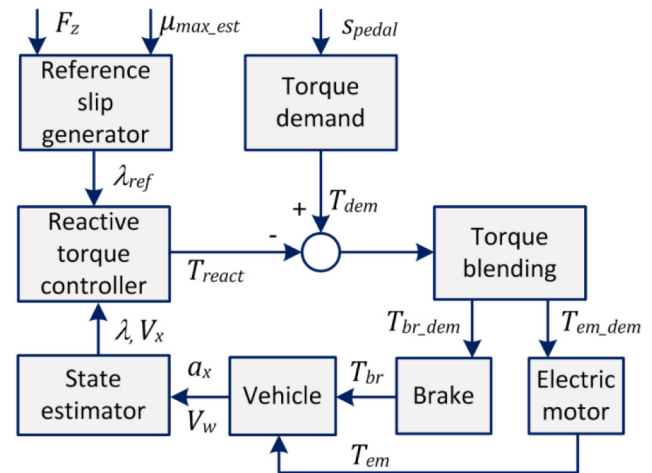


Figure 4. ABS architecture

The proposed ABS utilizes the gain-scheduled proportional-integral direct slip control with feedforward and feedback control contributions. Such approach realizes the functions of *continuous* ABS control aimed on accurate tracking of the wheel slip ratios and as a result provides maximal forces on each of the wheels with significantly reduced level of tyre force oscillations. The brake torque demand T_{dem} for each wheel is generated in accordance with the driver control action measured as the brake pedal travel s_{pedal} . The brake torque demand is added up with the reactive torque T_{react} computed by the reactive torque controller, which uses the reference wheel slip λ_{ref} , the actual wheel slip λ and the vehicle velocity V_x as input parameters. The reference wheel slip is calculated in the reference slip generator taking into account the wheel loading F_z and the estimated maximum value of the tire-road friction coefficient μ_{max_est} . The resulting torque from T_{dem} and T_{react} are processed in the torque blending block allocating the torque shares for the electro-hydraulic brake system T_{br_dem} and the electric motors T_{em_dem} . These torque values are realized by the corresponding actuators, and then the actual torques T_{br} and T_{em} are applied to the corresponding wheels. The wheel slip ratios and the vehicle velocity are observed using the wheel velocities V_w , vehicle acceleration / deceleration a_x and actual wheel torque T_w .

More detailed description of the ABS algorithm is given in the previous SAE technical paper of authors [11].