

Development of an ESP Control Logic Based on Force Measurements Provided by Smart Tires

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ABSTRACT

The present paper investigates possible enhancement of ESP performance associated with the use of smart tires. In particular a novel control logic based on a direct feedback on the longitudinal forces developed by the four tires is considered. The control logic was developed using a simulation tool including a 14 dofs vehicle model and a smart tires emulator. Performance of the control strategy was evaluated in a series of handling maneuvers. The same maneuvers were performed on a HiL test bench interfacing the same vehicle model with a production ESP ECU. Results of the two logics were analyzed and compared.

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INTRODUCTION

Since its first appearance in 1995, ESP (Electronic Stability Program) started to be part of standard equipment of high-class and middle-class vehicles. Improvements of road safety associated with this device proved to be so effective that, in 2009 the European Parliament agreed to make ESP mandatory for all new vehicles. Based on the measurements of vehicle speed, yaw rate, lateral and longitudinal accelerations, steer angle, gas pedal position and braking pressure, the ESP system derives the vehicle desired motion, which is compared with the actual vehicle response. To minimize the difference between actual and desired motion, ESP independently brakes the four wheels and eventually controls the driving torque developed by the engine [19,20,21]. For instance, oversteer can be mitigated though the actuation of the callipers on the front outer wheel; on the contrary understeer could be prevented with the actuation of the brake on the inner rear wheel. Even if reliability and effectiveness of ESP have been definitively proved by experimental evidences, its performance could be further improved if additional information were provided to the control logic. In particular, in production ESP, some key parameters like vehicle sideslip angle, contact forces and friction coefficient have to be estimated, since they are not directly measured.

This paper investigates the possibility of enhancing the ESP performance thanks to the use of smart tires, i.e. tires with embedded sensors and digital-computing capability. In particular, a smart tire able to estimate contact forces and tire-

road friction coefficient is assumed [2-3]. Then ESP control logic has been modified including information provided by smart tires. Measurements of longitudinal contact forces are used to provide a direct feedback on the yaw moment actually generated by independently braking the four wheels. In addition, to fully exploit the actual capability of each tire, braking pressures are distributed based on the vertical loads acting on the four wheels.

Performance of the developed control logic was assessed using a simulation tool including a 14 dofs (degrees of freedom) vehicle model and a smart tire emulator allowing to take into account the effect of measurement frequency (one estimation per wheel turn), delay, resolution and estimation accuracy of the measures provided by this device.

Results of the implemented control logic were compared with the ones of a production ESP system. Production ESP results were obtained by interfacing the numerical model of the vehicle with a commercial ESP ECU (Electric Control Unit) using a HiL (Hardware-in-the-Loop) test bench.

SMART TIRES

In recent years, different types of smart tires were presented in technical literature [1,2,3,4,5,6,7,8,9,10,11,12]. Aim of these devices is to turn the tire into a sensor, able to provide direct information about the contact dynamics. Different technologies were proposed: optical devices fixed on the rim measuring the displacement of a LED installed on the inner liner [1], sensors embedded inside the tread based on surface acoustic wave (SAW, [5]) or on Hall effect [6].

Other authors used the tire structure itself as a sensing devices by measuring the variation of impedance between the steel wires associated with the change of spacing between them produced by contact forces [7]. Several smart tires presented in literature are built by fixing a measuring device directly on the inner surface of the tire; polyvinylidene (PVDF) based sensors are used in [8], flexible capacitive sensors in [9] and accelerometers in [1]. These approaches are all characterized by a simple installation of the sensor and by the direct measurement of the deformation of the tire structure.

The scheme proposed in [1,10,12] is considered in this study. It is based on a three-axial MEMS accelerometer directly glued on the inner liner; the adopted sensor presents the advantages of tiny dimensions, low weight, minimal impact on the production process, wide bandwidth, high reliability and the robustness required to withstand the impulses occurring when the sensor enters and exits the footprint. Data recorded and processed by smart tires are sent on board through an RF transmission. The smart tire considered in this work is able to provide data relevant to the contact conditions only once per revolution [2-3]. Through post-elaboration of the acquired acceleration signals it is possible to determine, among others:

- the dimensions and shape of the footprint area;
- the longitudinal and vertical load exerted on the tire;
- the angular speed;
- the maximum available friction coefficient (close to free rolling conditions).

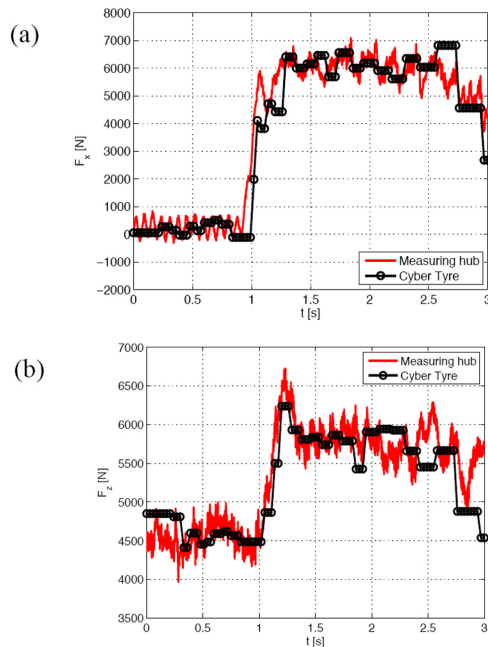


Figure 1. Comparison between measured and estimated loads during ABS braking maneuver: a) vertical force, b) longitudinal force.

While some of these quantities are directly determined from the shape of the accelerations (such as the dimensions of the footprint area), some others require sophisticated algorithms developed through preliminary indoor calibration tests. For instance, [Figure 1](#) shows the capability of smart tires of estimating the normal and longitudinal contact forces during an ABS braking maneuver performed on straight track; the comparison between the forces measured with a dynamometric hub and the corresponding values produced by the smart tire, clearly points out the ability of the sensor to provide reliable estimations of contact forces; since the estimation is provided once per wheel revolution a small time shift is revealed.

VEHICLE MODEL

A 14 dofs vehicle model of a segment D passenger car ([Figure 2](#)) has been used to test and compare the performance of the ESP+ST logic. To allow simulation of closed loop manoeuvres, the vehicle is coupled with a path follower driver model [13]. The vehicle model has been validated comparing its outputs to experimental data relevant to the passive vehicle. As an example [Figure 3](#) reports comparisons between numerical results (dashed lines) and experimental data (solid lines) during a double lane change manoeuvre. Time histories of lateral acceleration and yaw rate are shown.



Figure 2. Instrumented vehicle.

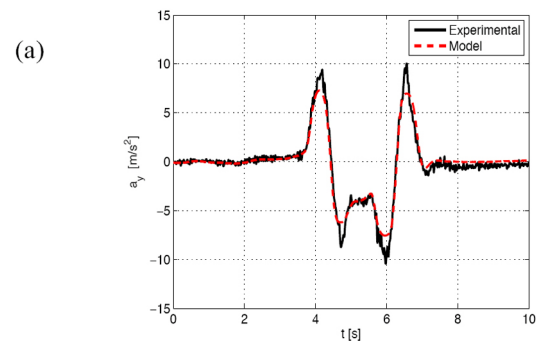


Figure 3. Numerical-experimental comparison, lane change maneuver: a) lateral acceleration, b) yaw rate.

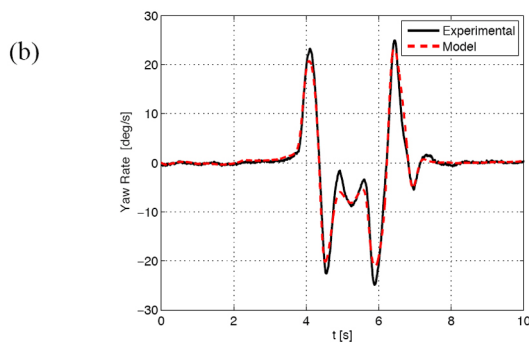


Figure 3 (cont). Numerical-experimental comparison, lane change maneuver: a) lateral acceleration, b) yaw rate.

SMART TIRE SENSOR EMULATOR

In order to embed a real-like measure into the vehicle model and then investigate the response/robustness of the control logic when the measurements are affected by errors (Figure 4), a smart tire emulator has been designed. In fact consequences such as a decay of the performances of the logic, or even a much more unwelcome destabilization of the car dynamics, may be expected. The introduced error may be too big or even preponderant with respect to the sensitivity of the measure that the control logic requires. Hence, it would be pleasant to get a rough idea about whether or not an implementation of the presented logic onto the actual vehicle controller is possible, before going through a refinement of the signal quality of the sensor.

Goal of the emulator is to reproduce some typical built-in characteristics of a smart tire sensor, like:

- measurement frequency: the information provided by the sensor are updated with a variable frequency depending on the wheel speed and not continuously during the rotation of the wheel. The measure is in fact assumed to be available once per tire revolution;
- time delay τ : the signal measured at time t is available at the control unit only after a time gap τ , due to the transmission and to the processing of the measured data. During the simulations the time delay τ has been assumed equal to one wheel turn;
- resolution: quantized measure due to the digital sensor architecture;
- systematic error: expressible as mean value μ of Gaussian distribution which represents the error affecting the measure. The mean value μ is assumed equal to 0, since it may affect a possible offset in the measured value with respect to the actual one, but it can be supposed to be filtered after a sensor calibration;
- statistic error: expressible as standard deviation σ of Gaussian distribution which represents the error affecting the measure.

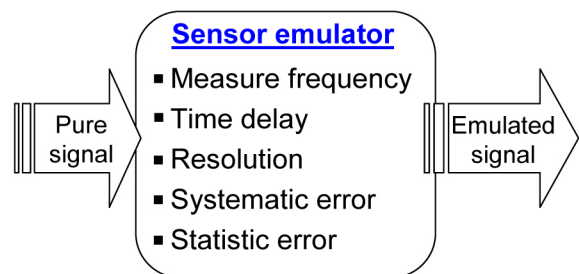


Figure 4. Sensor emulator architecture.

HIL TEST BENCH

In order to compare the results of the implemented control strategy with production ESP systems, Hardware-in-the-loop (HiL) technique has been applied [14,15,16,17,18]. In the considered HiL test bench [16,17,18] the hardware part consists of the ESP/ABS ECU and of all the components of the braking system, i.e. the master cylinder, the pressure modulator integrated with the ECU, the brake calipers and a sensor cluster allowing measurements of lateral/longitudinal accelerations and of yaw rate (Figure 5). The brake pedal force is applied by an hydraulic actuator directly acting on the master cylinder (the brake booster is absent). The braking pressures at the calipers are measured by pressure transducers and fed to the vehicle model simulator in order to update its state. The vehicle model is implemented on a real-time board (dSpace 1103) and outputs the four angular speeds of the wheels, the lateral and the longitudinal vehicle accelerations and the yaw rate. Measures provided by the sensor cluster (lateral/longitudinal acceleration and yaw rate) are only used during an initialization phase to enable the ECU, then they are excluded and the signals transmitted by the sensors are replaced with the ones provided by the vehicle model [14,17,18]. The steer angle, the lateral/longitudinal acceleration, the yaw rate are transmitted to the ESP/ABS ECU via CAN, while the wheels speed are provided to the ECU via direct lines. Emulation boards for wheels speed signals have been developed in order to increase the model performance reducing the computational effort.