

Experimental Investigation of Tire Dynamic Strain Characteristics for Developing Strain-Based Intelligent Tire System

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ABSTRACT

The increasing demand for ground vehicles safety has led to the requirements for effective and accurate vehicle active safety systems, such as Anti-lock Braking System (ABS) and Traction Control System (TCS). As the only link between vehicle and road, the tire is in a very privileged position in a vehicle to acquire vital information which could be used to improve vehicle dynamics control systems. Hence the requirement for an “intelligent tire” that incorporates a system that is able to sense the tire and road conditions, and then interact with the vehicle dynamics control system to optimize the vehicle performance as well as provide warning information to the driver. In this paper, an experimental tire strain-based system is used to establish the proof of concept of an intelligent tire prototype. This experimental system comprises a data acquisition device and three rectangular rosette strain sensors, which can measure the tire surface dynamic strain in real time. Indoor tire rolling tests including steady state straight line and cornering are used to demonstrate the feasibility of the measuring tire strain history with a view to determining tire dynamic strain characteristics. Tire dynamic strain characteristics are extracted and analyzed with respect to the variation of tire operational conditions, such as inflation pressure, rolling speed and pre-loading. These relationships between dynamic strain characteristics and tire operational conditions indicate potential application of tire strain measurement in estimating tire behavior.

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INTRODUCTION

The vehicle safety issue has always been of great concern to the public as well as vehicle manufacturers. For this purpose, the tire plays a major role in electronic driver-assistance systems, as it is the only link between the vehicle and the road surface. The vehicle active safety system can help prevent accidents by providing the driver with better means of vehicle control, such as Anti-lock Braking System (ABS), which can prevent the tire from locking up and thus prevent skidding during braking. In order to achieve the functions of a vehicle active safety system, the vehicle dynamics control system needs accurate and reliable information about the tire working conditions. Instead of

playing a passive role in the vehicle system, the incorporation of different sensors in the tire would enable it to play an active role with the capability to provide useful information including tire/road contact forces, road conditions and driving conditions to the vehicle dynamics control systems, such as ABS, Traction Control System (TCS), Vehicle Stability Control System (VSCS), Suspension Control System (SCS), etc. Such an “intelligent tire”, equipped with sensors, could contribute greatly to accident prevention and thus enhance the tire's important role in improving vehicle safety.

In 2002, the USA passed the Tread Act [1] to require installation of Tire Pressure Monitoring System (TPMS) to warn the driver if a tire is significantly under-inflated. This legislation could be considered as the first major step in the

development of the intelligent tire. Likewise, since November 1st 2012, the TPMS has become mandatory in the European Union as well. This measure is intended to not only improve vehicle safety, but also reduce CO₂ emissions. These legislations would not only boost the potential market for intelligent tire technology related products but also promote the development of intelligent tire technology for the purpose of tire data collection transmission and fusion.

As a critical sub-system of the intelligent vehicle system, a lot of effort has gone into developing the intelligent tire system in the last decade. Many related works are ongoing in order to realize an intelligent tire system, such as the Darmstadt sensor [2] and the SideWall Torsion sensor [3]. The Darmstadt sensor can detect three-dimensional movements of a tread embedded magnet. The SideWall Torsion sensor provides an estimate of the longitudinal and lateral forces in the contact patch by monitoring the magnetic field generated by alternate north-south poles embedded in the tire. A magnetic sensor was developed by Miyoshi et al [4] to monitor an analog output corresponding to the variation of the magnetic flux representing the tire wall strain. The magnetic sensor can measure different types of strain such as circumferential strain, radial strain and shear strain on the tire surface. The strain data can then be correlated with the tire forces. A Surface Acoustic Wave (SAW) sensor [5-6] was also developed which, apart from measuring tire inflation pressure and temperature can also measure other mechanical properties such as deformation. It is claimed that the SAW sensor can also be directly vulcanized into the tread elements of tires, and used to measure the road friction coefficient which can provide valuable information for driver-assistance systems and for optimizing slip-control and vehicle-stability systems, even more accurately than ABS [7]. An ultrasonic sensor was mounted by Magori et al [8] on the base of the wheel rim inside the tire to evaluate the tire vertical load, deformation, tire temperature and tire-road contact parameters by measuring the varying distance to the opposite tire inner wall in real time. Ari Tuononen [9-10] carried out a series of studies on measuring tire carcass deflections for vehicle state estimation using the optical sensor. By measuring the position of a Light-Emitting Diode (LED) relative to the rim, it can capture the characteristics of tire behaviour. This optical tire sensor is not designed for the commercial market as re-calibration is required when the tire's carcass property and inflation pressure change. Furthermore, the problematic measurement of light intensity will also influence the accuracy of measured data. In the work of Erdogan et al [11], tire lateral tread deflection and sidewall deflections were measured using a Polyvinylidene Fluoride (PVDF) sensor. The tire slip angle was estimated based on tire sidewall lateral deflection, which was very consistent for both the camera measurement and piezoelectric sensor. Cullen, J.D. [12] used segmented capacitance rings to measure the tire pressure. In the field trials, some validated results were obtained successfully. There are more available

applications of the capacitive sensor focusing on the measurement of deformation or strain of the tire. The monitored tire strain in service would be processed by pre-set algorithm to estimate tire tri-axial forces occurring on the tire road contact patch. Then, these estimated forces are integrated into vehicle chassis control algorithm to offer significant benefits for improving vehicle safety and handling performance. Akira Todoroki, et al [13, 14] employed the tire itself as a sensor by adopting the steel wire belt of the tire as electrodes. A small oscillating circuit was embedded in the tire to monitor the capacitance change (related to strain) of the tire comprising steel wire and rubber. Braghin et al [15] proposed a three-axis Micro Electro Mechanical Systems (MEMS) accelerometer which was used to measure the acceleration inside the tire tread. Its feasibility and potential application have been proven by both finite element analysis and indoor experiment. Although the acceleration measurement was adopted in some of the past researches, acceleration measurement is very sensitive to noise and rolling speed which make it more difficult to extract the features of interest from the measured signals. Some useful results about tread acceleration measurements and wireless tire data transmission systems are presented by Negrus et al [16].

Overall most of the sensors used in existing intelligent tire systems are based on measured deformation of the tire, such as strain, deflection, distance, acceleration, etc. An evaluation of past research in the development of these strain-based intelligent tires indicates that a strain-based sensor system satisfies the requirements of developing an advanced intelligent tire system, because commercial products capable of providing the full range of capabilities required for vehicle safety and control systems are yet to emerge.

Since it is less expensive to measure strain data, which is directly related to the tire operating characteristics; and after careful consideration of the pros and cons of these technologies; it was decided to evaluate a strain-based experimental system in this study as the basis for the development of an intelligent tire system which could find application in future vehicle dynamics control systems by estimating real-time tire working conditions based on the features of tire strain time history measured during tire service.

OBJECTIVES OF STRAIN-BASED INTELLIGENT TIRE SYSTEM

From the literature review about strain-based intelligent tire systems, it was found that the strain is measured at the tire tread in most of the relevant researches. It is widely accepted that a strain sensor placed in the inner liner of the tread can provide significant, accurate and stable information about the forces generated at the tire/road contact patch [17]. The strain sensors used in this study are also located at the inner liner surface of the tire tread. Although the determination of the best location for a sensor can be



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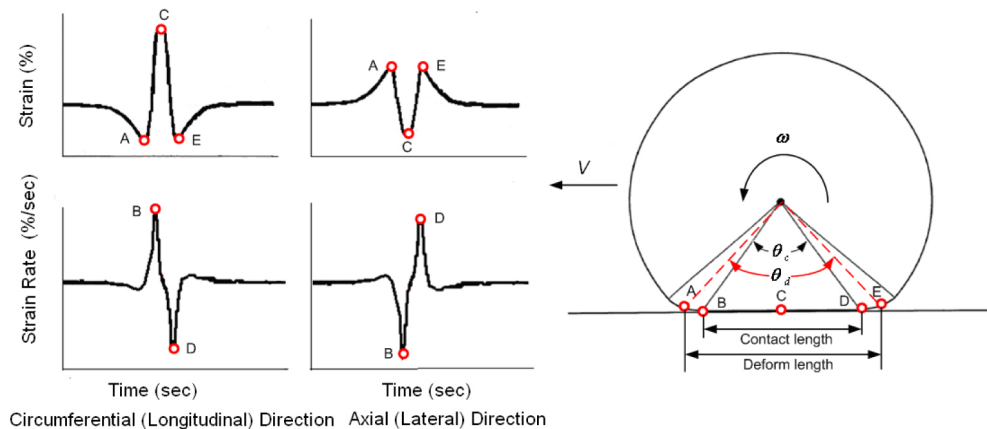


Figure 1. Characteristics of Tire Strain Time History [17]

evaluated by the signal-to-noise ratio of the sensor output, it is also constrained by the range of strain the sensor can measure as well as the available space on the tire inner liner surface. The ideal strain time histories acquired from the inner liner surface of the tire tread along the tire's circumferential (longitudinal) direction and axial (lateral) direction respectively, for one revolution during tire steady state straight line rolling, are illustrated in Figure 1[17]. The strain rate is defined as the time differential of strain value.

The tire strain waveform under steady state straight line rolling shows a nearly symmetric shape with respect to the centre of the tire contact patch, because there is no braking, traction or steering force applied on the tire. It is evident that the rolling tire deformation characteristics cause the corresponding variation of strain. The bending deformation occurs around the tire contact patch area due to the combined effect of vertical load and friction load [18].

For the circumferential strain, tensile strain occurs in the contact patch (region between point B and point D) and peaks at the centre of the contact patch, namely point C in Figure 1. Compressive strain occurs in the leading region (left region of point B) and trailing region (right region of point D) outside the tire contact patch. Therefore, the tread element is under compression before entering the contact patch and after leaving the contact patch, and is stretched within the contact patch during the steady state straight line rolling.

According to Ryosuke et al [18], the contribution from friction load to the generated strain during steady state straight line rolling is modest, which just slightly reduces the variation in the tensile strain. The time derivative waveform of circumferential strain, shown in Figure 1 exhibits two peaks. These peaks correspond to the two points with the maximum strain rate at the leading edge and trailing edge of the tire contact patch. The time difference between these two peaks, i.e. points B and D, is the time taken to traverse the contact length between points B and D as shown in Figure 1. The strain distribution in the tire contact patch when the tire is under traction, braking or cornering becomes asymmetric due to the change of contact pressure distribution as well as

the shear stress effect which leads to the generation of tire force and moment. The strain data measured from a rolling tire depends on the tire working conditions, as well as the tire structure parameters. Conversely, the strain data also reflects the variation of these tire working conditions and could be used to identify them. Axial strain and circumferential strain are the result of shear stress in tire axial direction and circumferential direction, respectively. They give significant indications about tire in-plane dynamics and out-of-plane dynamics such as braking/traction force and cornering force. Since these strains are generated due to the corresponding stresses, especially those which occur in the tire-road contact patch, their distribution and features play a decisive role in estimation of tire rolling resistance, tire tread wear and other characteristics [19].

The potential features which may contribute to the estimation of tire working conditions and provide information for the vehicle active safety system are recommended herein firstly in order to have a better understanding of strain waveform characteristics. Figure 1 reveals that the strain far from the contact patch region in steady state rolling has a constant value during one revolution of the tire. The constant strain value is affected mainly by the tire inflation pressure. Hence, it is an explicit reflection of the tire inflation pressure. The tire/road contact length is reflected by the time difference between points B and D in the strain rate waveform. The time difference between points A and E is related to the deformed length in Figure 1. The angles θ_c and θ_d are the rotational angles corresponding to the contact length and deformed length respectively. These features described above can be used to evaluate the tire inflation pressure, vertical load, rolling speed, contact patch dimensions and tire forces, etc.

Besides, the amplitude of the strain waveform and the strain shape feature obtained from the tire under different working conditions can also be helpful for determining tire forces [11]. It can therefore be concluded that the main tire strain time history characteristics are directly related to, and can be used to measure, certain tire operating parameters such

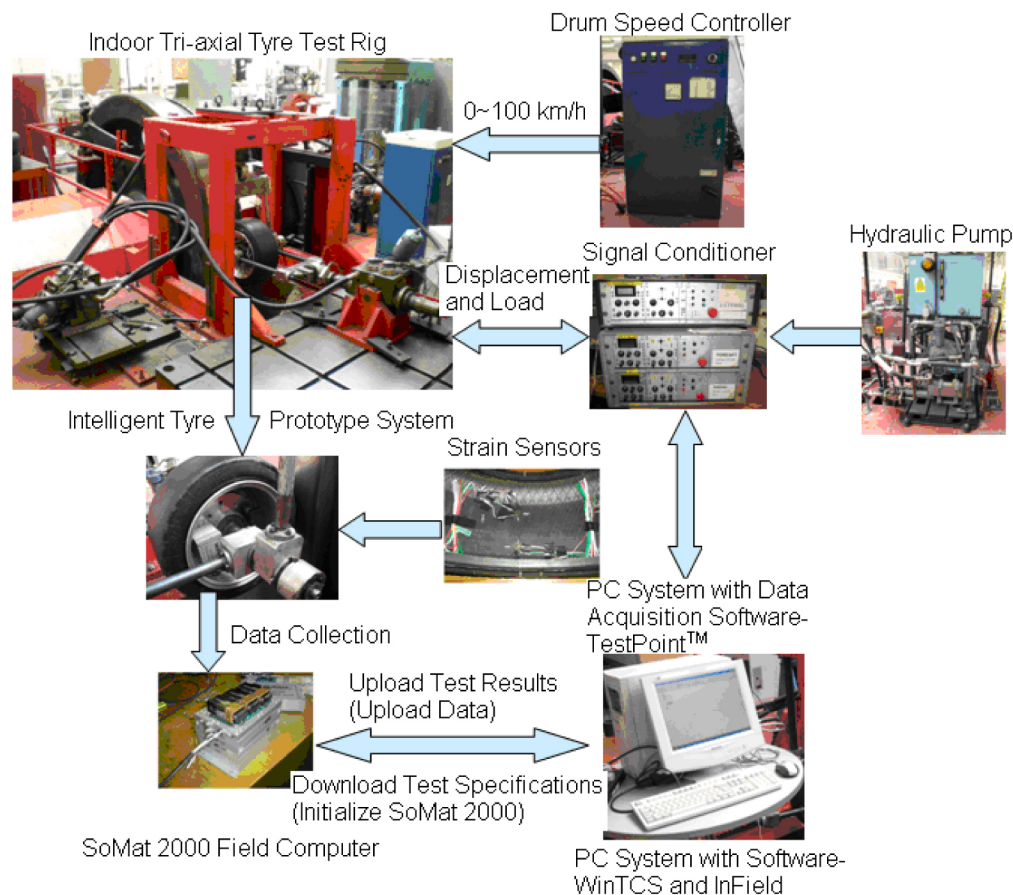


Figure 2. Experimental Configuration of Strain-based Intelligent Tire Test System

as tire pressure, period of revolution (hence rolling speed), tire/road contact length, vertical load, etc.

A major aspect of the work presented in this paper is to investigate the feasibility of a preliminary strain-based intelligent tire system measuring tire dynamic strain with a view to studying dynamic strain characteristics correlated with tire operational conditions in real time.

EXPERIMENTAL STRAIN-BASED INTELLIGENT TIRE SYSTEM

Strain Sensors Configuration and Experimental Setup

An experimental strain-based intelligent tire system has been developed in the Vehicle Dynamics Laboratory, University of Birmingham. A slick radial tire 175/505 R13 for SAE Formula Student (FS) was selected as the candidate tire. The operational range of parameters used for the tire test are:

- Tire inflation pressure: 80 kPa~140 kPa;
- Tire preload: 250N~1000N;
- Tire speed: 10 km/h~50 km/h;
- Tire slip angle: 0 degree~8 degree;

- Tire camber angle: 0 degree (due to the limitation of the test rig).

The configuration including the indoor tire test rig equipped with the strain-based intelligent tire prototype system is shown in [Figure 2](#).

The strain sensors adopted in the system are high-elongation foil strain gauges which can measure up to 15% strain. These strain gauges are applicable for large strain measurement. The gauge length is 2 mm with gauge resistance 120 Ω . The rectangular rosette arrangement of the strain gauges on a base (10 $\times$ 10 mm) is shown in [Figure 3](#). The strain gauges were attached to the inner liner of the tire which is so thin that its deformation is dominated by the stiffness of the carcass cords. Therefore it can be considered that there is no local stiffening effect caused by the stiffness of the strain gauge.

The rectangular rosette strain sensors' support were mounted symmetrically about the tire tread centre line on the tire inner liner surface of the tread as shown in [Figure 4](#) with the manufacturer recommended adhesive, where the d and l are about 0.040 m and 0.515 m, respectively. The selection of d value needs to guarantee the sensors located in the contact patch for different tire test operational conditions.

The strain sensors arrangement was designed to not only measure the strain in tire circumferential, axial and 45 degree