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Recent Advancements in Continuous Wheel Slip Control

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Abstract. The paper presents an overview of continuous wheel slip control (WSC) methods as the part of anti-lock braking system (ABS) for the several vehicles configurations with friction brakes and electric motors. Performance of proposed WSC design variants using several control techniques has been experimentally evaluated for three different test vehicles: Sport Utility Vehicle (SUV) with decoupled electro-hydraulic brake (DEHB) system, SUV with four individual on-board electric motors (OBM), and compact vehicle with four individual in-wheel motors (IWM). Obtained results demonstrated that proposed continuous WSC variants provide a simultaneous effect on braking efficiency and ride quality as well as robust operation in various road conditions. Presented summary provides outlook on future perspectives of the continuous WSC and compares its status with conventional rule-based ABS systems.

Keywords: Wheel Slip Control, Electro-hydraulic brakes, Electric Motors.

1 Introduction

The wheel slip control is a key element of active vehicle safety systems such as anti-lock braking, traction control, torque vectoring, and electric stability control. The approaches to the WSC design can be conditionally separated into methods based on discrete (or rule-based) and continuous logic.

The discrete logic consists in modulation of the wheel torque depending on allocated control thresholds. These thresholds are usually empirically defined or identified from wheel dynamics during the ABS braking event and correspond to the optimal area of the friction-slip curve. The wheel torque modulation refers to cyclic activation of control phases for the increase, decrease or hold of the brake torque. This kind of WSC logic is discussed in many reference sources, as for example in [1-3].

Emergence of matured technologies for brake-by-wire systems and vehicle electrification made possible implementation of continuous WSC algorithms as a reasonable alternative. This is caused by a wider bandwidth and quicker time response of brake-by-wire systems and electric motors as compared to conventional brake systems. The main distinction of continuous WSC algorithms compared to the rule-based is a continuous tracking of reference wheel slip λ*. The λ* is usually being estimated as the value corresponding to the maximum of tyre-road friction μ for given driving conditions.

One of the first studies on the continuous WSC was introduced in [4]. The relevant method realizes the model-based control with local linearization and gain-scheduling based on the linear-quadratic regulator for the vehicle with electromechanical brake actuators. To improve the control quality, automatic initialization of the controller state based on an estimate of actual road conditions and automatic resetting were considered. To simplify the definition of the wheel slip dynamics, another approach is proposed in [5, 6], where the slip ratio observer and estimator are composed without the use of the vehicle velocity. The corresponding WSC demonstrated sufficient performance on the low-μ road conditions with relative high reference slip ratio. Author in [7] investigated the closed-loop proportional-differential WSC and evidenced that the controller will be stable when the assumption of local linearity of a μ-λ-curve takes place. The linearized feedback control has been used in [8], showing stable WSC behaviour both in stable and unstable areas of the μ-λ-diagram.

The overviewed methods can be implemented on continuous traction and braking controllers of both conventional and electric vehicles. In the case of electric vehicles, for the presented wheel slip formulation tools, a controller can be based on various logic such as PID, sliding mode, computational intelligence technique, etc. A further analysis of recent studies dedicated to the corresponding WSC of electric vehicles, performed by the authors of this paper, showed that there are no unambiguous recommendations in favour of one or another approach. The commonly occurring solutions in this regard belong to the model-based and model-predictive control [9, 10], and various implementations of PID control [11, 12]. However, most the analysed studies are limited by the applications for small-sized cars and simplified consideration of driveline dynamics.

To demonstrate eventual challenges and observed advantages and functionality of the continuous WSC, the presented study provides a review of original controllers developed by the authors for three different vehicle configurations. A set of control methods used in this study is summarized in Table 1.

Table 1. Control methods implemented in continuous WSC systems on different vehicle demonstrators.

SUV with on-board electric motors	SUV with decoupled electro-hydraulic brakes	Compact vehicle with four individual in-wheel motors
PI	PI Sliding Mode PI (SMPI) Integral Sliding Mode (ISM) Nonlinear model predictive control (NMPC)	Variable Structure PI (VSPI) First-order Sliding Mode (FOSM) Integral Sliding Mode (ISM) Continuous Twisting Algorithm (CTA)

2 WSC for SUV with Four Individual On-board Electric Motors: PI Control with Brake Blending

Known disadvantages of the existing ABS methods has motivated authors to initiate a set of research projects focused on continuous WSC and its application to various brake actuators. As the first research object, SUV with four individual highly dynamic on-board electric brakes has been selected. In the corresponding powertrain architecture, used in this study, each on-board motor is connected to the wheel through the transmission and the half-shaft as shown on Fig. 1. The vehicle has the total weight of 2117 kg and uses 235/55 R 19 tyres. The electric motors are of switched reluctance type with peak torque / power 200 Nm / 100 kW, nominal torque / power 135 Nm / 42kW, and maximum speed 15000 m^{-1}. The motor transmission is represented by a 2-stage reducer with helical gears and gear ratio 1:10,5. The torsional stiffness of a half-shaft is 6500 Nm/rad.

Fig. 1. SUV demonstrator with individual on-board motors.

Proposed WSC strategy uses PI control with anti-windup contribution and the proportional and integral parts scheduled according to the estimated vehicle velocity V_x. Implementation of the anti-windup and a set of modifications in PI itself provides more gentle control in the stable area of tire force – wheel slip diagram and agile reaction in unstable part of this tire characteristics. Another feature of this design is the blended WSC using both on-board electric motors and friction brakes as actuators. This was achieved by a proper allocation of the low-frequency torque demand to the friction brakes and high-frequency demand to the regenerative brakes. This study was limited by the use of measured vehicle velocity instead of using estimation and by consideration of fixed reference wheel slip $\lambda*$, which was placed at the optimal wheel slip. Mathematical formulation and detailed description of this controller can be found in [13].

The vehicle testing has been performed at the testing track with road surface composed of basalt tiles, which was continuously wetted by water sprinklers. Average road coefficient of friction at this surface was around 0.2. Application of the developed WSC strategy has demonstrated precise wheel slip tracking at $\lambda*$ with near-to-optimum values. Direct comparison with serial production vehicle of this type with conventional EHB has revealed that up to 20% braking distance reduction by application of continuous WSC strategy and high-performance electric brake actuators can be achieved on the same track. Enhancement of the braking performance can be seen on the vehicle deceleration profile presented in Fig.3. These tests have shown visible reduction of the initial peak at the beginning of braking event and smooth and precise wheel slip tracking during the whole braking. Such behaviour has led to the reduction of the vehicle longitudinal jerk up to 76% compared to the serial production vehicle with EHB and rule-based ABS [14].

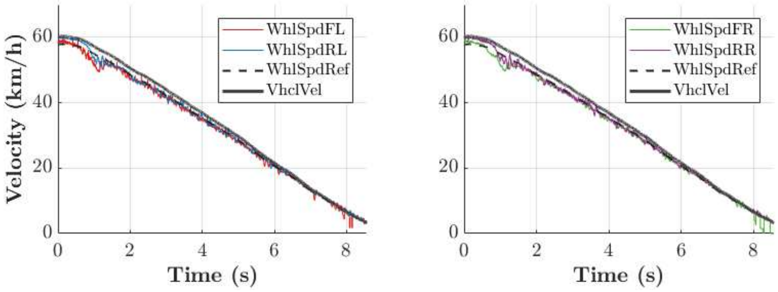

Fig. 2. ABS braking with continuous PI-WSC on low-μ surface.

These effects have been achieved by the high-frequency actuation of the torque at electric brakes. Brake blending strategy during this manoeuvre was configured to the maximally possible use of electric brakes. In the investigated case, friction brakes were engaged proportionally to the vehicle velocity reduction to hold the vehicle in standstill position at the end of the braking test.

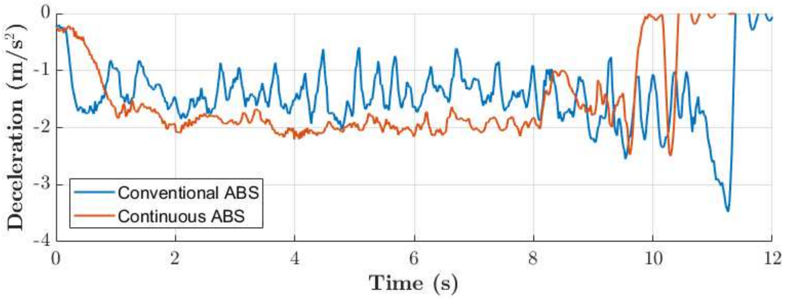

Fig. 3. Vehicle deceleration with conventional and continuous ABS.

However, braking tests on surfaces with higher μ showed that the PI-control requires separate tuning for these surfaces and cannot be considered as robust. These observations motivated next studies, where the authors investigated a possibility to achieve the consistent WSC operation independently from the road surface. Besides that, applicability of continuous ABS on decoupled electro-hydraulic braking system has been analysed. The corresponding results are discussed in next section.

3 WSC for SUV with Decoupled Electro-hydraulic Brakes: Sliding Mode Control and Reference Slip Adaptation

Promising results obtained during the testing of continuous ABS with highly-dynamic on-board electric brakes and observed issues with the system robustness lead to the further investigation of advanced continuous WSC strategies on the vehicle with decoupled electro-hydraulic brake system. In this part of the study, the baseline SUV from Section 2, but with conventional powertrain, has been used. Developed control algorithms were implemented on the electro-hydraulic decoupled brake-by-wire system based on TRW SCB technology [15]. Its performance is considerably higher, as compared to conventional electro-hydraulic braking systems, thanks to the use of high-pressure accumulator, which can keep 180 bar. This ensures a relatively quick build-up of the calliper pressure providing 85–200 ms shorter rise time during the step pressure request [16].

Considering the observed robustness issues, two new control methods were designed for WSC: Sliding Mode PI (SMPI) and Integral Sliding Mode (ISM) control. Both strategies handle variation of the vertical tire load and road coefficient of friction as the external disturbances. Based on the Lyapunov stability analysis and knowledge about level of disturbances, corresponding control gains were analytically chosen to provide stable operation of WSC. Additionally, reference wheel slip adaptation strategy as well as vehicle velocity estimation were introduced and included in the control architecture. This allowed producing an ABS control, which does not utilise non-conventional sensors, and providing more objective experimental assessment of the developed WSC strategies.

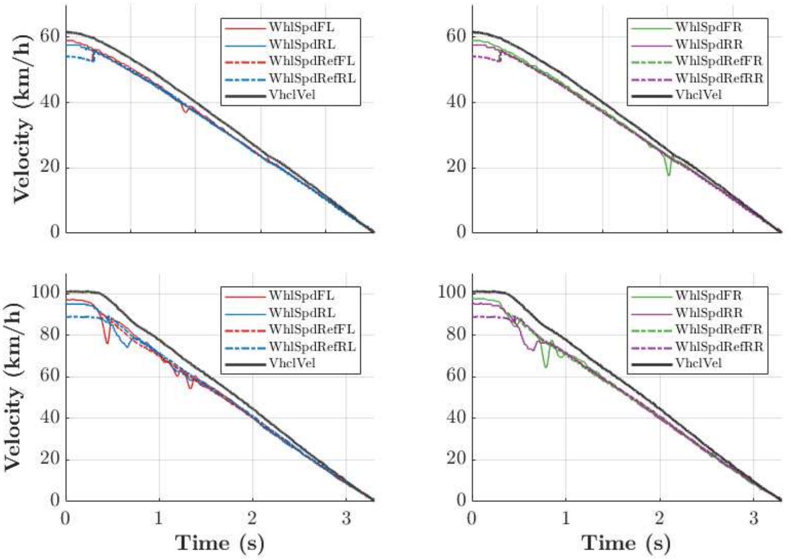

Fig. 4. ABS braking with ISM-WSC on low-μ (top) and low-μ (bottom) surfaces.

Analysis of braking manoeuvres on both high-μ and low-μ surfaces confirmed high efficiency of all implemented control methods. Across proposed PI, SMPI and ISM strategies, ISM has demonstrated the most robust operation both in high-μ and low-μ friction conditions, as shown in Fig. 4. In general, proposed continuous WSC variants demonstrated up to 31 % (on low-μ) and 9 % (on high-μ) reduction of the braking distance as compared to industrial rule based WSC realised on the same decoupled electro-hydraulic brake system. It should be also noted that the vehicle jerk has been minimised by each continuous WSC variant, but more smooth dynamics has been achieved with the ISM. Interested can refer to [16] for more detailed description of the control algorithms and analysis of experimental results. Robust operation of WSC based on SM control methods has motivated authors to conduct a comparative study of WSC strategies based on SM and variable structure approaches. Outcomes of this research are presented in next section.

4 WSC for Compact Vehicle with Four Individual In-wheel Electric Motors: Comparative Analysis of Sliding Mode Control Methods

The use of in-wheel motors is one of crucial factors for the further developments in the field of electric vehicles. From this viewpoint, the role of IWM as the actuators of WSC deserves particular attention. Authors of this paper have performed a corresponding feasibility study using a compact vehicle FPEV2-Kanon of the University of Tokyo with full mass 847 kg and individual IWMs providing maximal torque 500 Nm for the from wheels and 530 Nm for the rear wheels, Fig. 5. In-wheel motors ensure a quicker torque response and have higher system bandwidth compared to the brake actuators in Sections 2 and 3.

Fig. 5. Vehicle demonstrator FPEV2-Kanon with four individual in-wheel motors.

Therefore, one of the main targets of this feasibility study was to compare four control methods including the approaches, which potentially can meet issues with the implementation on on-board motors or electro-hydraulic brake-by-wire systems. In this regard, Variable Structure PI (VSPI), first order sliding mode (FOSM), ISM and continuous twisting algorithm (CTA), recently described in [17] and [18], were applied to the WSC formulation.

Experimental results of braking with these WSC variants on an inhomogeneous low-μ surface have demonstrated that all controllers provide comparable braking performance, Fig. 6.

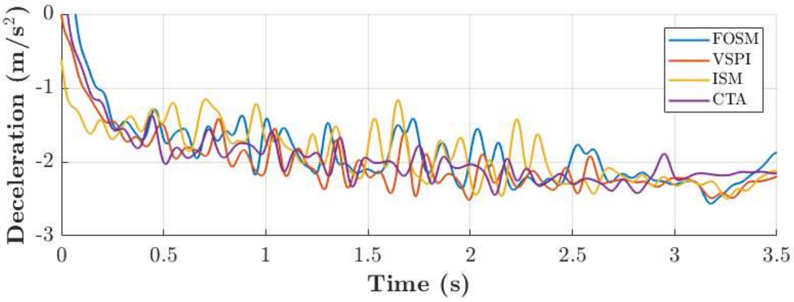

Fig. 6. Vehicle deceleration profile with FOSM-, VSPI-, ISM- and CTA-WSC.

Despite insignificant differences in braking performance, FOSM and VSPI control strategies have produces higher chattering in the demanded torque. In VSPI case high deviations from the reference wheel slip λ* caused by lack of robustness and, therefore, oscillations in longitudinal following to unpleasant ride properties.

Important observation in this study was that CTA strategy has provided very smooth wheel slip tracking, Fig.7, which is leading not only to the enhancements in the braking performance, but also confirms potential applicability of this method not only with IWM, but, as in case of ISM, also to the decoupled electro-hydraulic brake systems

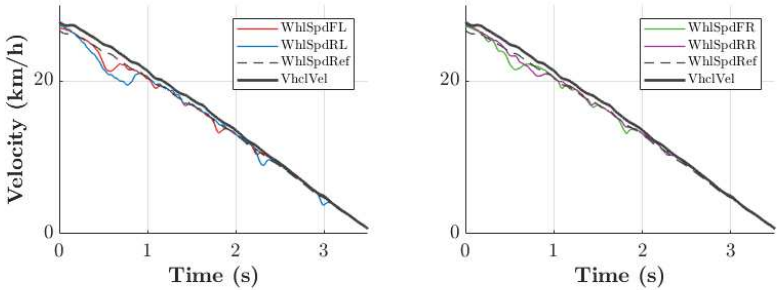

Fig. 7. Braking diagrams: ISM WSC on low-μ (top) and low-μ (bottom) surfaces.

From the analysis provided in Sections 2-4 it can be concluded that application of the SM control strategies allows resolving the main milestone with robustness, which did not allow continuous WSC strategies to find wide application in serial production ABS systems. Next Section discusses alternative solution for the continuous WSC by application of advanced sensor technologies and MPC control methods.

5 WSC for SUV with Decoupled Electro-hydraulic Brake System: Nonlinear Model Predictive Controller with the Use of Wheel Load Information

A further approach to the continuous WSC design with the brake-by-wire system lies in the use of the wheel load information for formulating the control parameters. Wheel load information supports an easier estimation of the maximum of tyre-road friction coefficient. Currently, load-sensing bearings or intelligent tyres allow reconstructing the wheel forces with enough accuracy and bandwidth and, thereby, enable the application of these technologies in the near future for the vehicle dynamics control purposes [19]. From another side, wheel load information helps to avoid a large plant-model mismatch in the case of model-based approach. Therefore, it allows to implement nonlinear MPC with the high accuracy of predictions, and therefore, a nonlinear model can be used for predictions. In the considered case, the model in nonlinear MPC describes the wheel slip dynamics of each wheels; additional four augmentation equations allow controlling the torque and the chassis longitudinal dynamics. The presented study used ACADO Toolkit as modelling environment to define the optimal control problem with a prediction horizon 20 ms and sampling time 5 ms. More details regarding this controller design can be found in [19].

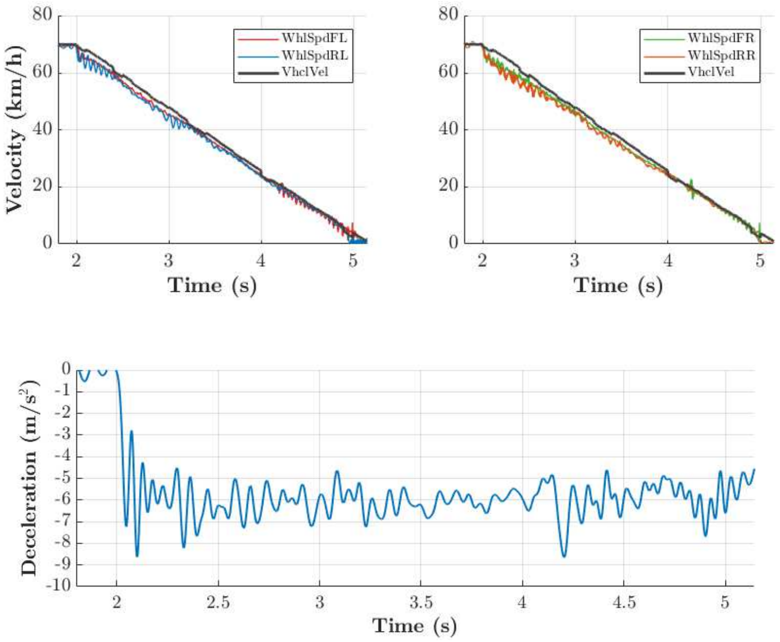

Fig. 8. ABS braking on uneven road with MPC.

The assessment of WSC performance has been evaluated for smooth various constant and varied friction conditions: dry /wet asphalt and show, friction jump, and uneven road. For this paper, the example of the braking with WSC on uneven road (red bricks) is shown on Fig. 8. It was observed that this variant of the controller allows overcoming a well-known effect of the brake performance reduction for uneven roads when an essential amount of noise, which can be injected to the system by the road profile. The use of wheel load information in this case contributed to achieving a satisfactory braking performance with better overall efficiency as compared to the rule-based logic used for the comparison [20].

6 Paper Summary

Observed advantages		
	Conventional rule-based ABS	*Continuous ABS*
Efficiency	Suboptimal operation	Wheel slip is kept close to the optimal point
Control law	Sophisticated control based on the set of semi-empirical rules	More compact formulation of the control laws
Calibration	Sophisticated tuning procedure due to the presence of high number of calibration parameters	Significantly reduced number of tuning coefficients allowing faster tuning of the system
First peak	Significant deviation from optimal value	First peak can be significantly reduced depending on the type of brake actuator
Robustness	Robust to variation of the road friction	Robustness to the variation of road friction is achievable using advanced control methods
Brake blending	Requires significant changes in the control approach	Proposed filtering procedure allows direct implementation on combined brake systems without changes in the control law
Drawbacks		
Velocity estimation	Cyclic application of the brake torque allows	Periodic unlock of the wheels is still necessary to obtain vehicle velocity; presence of longitudinal deceleration sensor is necessary
Adaptability	Allows robust detection of the rapid road surface variation	Cases with transition from low-µ to high-µ road surfaces can lead to underbraking
Perspectives		
Force measurements	Use of the kinetic wheel parameters (wheel slip speed or wheel slip) obligates the system to operate in cyclic mode for obtaining proper vehicle velocity values	Such technologies as intelligent bearings can completely change the paradigm of ABS control providing close-to-optimal continuous system operation without knowledge on velocity

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