Cost-Effective Wireless Sensing System for an Intelligent Pneumatic Tire

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Abstract. Intelligent tires constitute one of the approaches that allow to increase the effectiveness of the active safety systems of vehicles. Several areas of improvement concern these systems, all of them focused on the information about tire-road states. This study introduces the use of cost-effective flex sensor technology in intelligent tires in order to estimate the tread rotational speed and the vertical load. This technology has been combined with a wireless data transmission and a suitable prototype has been realized. First experimental tests have been conducted and the obtained results show the goodness of the proposed solution.

Keywords: Intelligent tire · Flex sensor · Vehicle dynamics · Smart systems

1 Introduction

Electronic controls these days are necessary for road safety: radars, electronic stability controls (ESC), active breaking systems (ABS) and so on. All the currently-used controls are based on on-board sensors, this means that many of all the important parameters for the vehicle dynamics are estimated indirectly. This kind of estimation could generate imperfections and delays in the metering system and so an incorrect or late response of the vehicle controls. Many researchers realized that to improve the electronic controls, measurements should have been made directly on the tire, since tires are the vehicle part in contact with the road surface, where all the road disturbances act and where the forces are generated. They called this new technology “Smart Tire” or “Intelligent Tire” to emphasize the tire autonomy in measuring its own forces, deformations, accelerations and then communicate them wireless [1]. This aspect could be also crucial for the design of vehicle diagnostic systems based on modern signal processing techniques [2, 3] and self-learning methods [4].

The research in Smart tire applications began in the early ‘80s with the “Tire pressure monitoring system” (TPMS) which allows the driver to know the tire pressure conditions. Many steps have been made in this area and many different ideas have been followed. The sensors adopted are various: an optical sensor in [5], segmented

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capacitance rings for measuring tire strain in [6], ultrasonic sensor in [7] for contact patch deformations, piezoelectric PVDF sensors to measure the strain [8, 9], oscillating circuit to detect capacitance variations linked to the strain [10]. In [11], spectral features of the capacitance output signal are used to improve the accuracy of the strain measurement. A new type of capacitance sensor based on ultra-flexing epoxy resin is shown in [12] and a Hall effect based magnetic sensor is used in [13] to measure the thread deformation. In [14–16], algorithms for the estimation of slip angle and tire working conditions from strain measurements have been presented.

The aim of this paper is to show that an intelligent tire prototype can be designed to be functional, simple and economical. In particular, a cheap flex sensor, bonded on the inner liner of a pneumatic tire, with a wireless communication system, has been adopted in order to obtain some tire working condition features. The prototype described in this paper is a first attempt and preliminary results are illustrated.

2 Intelligent Tire System

This prototype of intelligent tire is based on a flex sensor (see Figs. 1a and b). Due to a series of carbon resistive elements, it works like a variable resistance from a constant value for flat sensor to a maximum value in totally bended condition. Once attached to the inner part of the tire (Fig. 1c), the sensor can be used to estimate the curvature variation of the tire due to the bending action, which can be linked to the needed working conditions (*e.g.* rolling speed, vertical load, length of the contact patch).

In this first prototype, the wires connected to the sensor pass through a sealed hole on the rim where the wireless system is placed. The tire used for the actual setup has the size 245/40/R18.

The data acquisition system (DAS) implemented in this work is shown in Fig. 2. The conditioning circuit is formed by a voltage divider and an impedance buffer.

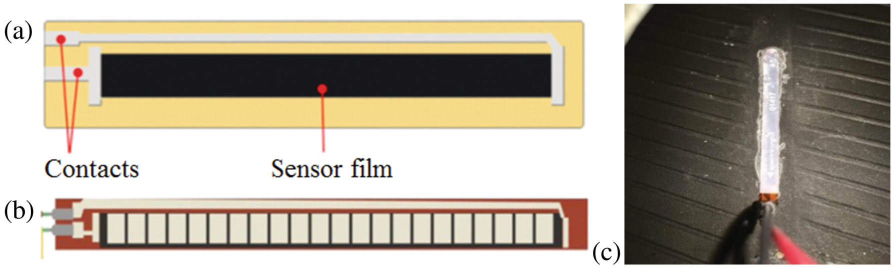

Fig. 1. (a) Scheme of a resistive flex sensor; top view: electrical contacts in grey, conductive film in black; (b) Flex sensor by Inage SI Inc. Courtesy of Flexpoint Inc; (c) Flex sensor attached to the inner part of the tire.

The resistor R_2 can be adjusted to obtain an output voltage equal to $V_{in}/2$ when no deformation is applied to the flex sensor. The voltage V_{out} is converted to a digital signal

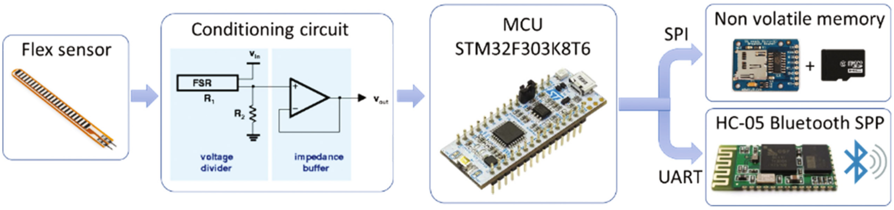

Fig. 2. Block diagram of the data acquisition system for smart tire sensors.

by means of a microcontroller (MCU) based circuit board (STM32F303K8T6) (see Fig. 2). The used MCU has also two fast 12-bit ADCs with 5 Msps maximum sampling rate, while in our application the sampling frequency is chosen to be f_S = 10 kHz. The developed DAS can be configured to retrieve data from the sensor both in real-time or off-line. In the first case, the microcontroller sends data packets over a Bluetooth channel to a personal computer. In the second case, once the microcontroller has collected the signal data, all the information and numerical data can be stored in a non-volatile SD card through serial interface.

The MCU firmware is written with the Arm Mbed IoT Device Platform and it is based on the Mbed OS 5.8 release. The synchronization between the sampling operation and the writing operation is ensured by interrupt/tread mechanisms.

3 Characteristics of the Flex Sensor Signal

When the flex sensor enters in the contact patch it is deformed simultaneously with the tire treadband (See Fig. 3a). When the sensor is placed exactly in the contact patch, its curvature decreases. During the exit from the contact patch the sensor curvature increases again, due to the tire threadband deformation. The behaviour of the radius of curvature and its time variation, in free-rolling condition, is shown in Fig. 3b.

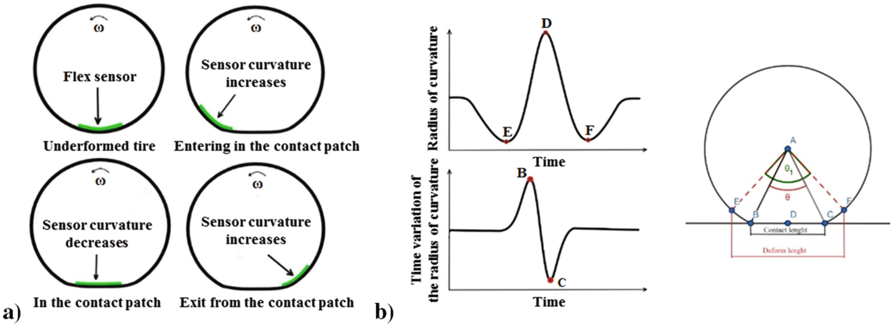

Fig. 3. (a) Flex sensor deformation during tire rolling; (b) Waveforms of the radius of curvature and its time variation.

In absence of braking, traction or steering forces, the radius of curvature is almost symmetric with respect to the contact patch centre (D in Fig. 3b). The time variation of the radius of curvature related to the flex sensor can be adopted for estimating the length of the contact patch as shown in Fig. 3b.

4 Tire Test Rig

The test rig used during the tire testing session (shown in Fig. 4) is composed by a portal that works as support for the axis and therefore the tire.

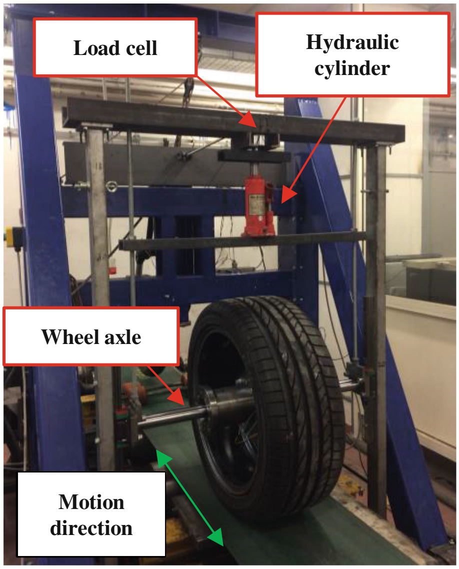

Fig. 4. Tire test rig.

The wheel axle is mounted on two vertical linear guides in order to transmit the vertical load to the pneumatic tire. On the top of the portal there is a housing for the loading cell, which allows to measure the vertical applied load.

A hydraulic cylinder is then placed between the load cell and a horizontal beam, which is directly connected to the guides. The measurements provided by the flex sensor have been obtained for different values of vertical loads and tire rolling speeds.

5 Experimental Results

In this section, some results of the experimental activity are presented. The main goal of the present study is to explore the possibility of using a low-cost system to estimate some tire working conditions. The tests have been performed for rolling speeds up to

20 km/h in order to evaluate the shape of the sensor signal for low tire rolling speeds. Figure 5a shows the experimental results for different values of the vertical load and for

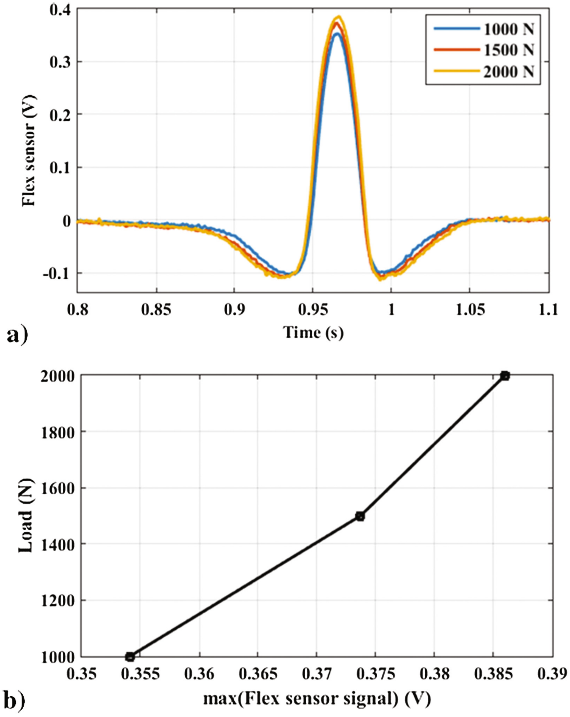

Fig. 5. (a) Measurements for different vertical loads (tire rolling speed: 10 km/h); (b) Vertical load for different maximum values of the sensor signal.

the same tire rolling velocity of 10 km/h. Figure 5b shows the behaviour of the vertical load with respect to maximum values of the sensor output (Fig. 5a).

The signals of Fig. 5a have a qualitative behaviour similar to the theoretical radius of curvature signal presented in Fig. 3b. The experimental results clearly highlight a method for estimating the vertical load from the sensor measurement. Indeed, a linear interpolation function of the data presented in Fig. 5b could provide the tire vertical load for each revolution of the tire.

Figure 6a presents the flex sensor measurements obtained with a constant tire vertical load (2000 N) by varying the wheel rolling velocity. Figure 6b shows the wheel rolling velocity for different values of the sensor rotational speed, obtained from the time period between two consecutive positive peaks of the sensor output.

Also the experimental results presented in Figs. 6a and b demonstrate that it is possible to obtain an estimation of the wheel rolling velocity from a signal processing method applied to the wireless measurements. Indeed, under the hypothesis of a perfect bonding of the flex sensor on the tire inner liner, the sensor rotational speed coincide to

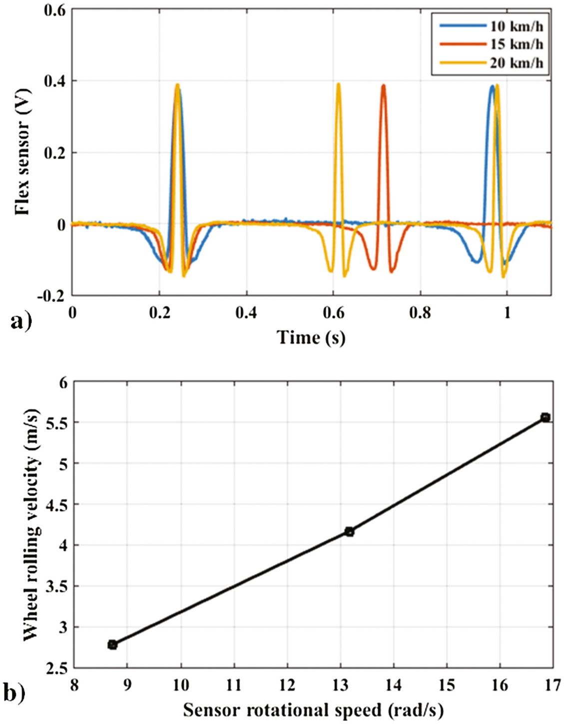

Fig. 6. (a) Measurements for different wheel rolling velocities (vertical load 2000 N); (b) Wheel rolling velocity for different values of the sensor rotational speed.

the one of the tire carcass. Moreover, the results of Fig. 6b show the linear relationship between the sensor rotational speed and the wheel rolling velocity.

6 Conclusions

In this paper, a cost-effective wireless system for an intelligent tire prototype is presented. The proposed apparatus mainly consists of a low-cost flex sensor, bonded on the tire inner liner, equipped with an electronic device for a wireless transmission during the wheel rotation. An experimental activity has been conducted in order to analyse the feasibility of the proposed approach. In particular, a test rig has been adopted to evaluate the possibility of estimating some tire working condition features from the flex sensor. The intelligent tire has been tested in free-rolling and for low values of the wheel rolling speed. The next step of the research will involve the evaluation of the sensor system performance at higher velocities and applying a driving/braking torque to the wheel. Moreover, a model-based approach able to correlate the sensor signal to the tire physical parameters could be another important step for this research activity.

References

1. Lee, H., Taheri, S.: Intelligent tires-a review of tire characterization literature. IEEE Intell. Transp. Syst. Mag. **9**(2), 114–135 (2017). Art. no. 7904765
2. Niola, V., Quaremba, G., Pellino, G., Montanino, A.: A nonlinear spectrum for the diagnostics of a complex dynamical system. Int. J. Appl. Eng. Res. **11**(18), 9569–9575 (2016)
3. Vincenzo, N., Giuseppe, Q., Aniello, F.: The detection of gear noise computed by integrating the Fourier and Wavelet methods. WSEAS Trans. Sig. Process. **4**(3), 60–67 (2008)
4. Niola, V., Quaremba, G., Savino, S.: The objects location from images binarized by means of self-learning neural network. WSEAS Trans. Syst. **4**(4), 417–423 (2005)
5. Tuononen, A.: Optical position detection to measure tyre carcass deflections. Veh. Syst. Dyn. **46**, 471–481 (2008)
6. Cullen, J., Arvanitis, N., Lucas, J., Al-Shamma'a, A.: In-field trials of a tyre pressure monitoring system based on segmented capacitance rings. Measurement **32**, 181–192 (2002)
7. Magori, V., Magori, V.R., Seitz, N.: On-line determination of. tire deformation, a novel sensor principle. In: Proceedings of the IEEE Ultrasonics Symposium, Sendai, Japan, 5–8 October 1998
8. Moona, K.S., Liangb, H., Yi, J., Mika, B.: Tire tread deformation sensor and energy harvester development for smart tire applications. In: Proceedings of the Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace System, San Diego, CA (2007)
9. Yi, J.: A piezo-sensor-based 'smart tire' system for mobile robots and vehicles. IEEE/ASME Trans. Mechatron. **13**(1), 95–103 (2008)
10. Todoroki, A., Miyatani, S., Shimamura, Y.: Wireless strain monitoring using electrical capacitance change of tire: part I—with oscillating circuit. Smart Mater. Struct. **12**(3), 403–409 (2003). IEEE Intelligent Transportation Systems Magazine **134** (2017)
11. Matsuzaki, R., Todoroki, A.: Passive wireless strain monitoring of actual tire using capacitance–resistance change and multiple spectral features. Sens. Actuators A **126**(2), 277–286 (2006)
12. Matsuzaki, R., Todoroki, A.: Wireless flexible capacitive sensor based on ultra-flexible epoxy resin for strain measurement of automobile tires. Sens. Actuators A **140**(1), 32–42 (2007)
13. Yilmazoglu, O., Brandt, M., Sigmund, J., Genc, E., Hartnagel, H.L.: Integrated InAs/GaSb 3D magnetic field sensors for 'the intelligent tire'. Sens. Actuators A **94**(1/2), 59–63 (2001)
14. Garcia-Pozuelo, D., Olatunbosun, O., Yunta, J., Yang, X., Diaz, V.: A novel strain-based method to estimate tire conditions using fuzzy logic for intelligent tires. Sensors (Switzerland), **17**(2) (2017). Art. no. 350
15. Garcia-Pozuelo, D., Yunta, J., Olatunbosun, O., Yang, X., Diaz, V.: A strain-based method to estimate slip angle and tire working conditions for intelligent tires using fuzzy logic. Sensors (Switzerland) **17**(4) (2017). Art. no. 874
16. Yang, X., Olatunbosun, O., Garcia-Pozuelo Ramos, D., Bolarinwa, E.: FE-Based Tire Loading Estimation for Developing Strain-Based Intelligent Tire System. SAE, Detroit (2015)