Reifensensorik zur Reibwertschätzung

Tyre Sensing Approach for Friction Estimation in FRICTI@N Project

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Abstract

Advanced driver assistance systems would benefit from accurate information on tyre operating states. An optical tyre sensor was developed in the EC project APOLLO, and it has been further developed in the FRICTI@N project. Many steps forward have been taken and the optical tyre sensor can at the moment deliver tyre forces for the CAN bus in real time. Real-time capable algorithms are presented, which are tested on several cars and a truck. The tyre sensor signal waveforms are compared to the FEM simulations and force estimations are compared to the test rig measurements. Some results concerning optical tyre sensor behaviour in aquaplaning are also presented.

1 Introduction

The main target of the FRICTI@N project is to develop on-board measurement of friction potential in order to enhance the performance of integrated and cooperative safety systems. The purpose was not to develop any new sensors, but exploit existing ones by sensor fusion in a novel way.
The sensors considered can be divided into three groups:

1) existing vehicle sensors in an ESC-equipped vehicle (wheel speeds, lateral acceleration, yaw rate etc)

2) environmental sensors (especially the ibeo LUX Laser scanner and RoadEye [1])

3) the tyre sensor from the APOLLO project (only optical tyre sensor) [2,3]

This paper explains how the optical tyre sensor is further developed towards real-time tyre force estimation. In addition, the tyre sensor’s capability to detect aquaplaning is reviewed.

2 Optical tyre sensor development in FRICTI@N

A predecessor project of FRICTI@N, the APOLLO project [3] concentrated only on tyre sensors and the project resulted in a special 3-in-1 test tyre. The tyre possessed three different sensors: a MEMS (micro-electro-mechanical system) acceleration sensor, a piezoelectric strain sensor, and an optical position detection sensor. Since tyre sensors had a minor role in the FRICTI@N project, it seemed obvious that there are no resources to develop all these sensor types further. The optical position detection sensor showed excellent performance in tyre force estimation, and it was selected to be the tyre-based sensor in the FRICTI@N project. Although the acceleration sensor was extremely interesting, at the moment it is being studied from many angles, which made it unattractive in that sense. The piezoelectric strain sensor was not durable enough even for research purposes and it was the easiest to ignore. Thereafter some interesting results based on strain sensors have been presented though [4].

The optical tyre sensor principle is shown in Fig. 1 The core of the optical tyre sensor is a two-dimensional position-sensitive detector (PSD) that utilises photodiode surface resistance [5]. The PSD is located on the rim and can detect the movement of a light-emitting diode (LED) that is glued into the inner liner of the tyre. Note that the intensity of the LED is not constant versus angular displacement. For example, a 10° angular displacement means approximately 2 % lower intensity. A Plano-Convex (PCX) Lens with anti-reflection coating focuses the light onto the sensor. The effective focal length is 9 mm, which is roughly the distance of the lens from the sensor. The sensor setup has been installed into a special dividable rim. The tyre in these tests was a winter tyre without studs (friction tyre, 225/60R16). A Li-Ion battery was used as a power supply. [6]

The wireless data transfer system was the same as that used in the APOLLO project [7]. The resolution of each channel was 12 bits and the sampling rate was approximately 5100 Hz. The data were transformed into CAN message format to be ready for the vehicle network.
Fig. 1: Optical tyre sensor (taken from [6])

Fig. 2 shows the life cycle of the optical tyre sensor, starting from APOLLO until the end of FRIC TI@N. The first modification to the tyre sensor was to embed the displacement calculation in the tyre. In Apollo this calculation was done in post-processing, and thus the new sensor version saved a lot of processor time in real-time operation. In addition, the resolution of the data improved in practice as a result of the analogue signal processing before digitising. The improved electronics were located in the alloy housing, which made possible the exact parallel installation of the optical components (Fig. 3).

Intensive testing was completed with the 1st FRIC TI@N prototype sensor and there emerged a hunger to test the tyre sensor on a truck. The same sensor electronics were installed into a separate sensor module. The flange joint was welded to the truck wheel rim and the sensor module can be installed easily without the need to remove the tyre (Fig. 4).

**Fig. 2: Development of the optical tyre sensor from APOLLO to FRIC TI@N**
3 Tyre force estimation

3.1 Magnetic pick-up signal

The tyre forces can be calculated only once per rotation. Thus it is essential to know the exact position of the sensor. An additional magnetic pick-up sensor was used to synchronise the rotation angle of the optical tyre sensor exactly. The sensor was installed in the rim and aligned with the optical sensor. In addition, a magnet was installed into the suspension or test rig to indicate the upright position of the sensor. Basically, when the sensor passes by the magnet, a new tyre force estimate is calculated and a new rotation is started.
3.2 Vertical signal

The vertical movement of the LED can be calculated from the intensity $I_{psd}$:

$$z = \sqrt{I_{psd}}$$

(1)

Fig. 5 shows a comparison of the tyre sensor measurement and Finite Element Method (FEM) simulation. The peak value is found to be linear to the vertical force.

An area of movement $z$ is calculated:

$$A_z = \int_{-\pi/2}^{\pi/2} z d\varphi$$

(2)

where $\varphi$ is the rotation angle. The area is also linear to the vertical force and more independent of any noise or errors during the contact.

![Fig. 5: Tyre sensor vertical movement with different wheel loads (measurement on left, FEM on right)](image)

Even if the vertical movement correlates well with the vertical force, in the final version of the algorithms it is ignored. This is due to the fact that LED intensity depends on temperature, supply voltage, and LED orientation angle. The final vertical force estimation is based on the longitudinal movement signal, because it is almost independent of those environmental factors.

3.3 Longitudinal signal

The longitudinal signal carries a lot of information (Fig. 6). The amplitude is proportional to the contact length and it can be further exploited to estimate vertical force. The amplitude is calculated:

$$x_{amplitude} = \max[x_{-100...100}] - \min[x_{-100...100}]$$

(3)
where \([x_{180 \leq \lambda < 180}]\) consists of all values of the x-signal for one rotation.

**Fig. 6:** Tyre sensor longitudinal movement with different wheel loads (measurement on left, FEM on right)

The longitudinal force shifts the longitudinal signal up- or downward, but amplitude is maintained almost completely (Fig. 7). Therefore the recursive mean value of the longitudinal signal correlates with the longitudinal force. The mean value is calculated:

\[
\bar{R}_{k+1} = \bar{R}_k + \frac{x_{k+1} - \bar{R}_k}{c}
\]

(4)

and the longitudinal force is calculated after a completed rotation:

\[
R_{\text{L}} = \bar{R}_{\text{L,calib}} + c \cdot \text{offset}
\]

(5)

where \(c\) is the respective parameter defined from a calibration run. Fig. 7 shows the estimated tyre force comparison for the test rig measurement during braking. The tyre force estimate is slightly underestimated in some sections and values have some offset around zero forces, where only rolling resistance exists.
The vertical force is then calculated:

\[ F_z = x_z^2 \cdot \text{gap} \cdot \text{parabola} + x_z^2 \cdot \text{gain} + c_{z,x} \text{offset} + (\bar{F}_z \cdot \text{gain} + c_{z,x} \text{offset}) \]  \hspace{1cm} (6)

where the parabolic term is needed because of the inverse square relation of intensity and displacement. The \( \bar{F}_z \), \( c_{z,x} \text{gain} \), and \( c_{z,x} \text{offset} \) terms are needed to compensate the vertical force estimate under longitudinal force, which slightly increases signal amplitude. The tyre sensor estimate and test rig measurement are compared in Fig. 8. The tyre sensor can estimate vertical forces very accurately if no simultaneous longitudinal force exists. The influence of the compensation term can be seen on the right in Fig. 8, where the braking sequence is the same as in Fig. 7 (right). The additional term in Eq. 6 compensates for the increased amplitude during braking.
3.4 Lateral signal

The lateral force is calculated from the lateral movement signal. Equally to the vertical signal (Eq. 2), the lateral signal peak value and area of one rotation are proportional to the lateral force. However, the area of movement depends on rotational velocity and it has to be compensated. In real-time calculation this was a major problem because of the jitter and resulted in completely wrong lateral forces. Thus, the recursive mean value calculation (cf. Eq. 4) was implemented:

$$p_{k+1} = p_k + \frac{32\pi - \alpha}{\alpha}$$  \hspace{1cm} (7)

and lateral force estimate:

$$F_y = F_{y\text{gain}} + c_{y\text{offset}}$$  \hspace{1cm} (8)

The lateral movement signal is shown in Fig. 9 on the left and the tyre sensor estimate and test rig measurement are compared on the right.

![Fig. 9: Measured lateral displacement (left) and tyre forces for different slip angles [6]](image)

4 Aquaplaning detection from carcass displacements

Aquaplaning severely hampers interaction between the tyre and the road. In aquaplaning the tyre contact patch can be roughly divided into 3 sections [8] (Fig. 10). In zone A, the inertial effect of the water dominates and no contact between the tyre and the road surface exists. In zone B, some rubber-road contact exists, but the viscous effect of the water squeezing out from the contact area limits this area. Zone C represents full wet road contact.
Fig. 10: **Three-zone concept**

Fig. 11 shows the tyre sensor measurement in transition from dry tarmac to an 8-mm water reservoir. The left- and right-hand figures relate to the same data; only the view is different. The elevation of the front part of the contact patch can be seen from the increased distance between the LED and the unloaded radius. The signal also shifts slightly towards smaller rotation angles, which can be seen on the right in the figure. The drop in the peak values just before aquaplaning reveals the descent of the tyre into the water reservoir. In other words, it means reduced vertical tyre force. The most difficult task of real-time aquaplaning detection is to distinguish wheel load deviation from the aquaplaning phenomenon. This can be done, for example, by calculating the shifting of the area covered by the signal. However, this is, in contrast, influenced by the longitudinal force, which can be assumed to be minor for an aquaplaning tyre.

Fig. 11: **Tyre sensor measurement: dry tarmac rotations 0-61 and water 62**

More detailed analysis of optical tyre sensor in aquaplaning can be found from [9].
5 Discussion

The optical tyre sensor can very accurately estimate tyre forces if the tyre inflation pressure is known. In the previous results the inflation pressure was always the same as during calibration measurement in the test rig. The inflation pressure increases enough in normal driving to introduce a bias to the tyre force estimate. However, if there is ever a tyre force sensor based on carcass movements in production, the direct TPMS will certainly be standard equipment at that time.

The longitudinal movement signal has been found to carry most of the information. It reveals the contact length and the longitudinal forces. Furthermore, it can detect similar differences in aquaplaning to those presented in Fig. 11 for the vertical movement. The longitudinal forces cannot be accurately measured during ABS braking, since the update rate is limited to one sample per rotation.

Vertical movement signal (intensity) is disturbed by LED alignment, temperature etc. Despite the facts, these limitations (especially LED alignment) are characteristic only for an optical sensor which requires a light source in the inner liner. There are many optical devices which can measure distance without a light source in the object. This concept would be more production-oriented than the sensor considered in this paper. The reliable measurement of inner liner vertical movement would certainly allow at least dynamic wheel load estimation and possibly also the detection of aquaplaning.

The lateral tyre force can be accurately estimated from the lateral movement signal. It makes it possible to estimate the vehicle slip angle accurately and rapidly, because the tyre force is acting on the chassis in advance before accelerations and rotational velocities are generated. The side slip estimator based on tyre sensor forces is one of the further activities.

The lateral signal could also provide indications about the aligning moment of the tyre, but no systematic studies have completed on this subject. In some tests, it was observed that the lateral signal peak was shifted forwards (towards trailing edge) in the tyre contact patch at small slip angles, which could be influenced by the aligning moment. The aligning moment would be interesting to estimate, because it describes very nicely the tyre operating state, together with the lateral tyre force [10].

The optical tyre sensor has been an excellent research tool to study dynamic tyre behaviour. It is not even intended to be a product, but resources have been allocated to study what information is available if the deflections of the tyre carcass are known. In addition to vehicle and tyre state estimation, it can be exploited in validating complex physical tyre models such as FEM. In addition to tyre research, a lot of progress has been achieved in embedding the cyclic data analysis algorithms into standard low-cost MCUs.
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