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ADVANCED BRAKING SYSTEM CONTROL PROTOTYPING USING NETWORKED HARDWARE-IN-THE-LOOP TECHNIQUE

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ABSTRACT – Control functions for the base-braking and emergency braking situations are important element of the vehicle active safety and have high requirements to robustness. The corresponding control algorithms should be reliable, provide sufficient level of system adaptiveness and be able to reject external disturbances. This demands not only the well-organized controller from the theoretical point of view, but also its systematic experimental validation. Moreover, effects and factors, which can potentially produce deterioration of braking system control functions, should be properly taken into account in the simulation and during the experiments. Another important factor is that brake control systems have a closed-loop operation with the tyre-road interaction, and its operation is accompanied by such complex effects like (i) variation of disc/pad friction coefficient and (ii) brake hysteresis. This produces strong demand on extension of the conventional testing facilities for the braking system control evaluation. Therefore, besides the part of the control system design, this paper represents possible advancement of hardware-in-the-loop testing procedure for development and validation of braking system control functions.

INTRODUCTION

Current tendencies of braking systems development are moving towards x-by-wire architecture and enhancement in actuator performance. Such solutions allow simultaneous enhancement in vehicle safety, comfort and energy efficiency by avoiding traditional trade-offs between these characteristics. Due to these reasons, the brake-by-wire architecture has a demand on new arts of control systems design and requires more sophisticated control algorithms.

Potential of advanced braking system control has been recently investigated in a number of publications. In particular, the paper [13] has addressed the minimization of pitch oscillations during the braking. The corresponding approach has been proposed for a decoupled electro-hydraulic brake system by offline optimization of the braking forces distribution that allowed achieving better ride comfort. Another system variant related to the improvement of longitudinal ride comfort has been investigated in paper [15] for the control algorithm aimed at reduction of longitudinal vehicle jerk during service braking. Next example considers simultaneous operation of different braking actuators (e.g. electric motors and hydraulic brakes) to receive benefits in terms of energy efficiency and braking performance. This example is discussed in paper [16], where the reduction of braking distance on 20% was achieved by application of continuous anti-lock braking control strategy and proper blending of the braking torque between electric motors and hydraulic brakes. Another kind of functional advancement is introduced in [14]. This study has proposed to attenuate judder oscillations in electro-mechanical brakes using an adaptive control approach. A number of studies are also investigating the functionality of the braking systems in the control loop beyond a stand-alone operation. For instance, the paper [19] shows the integration of several active chassis systems in framework of integrated chassis control, which resolves the known issue with control effects overlap of over-actuated systems.

Such shift in principles of braking system control design must be supplemented with appropriate modifications of prototyping procedure. Next section of this paper will introduce investigations, where influence of several physical phenomena can produce deterioration of braking performance. By means of brake-by-wire systems they can be attenuated, but as close-loop control system it requires using of more complex testing procedure, demand in which will be shown on some examples. After this section proposed prototyping technique will described in details.

ADVANCED BRAKING SYSTEM CONTROL

To fully utilize the potential of x-by-wire systems, the control algorithm should consider several physical phenomena, which can produce negative influence on the braking performance. In recent years Automotive Engineering Group from Technische Universität Ilmenau performed several investigations aimed at understanding of physical processes, which influence the performance of braking control systems. In this section some of results will be discussed and demand in further development of testing techniques will be shown.

Authors in [18] indicated that variation of the coefficient of friction in brake pads and disc can distort the brake pedal feel characteristics. In the same paper the algorithm on attenuation of such sort of disturbances was proposed through estimation of vehicle state and parameters and establishing the correction factor for compensation of forces generated by variation of brakes coefficient of friction, road grade and vehicle mass. The testing procedure has included (i) separated investigation of the coefficient of friction variation on the dynamometric test rig, and (ii) validation of the vehicle state and parameter observer on the real vehicle. Further, all these outcomes were used to test the disturbance attenuation algorithms on the hardware-in-the-loop test rig with installed decoupled braking system. As it can be seen, validation of such closed-loop algorithms demands a multi-domain real-time testing procedure.

In respect to the judder oscillations of brakes and their compensation, the paper [14] has investigated possibilities of the electro-mechanical and electro-hydraulic actuators to attenuate low-frequency disturbances caused by disc thickness variation (DTV). At the test rig with decoupled EHB system reference information about DTV data has been utilized and allowed to prove applicability of developed control algorithms.

In the paper [3] investigation of brakes behaviour and its influence on anti-lock braking system has been discussed. It offers combined testing technique, where two test rigs, namely hardware-in-the-loop and dynamometric test rig, were physically coupled. It evidently showed influence of the physical processes in friction brakes on the control performance producing phase shifts in ABS. This research was aimed not at investigation of physical phenomenon, but at showing demand in coupling/networking of test rigs.

Influence of tire characteristics on ABS performance was studied in [17]. It shows considerable changes in the braking performance due to variation of tire pressure. In absence of reliable tire models for simulation, prototyping and adjustment of the ABS could be done before the road tests if braking system and tire testing rig can be coupled together.

Outcomes of aforementioned papers in relation to the concept of networked testing environment were summarized in Figure 1. In these studies, authors were forced to perform

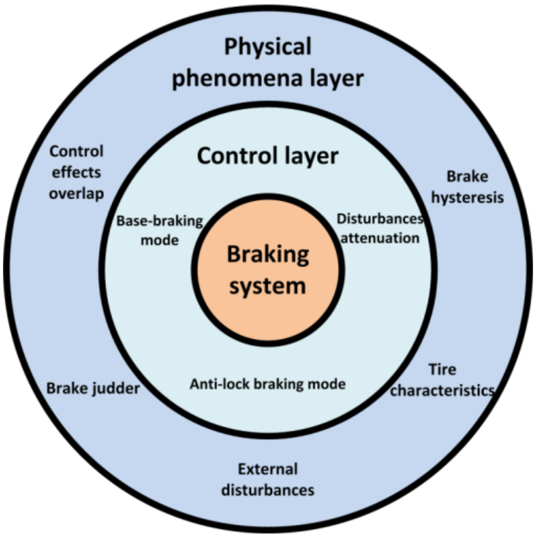


Figure 1: Factors influencing on braking system control performance

testing procedures separately from each other or move straightforward to the road tests. It applies several limitations on testing of control algorithms, which use reference experimental results instead of direct information receipt from vehicle subsystems. This gap can be fulfilled by networking the testing environment for validating closed-loop control algorithms and investigation of physical phenomenon influence on brake control systems. In the next section of paper, it will be discussed how to break some certain limitations in development, testing and validation procedures though new experimental approach.

PROTOTYPING TECHNIQUE

The proposed methodology for developing of braking systems is based on coupled test rigs, embedded hardware, and real-time simulation tools. This technique was already investigated partially in some previous publications, for instance, in [3, 7, 8, 10, 11, 12]. However, until today there are no common philosophies or standards to describe this methodology. In order to clarify and to ensure a consistent definition of terms, the concept is explained and its motivation is given in more detail.

Motivation – Despite the increasing mechanization, mechatronization and complexity of subsystems in ground vehicles, the technical benefits converge rapidly. The development process of vehicle components and other technical products are still designed in stand-alone operation mode. By coupling relevant vehicle subsystems in numerous physical, computing, electrical and relevant cyber-physical domains the benefits for the system design will be significantly multiplied. Consequently, e.g. on the field of active safety and driver assistance systems, a higher effect can be achieved if all the subsystems are coordinated. For such systems there is a strong requirement for novel testing techniques and developing environments to improve their functionality.

Besides that, it is expected that this methodology will enable a higher level of basic research on multidisciplinary subject areas under reproducible conditions. Accordingly complex relationships (e.g. between brake friction behaviour and vehicle dynamics control) can be investigated. For these reasons, new methods, procedures and standards are desirable to drive future advanced system for ground vehicles preceded.

Clarification of concept – As it was already mentioned, the anticipated prototyping technique is established on networked test rigs across different domains. Beyond that, more tools and equipment are needed to perform advanced functionality, simulate virtual vehicular systems or evaluate software code. Commonly these developing and testing platforms are considered into the three main categories: hardware-in-the-loop, software-in-the-loop and model-in-the-loop [9]. In [12] it was proposed by authors to extend these elementary categories to a test-rig-in-the-loop concept to close the gap between embedded computing systems and physical test beds respectively. Thereby, the “In-The-Loop” convention refers to the feedback of the response back to the input. The major terms are defined as follows:

Model-In-The-Loop (MiL) – On the very early stage of designing cyber-physical systems simulation models are used for verifying basic functionality and behavior. These simulation models are executed on higher leveled software systems which are abstractly related to the actual system.

Software-In-The-Loop (SiL) – For software evaluation, a compiler generates a software code out of the simulation model or parts of it. The generated code is running instead of the higher leveled simulation software or their parts.

Hardware-In-The-Loop (HiL) – To execute the developed functionality under realistic conditions like peripheral equipment or stimulus signals, the compiled software code is loaded and running on a real-time embedded system. The HiL is regularly used for measuring, (signal) processing, communicating or controlling tasks. HiL is also called processor-in-the-loop (PiL).

Test-Rig-In-The-Loop (TRiL) – Finally, at the end of the developing chain, a Test-Rig-In-The-Loop is needed to verify and proving the functionality. TRiL represents the physical part of the developed systems, e.g. a brake system.

Table 1: Overview of closed-loop prototyping techniques

In-The-Loop Category	**Model-In-The-Loop**	**Software-In-The-Loop**	**Hardware-In-The-Loop**	**Test-Rig-In-The-Loop**
Real-time capability	No/partially	No/partially	yes	Yes
Developing stage	very early	early	proceeded	late evaluation
examples	Matlab/Simulink IPG CarMaker	Microtec PowerPC C Compile GNU C Compiler	dSpace RT-hardware AVL InMotion	Brake Dynamometer Vehicle Chassis Dynamometer
application	vehicle simulation model	Emulation of protocols/functionality	CAN I/O, Voltage I/O, signal processing	ABS, ESP, brake dust investigations, NVH

X-In-The-Loop – Superordinate all featured In-The-Loop techniques are summarized in X-In-The-Loop. With this background XiL is a real-time holistic networking requiring interdisciplinary approach (Physics, IT, Control Engineering, Systems Analysis, etc.). In this form all XiL participants are modular combinable to optimize the outcomes of testing procedures. Therefore, a generic real-time interface is required to exchange configurations, parameters, inputs and outputs between applicants. A substantial flexibility is expected from this approach because all participants come/derived from different developing stages. This allows a rapid prototyping through all developing stages.

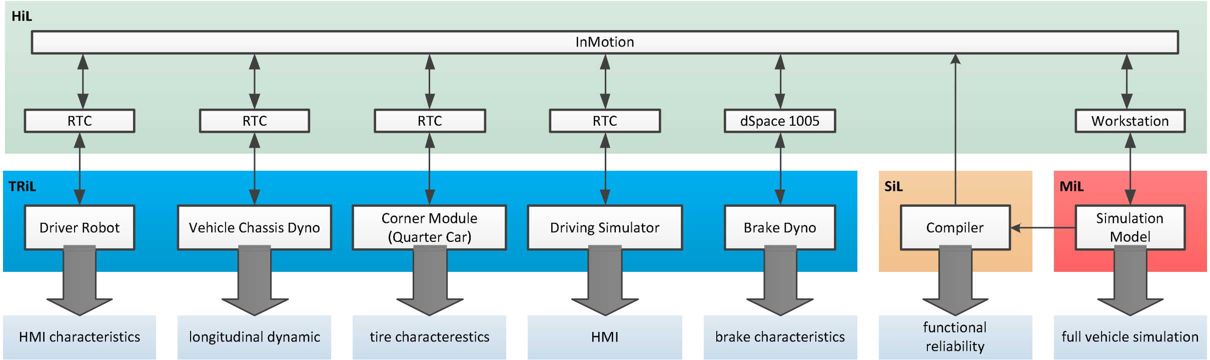


Figure 2: Overview of the superordinate XiL configuration at the Technische Universität Ilmenau

Use case configurations for prototyping advanced braking systems

Currently Technische Universität Ilmenau is implementing the proposed prototyping technique. As a very first step, a Vehicle Chassis Dynamometer (AVL), Brake Dynamometer

(Link Engineering), Embedded System (dSpace) and Real-Time Simulation (InMotion/IPG-CarMaker) should be connected. Initially, studies show a significant benefit in application of this testing technique.

Nevertheless, there are also still challenges in case of various number of degrees of freedom. In respect to study about braking systems prototyping, only one brake dynamometer was used, i.e. single DOF. But, for complex investigation like ABS performance for full vehicle dynamic, one DOF for each wheel is essential. Hence, the single reference is overdetermined. This become challenging due to an exchange between coupled real-time systems of different domains. For this issue a method for transformation of relevant system state from single to multi-degree of freedom was investigated. Figure 3 shows the basic conception, which will be explained using the example of brake systems. As illustrated, all wheel speeds are used to transform them to only one reference. This single reference is used to control the dynamometer. For controlling the brake pressure the pressure of the master cylinder is used. The responding braking torque and the temperature are reverse transformed and feedback to the RT-Simulation.

EXPERIMENTAL RESULTS

The performed experiments aimed at showing demand in coupling of the testing facilities for development of active control functions for brake systems. In this experiment following testing facilities were used: (i) AVL InMotion platform with IPG CarMaker software, (ii) dynamometric test rig and (iii) hardware-in-the-loop test rig equipped with electro-hydraulic brake system. The principal scheme of test rigs communication operating as closed-loop system is shown in Figure 3.

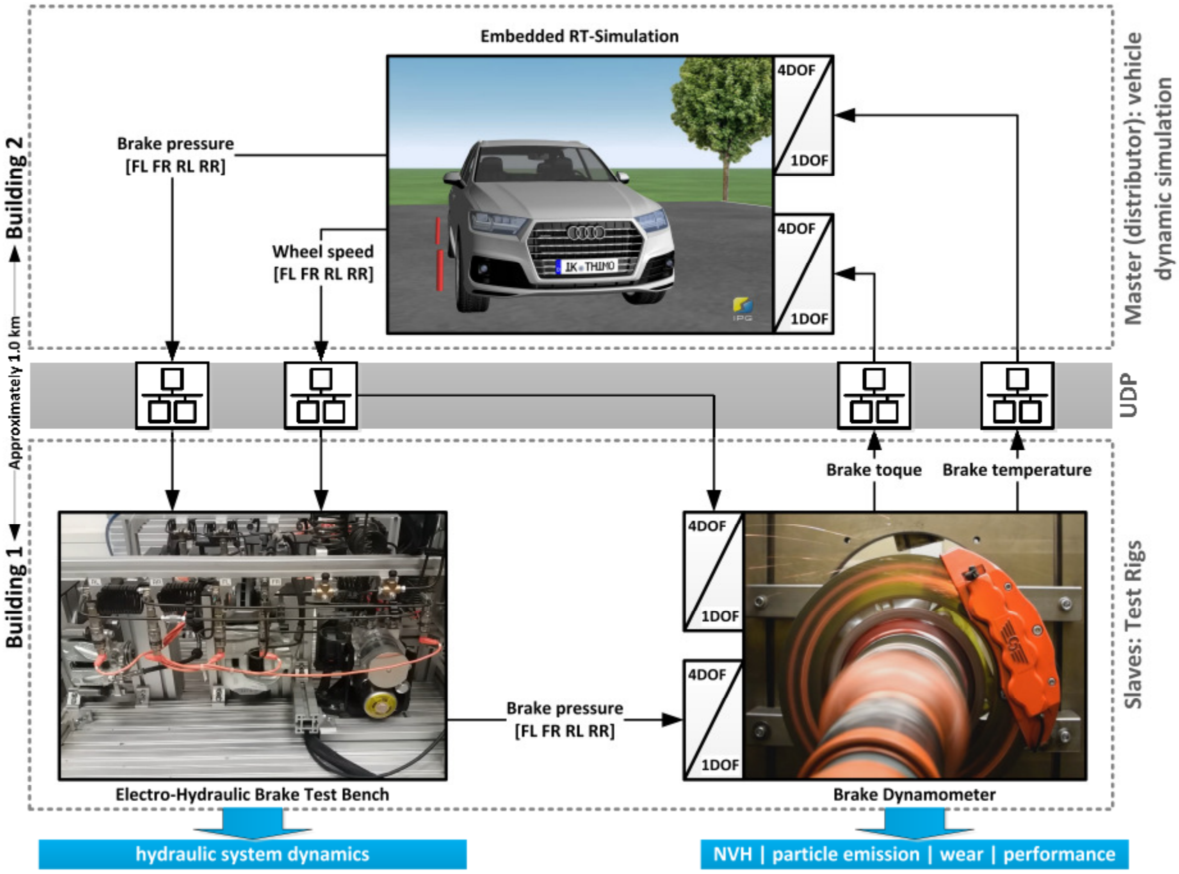


Figure 3: Brake Dynamometer coupled with an Embedded RT-Simulation

Considering known communication technologies and industrial communication standards for networking controller units, sensors and actuators, it is suggested to connect real-time platforms with Ethernet protocol. The Ethernet standard covers a high bandwidth and low communication latency, as it is represented in Figure 4. Due to this reason the proposed XiL environment was connected via User Data Protocol (UDP).

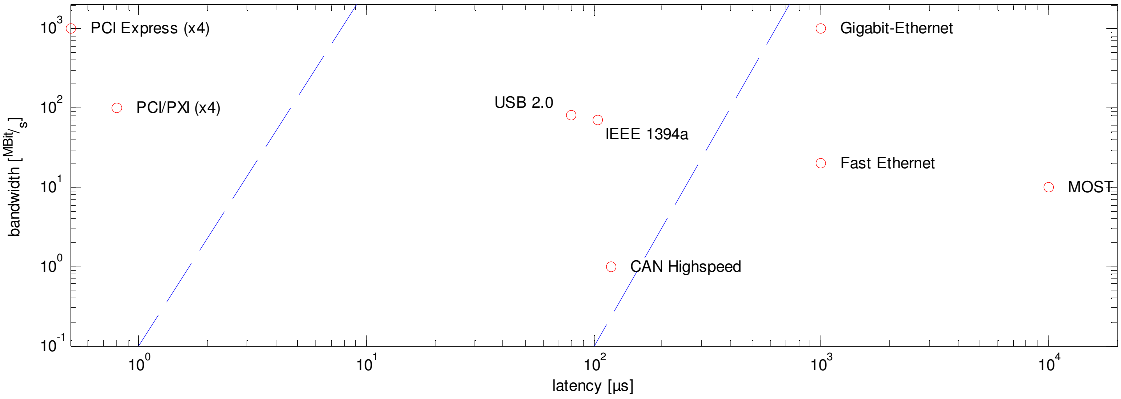
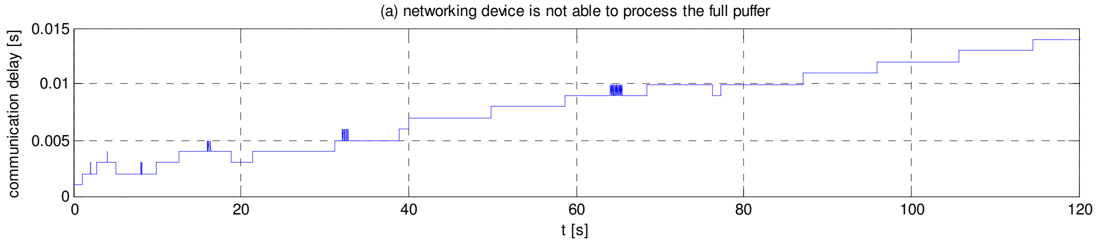


Figure 4: Performance of common communication standards

To investigate the performance of the communication network, aforementioned test rigs from different physical domains were crosslinked and the most remote of them (AVL InMotion platform and dynamometrical test rig) are located in different buildings with a distance of approximately 1 km. Real-time platform and control PCs at each end have an appropriate networking device, which supports Ethernet communication. According to the use case description in Figure 2 the Real-Time-Master (AVL InMotion) distributes reference inputs, namely braking pressure demand and wheel speed, to other participants (Slave) in the XiL Setup. The Slaves respond with an input for the Master-Device (in our case actual braking torque). In terms of communication quality, it was figured out, that the buffer of the networking devices accumulates rapidly after a few seconds, which leads to a steadily increasing communication delay, Figure 4. To solve this issue, it was decided to include pauses for handling the buffer processing as it is shown in Figure 5 (b). The processing of the network device buffer provides reliable real-time capability for frequencies up to 250 Hz. With such communication performance an adverse effect on operation of networked testing facilities is not expected. Therefore, this networking technique offers an opportunity in design and investigation of multi-domain physical and mechatronic systems, as the complete brake system (hydraulic lines, control, friction brakes etc.) in our case.



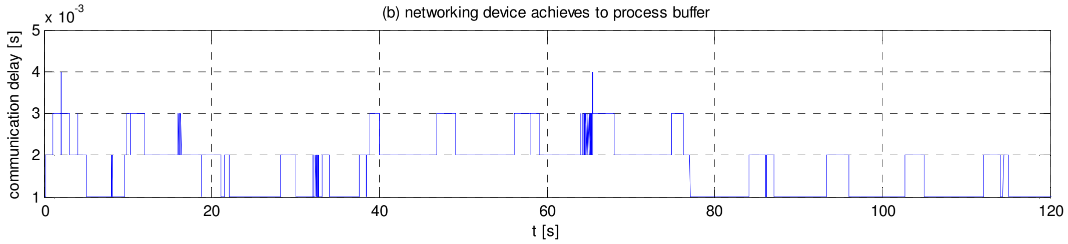


Figure 5: Communication delay of networking devices

The dynamometric test rig is used in this experiment to deliver information about the wheel torque to the simulation software at AVL InMotion platform. Compared to the simulation solutions, it considers tribological phenomena in brakes. As it known, the friction behaviour is depending on many factors such as the temperature of the friction area, relative velocity between friction components, pressure level (pressure distribution in the contact area) and pressure gradient.

Besides these factors, the brake system is characterized by hysteretic losses in friction pair, which cannot be neglected during design of brake control system. The commonly used mathematical models for modelling of hysteresis, like Preisach [20, 21], Jiles-Atherton [22] or Bouc-Wen [23, 24, 25], were initially designed for ferromagnetic problems and as any semi-empirical model does not consider all physical effects, especially if speak about brake system. Such approach in its initial form is not applicable for claims as a robust controller design.

As it is shown in Figure 7, the friction coefficient increases with rising temperature in the contact zone. However, it cannot be seen that the friction coefficient rises up to a maximum value. After this critical point the friction coefficient collapses until the so-called fading. In this case the organic ingredients of the friction linings become gaseous. Beyond, the friction coefficient indicates significant hysteresis behaviour while a dynamic actuating. In Figure 6 it is shown, that the hysteresis loop is getting wider with increasing actuating speed of the brake pressure. It is assumed that this behaviour is basically caused by tribological phenomena.

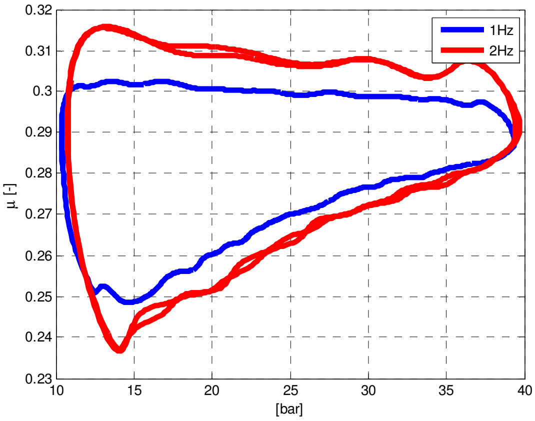


Figure 6: Impact of brake pressure gradient on Hysteresis characteristics of friction brakes (temperature, speed = const.)

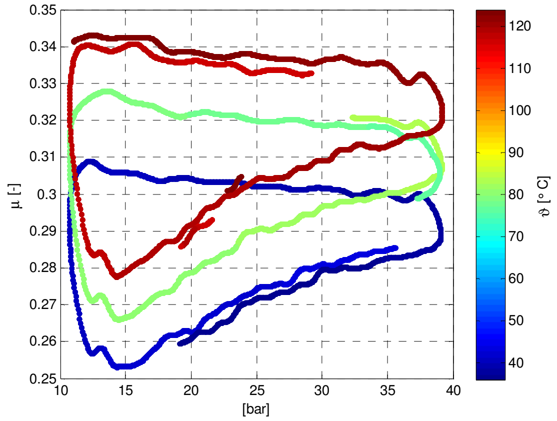


Figure 7: Hysteresis characteristics of friction brakes in dependence on temperature, brake pressure level and brake pressure gradient (speed = const.)

As it was mentioned in introduction, the ABS control is evidently dependent on the friction behaviour of brakes. The electro-hydraulic brake system at the testing platform uses the signals about brake pressure demand and wheel speeds realising ABS control functions. In the investigated cases it was found that hysteresis has a vital influence on braking performance during straight-line ABS braking especially on low-μ surfaces.

The velocity profile in Figure 8 clearly shows that braking time was increased on 2 seconds compared to the case, where hysteresis effects were not considered. It is caused by delays in brake torque generation and phase shifts in ABS control, as it is shown in Figure 9.

Such braking distance variation and deterioration of ABS function caused by influence of physical phenomena in brakes shows a strong demand in novel testing procedures. Proposed remote connection of test rigs provides new opportunities in combined testing techniques, where test rigs are located even on relatively long distance between each other.

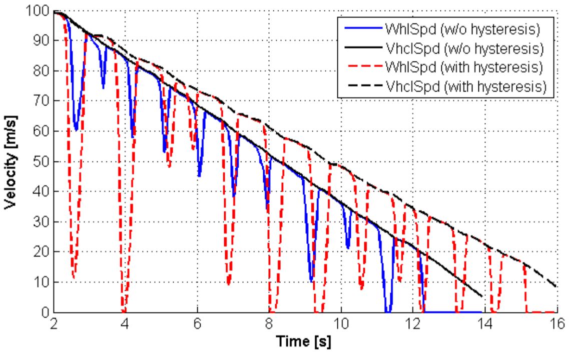


Figure 8: Speed profile for ABS braking without (blue line) and with (red line) consideration of brake hysteresis

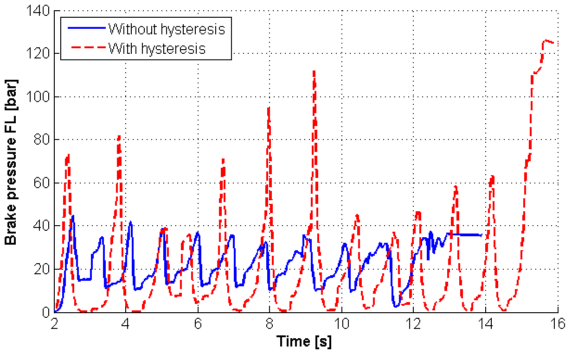


Figure 9: Brake pressure profile for ABS braking without (blue line) and with (red line) consideration of brake hysteresis

IMPACT AND CONCLUSION

Benefit – Obtained results in both areas of braking system control design and its testing by means of coupled test rigs show excellent opportunity to shorten the step between simulation and road tests with simultaneous enhancement of system performance, adaptability and robustness. Besides that, the research and investigation of complex coherent issues is under reproducible and steady conditions. By linking specialized testing, measuring, controlling and simulation systems will increase the precision of outcome of domain specified functionality, e.g. connected brake dynamometer with an embedded simulation and control system.

Future Challenges – Caused by growing quantity of prototyping platforms in the XiL-Environment and different locations the effort for preparation and configuration is increased. Moreover, the prototyping platforms such as test rigs (TRiL), embedded software (HiL/SiL) and advanced simulation (MiL) from different vendors are usually not applicable. An implementation of a centralized allocation system for distributing the configuration data will simplify the handling of information exchange and performing test procedures.

ACKNOWLEDGE

The proposed prototyping technique is represented on its initial stage of development and will be further evolved and tested in the following projects:

ACOSAR – The European founded project purpose the development a non-proprietary “Advanced Co-simulation Interface” (ACI) for RT-System integration and an according integration methodology, which shall be a substantial contribution to international standardization (FMI).

EVE – This work is supported by the European Union Horizon 2020 Framework Program, Marie Skłodowska-Curie actions, under grant agreement no. 645736. The research objectives are focused on the development of experimental tyre database that can be used in the design of new chassis control systems, advanced models of ground vehicles and automotive subsystems for real-time applications, and novel integrated braking control methods.

VISTA4F – This project is founded by the Thuringian Ministry TMBWK. Within the project, the use-case scenarios will be demonstrated.

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