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Wheel slip control for all-wheel drive electric vehicle with compensation of road disturbances

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Abstract

Development of wheel slip control for ground vehicles with electric powertrain belongs to the one of the most challenging problems in automotive control engineering. The realization of the wheel slip control for anti-lock brake (ABS) and traction control (TC) systems is a more complex task in the case of vehicles designed both for on-road and off-road conditions. In this situation a control strategy must be able to handle different tyre-surface contact dynamics. Within this context, the presented paper introduces the wheel slip control and corresponding ABS algorithm developed for the all-wheel drive sport utility electric vehicle with four individually controlled on-board motors. The proposed paper, in particular, includes: Analysis of state-of-the art solutions for off-road ABS; Description of the developed ABS architecture based on the direct wheel slip control with predictive and reactive wheel torque contributions; Results of ABS operation in the vehicle simulator software with special attention given to the braking on rough surface; Procedure of the system tuning using hardware-in-the-loop technique; Experimental results of the system testing on the vehicle demonstrator in real operational conditions. The theoretical and experimental outcomes have confirmed improved functionality of the developed wheel slip control in terms of vehicle safety and energy efficiency.

Keywords: Slip control; Electric vehicle; Anti-lock brake system; Rough surface; Off-road vehicle

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1. Introduction

Vehicle dynamics control (VDC) systems such as anti-lock braking systems (ABS) or electronic stability control (ESC), being a mandatory equipment for road cars and trucks, are receiving nowadays more and more attention in the area of off-road transportation, e.g. sport utility vehicles (SUV), agricultural machines, military vehicles etc. First of all, this is caused by permanent strengthening of requirements to the vehicle safety. An analysis of relevant studies shows a number of corresponding engineering solutions for off-road vehicle dynamics control. In particular, the rollover and yaw moment control systems, which are already well-established for the implementation on passenger cars and commercial trucks, are receiving further enhancements for the operation in off-road conditions (Hegazy and Sandu, 2014; Hopkins and Taheri, 2011; Wang et al., 2009). However, it should be mentioned that many publications in this area address only specific

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mobility machines like six-wheel drive/steered vehicles (An et al., 2008; Jackson et al., 2002; Kim et al., 2012).

Among other goals, most of VDC systems involve the braking control as an important functional task. In relation to the off-road mobility, the ABS and the braking control in general are being investigated now more intensively as before. For instance, recently published studies in this field introduce the ABS design for ground vehicles operated on deformable and rough surfaces (Hamersma and Els, 2014; Morselli et al., 2010). Next interesting and important topic is the integration of the braking and suspension control to improve the off-road mobility and comfort (Els et al., 2013; Kaldas et al., 2011; Reul and Winner, 2009; Shao et al., 2007). However, many specific problems like the adaptation of the ABS control to the operation on rough and deformable surfaces are still not sufficiently explored in the research publications. Many studies in this field refer to the classical work of Watanabe and Noguchi (Watanabe and Noguchi, 1990) investigating the compensation of road disturbances during the ABS operation. The proposed compensation mechanism is based on the analysis of sensor-based parameters of wheel dynamics, in particular, the wheel acceleration. A similar approach has been also discussed in Li et al. (2007), where the rough road texture is identified by processing of the wheel speed sensor data with high-pass filters implementing different cut-off frequencies.

The problem of ABS design for a vehicle driving on deformable, uneven or highly rough surfaces becomes more challenging in the case of an electric powertrain, where individual wheel motors can operate in the regeneration mode. Specific character of such configuration is that, on the one hand, electric motors offer improved operating performance as brake actuators in terms of torque modulation in comparison to friction brake systems; on the other hand, the ABS implies more complex control architecture under simultaneous fulfillment of requirements to (i) braking performance, (ii) regeneration efficiency and (iii) reliable and failsafe operation. The latter requirement determines that the friction brake system remains on the electric vehicle and should operate in parallel with the electric motors. Hence, the electric vehicle with individually controlled wheel motors potentially has several brake modes: pure electric braking (with the electric motors only); operation of the friction brakes only; combined/blended braking. However, the analysis of research publications shows that pure electric braking is rarely investigated, especially in context of serial production vehicles (Ivanov et al., 2014).

The listed arguments have motivated the study introduced in the next sections. In particular, they illustrate the design process of advanced brake control systems for the ground vehicle (i) operating on rough and deformable surfaces and on roads with inhomogeneous friction properties and (ii) having four individually controlled electric motors. The presented work shows both simulation and experimental results in order to validate the feasibility and functionality of the new method of continuous wheel slip control for a full electric vehicle with special attention given to the braking mode. The objectives of the paper are: (i) introduction of the vehicle layout and the wheel slip controller architecture; (ii) validation and verification of the controller functionality in a braking mode with the use of model- and hardware in-the-loop (HIL) simulation; (iii) analysis of experimental results obtained for the vehicle braking in real test conditions on the proving ground.

2. Vehicle configuration

The packaging features of a typical sports utility vehicle allows to implement various configurations of electric powertrain architecture. However, several requirements were of special importance by specifying the target powertrain discussed in the presented study: to realize the all-wheel drive and to guarantee required performance both for on-road and off-road mobility. As a result, individually controlled electric motors for each wheel are considered for the target vehicle. The technical data of the vehicle and its main components are:

- Total weight of 2250 kg.
- Four switched reluctance electric motors; peak torque/power (30 s): 200 Nm/100 kW; nominal torque/power: 135 Nm/42 kW; maximum speed: 15,000 min^{-1}.
- Motor transmission – 2-stage reducer with helical gears; gear ratio: 1:10, 5; half-shaft torsional stiffness: 6500 Nm/rad.
- Tyres 235/55R19.

A more detailed description of electric motors and drivetrain components is given in Theunissen et al. (2014). Fig. 1 shows the vehicle demonstrator and the packaging of powertrain components.

Although the developed base brake and wheel slip controllers are mainly designed for the actuation of the electric motors, the safety requirements specify that a conventional brake system actuating the friction brakes must still be installed on the vehicle. For this purpose the vehicle demonstrator is equipped with the decoupled electro-hydraulic brake system based on the TRW Slip Control Boost (SCB) system. Its basic diagram is depicted on Fig. 2. The SCB is coupled with other vehicle subsystems through two CAN connections. The Vehicle CAN enables embedding the SCB system into the vehicle architecture. The Private CAN is mainly used for status signals as well as the pedal travel and wheel speed signals. The single channel pressure control is applied both for the pure hydraulic and combined regenerative operational modes. The maximum hydraulic pressure, which can be realized by the SCB, is of 180 bar.

Hence, the wheel slip controller of the vehicle demonstrator can operate in three basic operational modes: pure electric, pure hydraulic and combined/blended braking. Further variations are possible by applying the modes independently to the front or rear axle of