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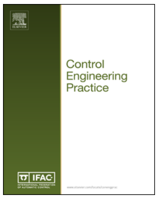

Vehicle sideslip estimator using load sensing bearings

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ABSTRACT

This paper investigates the potential of load based vehicle sideslip estimation. Different techniques to measure tyre forces have been presented over the years; so far no technique has made it to the market. This paper considers a new technology based on load sensing bearings, which provides tyre force measurements. Based on the features of the sensor, a vehicle sideslip angle estimator is designed, analyzed and tested. The paper shows that direct tyre force sensing has mainly two advantages over traditional model-based estimators: primarily, it avoids the use of tyre models, which are heavily affected by uncertainties and modeling errors and secondarily, providing measurements on the road plane, it is less prone to errors introduced by roll and pitch dynamics. Extensive simulation tests along with a detailed analysis of experimental tests performed on an instrumented vehicle prove that the load based estimation outperforms the kinematic model-based benchmark yielding a root mean square error of 0.15°.

1. Introduction

The field of wheeled vehicle active dynamics control is extremely active and vibrant both from the academy and industrial point of views. Active safety systems, of which electronic stability control (ESC) (Reif, 2014), electronic brake distribution (EBD) (Corno, Tanelli, Boniolo, & Savaresi, 2009) and torque vectoring (Panzani et al., 2010) are examples, improve vehicle stability during critical maneuvers by applying feedback control using braking, drive or steering actuators. Many vehicle dynamics control (VDC) systems (see for example Abe, Kano, Suzuki, Shibahata, & Furukawa, 2001; Reif, 2014; Tchamna & Youn, 2013) need to monitor, if not control in closed loop, the vehicle sideslip angle. The vehicle sideslip angle, defined as the angle between the vehicle longitudinal axis and the vehicle velocity vector, affects many dynamic properties of the vehicle. It determines, for example, the vehicle yaw moment sensitivity to steering angle (Shibahata, Shimada, & Tomari, 1993; Van Zanten, 2002; Van Zanten & Erhardt, 1995). This characteristic makes the vehicle yaw moment less sensitive to steering at higher vehicle sideslip. Furthermore, for certain range of vehicle sideslip and its time derivative, the vehicle motion is stable whereas outside this range, *i.e.* outside this stability area, the vehicle yaw dynamics are unstable. In addition, as the steering angle increases, the stability area shrinks (Inagaki, Kshiro, & Yamamoto, 1994).

For the above reasons, the design and study of vehicle sideslip estimation methods has grown into a specific subfield of the VDC literature. Many estimation methods have been presented. They can be classified along two main axes. On the one hand, different sensor suites call for different approaches; on the other hand, even within a given sensor configuration, different modeling approaches are possible.

Based on the type of sensors, the estimators can be classified into three main categories: using only inertial measurement sensors, using inertial measurement sensors and GPS, and using more exotic sensors. Thanks to the progress of MEMS technology, nowadays the basic vehicle sensor configuration is represented by three accelerometers, three gyros, four wheel encoders and steering angle. As the cost and availability of GPS sensors continues to decrease, the integration of the GPS to this basic vehicle configuration has been considered (Bevly, Gerdes, & Wilson, 2002, 2006b; Ryu, Rossetter, & Gerdes, 2002). The GPS information

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increases the estimator accuracy; however GPS signals are known not to be reliable in some conditions, for example, buildings in urban environment can degrade GPS accuracy. In the third category, other sensors have been considered. For example, Yoon and Peng (2012) considers magnetometers (with the obvious risk of disturbance and noise), or Yih, Paul, Ryu, Jihan, and Christian Gerdes (2004) uses steering torque measurements to improve the sideslip estimation. In Nam, Oh, Fujimoto, and Hori (2013), a sideslip estimator is proposed using lateral tyre force sensors and a linear tyre model. The estimator is computationally inexpensive and effective for lateral accelerations under 0.6*g* on a dry road. However, the estimator performance is not studied for lateral accelerations in the range $[0.6, 1]g$ where the tyre characteristics become nonlinear and the need for accurate sideslip estimators is more pressing. In addition, longitudinal tyre slips are assumed to be negligible and this might degrade the estimator performance during combined tyre slip situations.

Contributions can also be classified based on the estimation methods; all estimation approaches are model-based. Based on the type of model employed, one can distinguish dynamic model-based method and kinematic model-based methods.

At the core of kinematic model-based methods lie the kinematic relations between velocities, accelerations and angular rates. These methods neglect the forces that act on the vehicle. The kinematic model has the advantage of not depending on any physical parameter and as a consequence model calibration is simple and not affected by uncertainties. A well-known nonlinear vehicle state observer was first introduced in Farrelly and Wellstead (1996) and proved to be asymptotically stable for all cornering conditions (non-zero yaw rate). The method is later strengthened by an online sensor bias estimation in Panzani et al. (2009) and Oh, Noh, and Choi (2013). A similar method, with a more advance extended Kalman filter (EKF), is presented in Kim and Ryu (2011). The authors experimentally demonstrate the effectiveness of the method on short maneuvers. Wei, Wenying, Haitao, and Konghui (2012) develop a sliding mode observer based on the kinematic model; the observer is tested and analyzed in simulation. Kinematic model-based methods are reliable during transient maneuvers, and are robust to variation of the tyre characteristics, but suffer from estimation errors on nearly steady-state conditions. This issue is caused by an intrinsic lack of observability of the model when the yaw rate is close to zero.

Dynamic model-based methods can overcome the observability limitation. These approaches are based on dynamical models, *i.e.* models that describe the tyre force generation mechanism and how it affects the vehicle dynamics. These models have the potential of being very accurate, but require a tyre model. Many tyre models are available in the literature and are characterized by different level of complexity and accuracy. The simplest model introduces the concept of cornering stiffness, which is a linearization of the tyre force characteristics. The most used one is probably the semi-empirical Pacejka model (Pacejka & Bakker, 1992); other approaches are presented in Gim and Nikravesh (1990) and Zhang and Yi (2014). These models, when calibrated on very specific conditions, are very accurate; however the tyre forces depend on many factors that are not generally known a priori: road friction, tyre pressure and temperature to name a few. Identifying these parameters online has proven to be extremely challenging. Nevertheless dynamic-based models are used in a number of contributions. In Baffet, Charara, and Lechner (2009), an extended Kalman filter using adaptive linear tyre force model is studied. The tyre saturation characteristic is not considered in this work; for the method to work, the lateral tyre forces should be more than 2000 N. The estimator proposed in You, Hahn, and Lee (2009) is interesting as it uses online tyre cornering stiffness estimation. However it does not work on low friction surfaces such as ice and snow. In Phanomchoeng, Rajamani, and Piyabongkarn (2011), a nonlinear observer is designed to estimate vehicle sideslip by solving linear matrix inequalities (LMIs) and the estimator gives accurate results. However, solving LMIs real-time is computationally expensive. In Stephant, Charara, and Meizel (2004) four types of sideslip estimators are designed and compared: a linear observer, a nonlinear observer, an extended Kalman filter and a sliding-mode observer. From this insightful comparison, the best among the four, the sliding-mode observer, is studied using a test vehicle in Stephant, Charara, and Meizel (2007) showing good results for lateral accelerations lower than 0.6*g*. Dynamic model-based methods do not suffer from observability limitations, but they suffer from limitation due to the unknown nonlinear characteristic of the tires.

In general, dynamic and kinematic based methods have complementary properties: kinematic methods are accurate for large sideslip angles; dynamic methods are more dependable for low sideslip angles, where the kinematic model losses observability. In Piyabongkarn, Rajamani, Grogg, and Lew (2009) and Oh and Choi (2012), this complementarity is at the basis of the idea of integrating both approaches. At low frequencies, the physical model-based estimator is used and at high frequencies, the kinematic model-based estimator is used. This approach requires delicate fusion or blending methods.

The estimator proposed in this paper fuses the positive features of the kinematic and dynamic approaches by using a novel sensor configuration. The proposed sideslip estimator employs a new load sensing bearing (LSB) technology which can provide tyre force measurements (Van Leeuwen, Holweg, Wit, Zaaijer, & Ballegooij, 2005). Researches have been working on reliable and industrially viable methods to measure tyre force for years. Now, several sensor configurations are becoming available. Car manufacturers have been using measurement wheels (see for example Corrsys product, Vehicle Dynamics & Durability) to test their vehicles for years; other options include LSB from SKF (Corno, Gerard, Verhaegen, & Holweg, 2012), tyre-embedded force sensor (Zhang, Yi, & Liu, 2013), lateral tyre force sensor from NSK (Gunji & Fujimoto, 2014; Nam, Fujimoto, & Hori, 2012, 2014) and wheel force transducer (Lin, Pang, Zhang, Wang, & Feng, 2013). The force sensor proposed in Zhang et al. (2013) embeds the sensor inside the tyre; this yields one measurement per revolution and a sensor that is subject to tear and wear. In Nam et al. (2012, 2014) and Gunji and Fujimoto (2014), the lateral tyre force sensor from NSK is used to control vehicle motion. However, for sideslip estimation, the longitudinal tyre forces are also required, especially during combined tyre slip situations. The embedded force sensor in Zhang et al. (2013) and the wheel force transducer in Lin et al. (2013) requires wireless transmission of the measurements. Among the above approaches, bearing based technology is of particular interest because bearings are not subject to wear as tires, but are spatially close to the contact patch and can thus yield accurate measurement. Furthermore, the bearing being stationary, wireless data transfer is not necessary. Tyre force sensing is a realistic possibility in the near future and its advantages in terms of VDC warrants investigation. Tyre force-based control has been proven successful in lateral and longitudinal vehicle dynamics control (Corno et al., 2012; de Bruijn, Gerard, Corno, Verhaegen, & Holweg, 2011; Gerard, Corno, Verhaegen, Michel, & Holweg, 2011; Madhusudhanan, Corno, & Holweg, 2013, 2015b). The present work is an extension of Madhusudhanan, Corno, and Holweg (2015c) and studies the tyre force based vehicle sideslip estimation as it is important to implement and test the lateral vehicle dynamics control proposed in Madhusudhanan et al. (2013, 2015a, 2015b). The sideslip estimator proposed in this work is used in the road-tyre friction estimator proposed in Madhusudhanan, Corno, Arat, and Holweg (2016). The main contributions of this work are: