Assessment on the methods of measuring the tyre-road contact patch stresses

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Abstract. The paper reviews established and modern methods for investigating tri-axial stress distributions in the tyre-road contact patch. The authors used three methods of measuring stress distributions: strain gauge method; force sensing technique; acceleration measurements. Four prototypes of instrumented pins transducers involving mentioned measuring methods were developed. Data acquisitions of the contact patch stresses distributions were performed using each transducer with instrumented pin. The results are analysed and compared, underlining the advantages and drawbacks of each method. The experimental results indicate that the three methods are valuable.

1. Introduction
Currently, there are extensive research programmes under development in the field of intelligent tyre. A major role of intelligent tyre will be to provide vital information regarding tyre-road contact for the future autonomous vehicles. The vehicle tyre is strongly stressed by internal pressure, tyre carcass deformations due to contact with the road, and loads applied on the wheel. Consequently, distributions of stresses on three orthogonal directions appear in the tyre-road contact patch. These stresses are responsible for generating all forces in the contact patch which control the vehicle dynamics, but also the tyre / road wear. In this paper an assessment of several methods of investigating tri-axial stresses in the tyre-road contact patch is intended. These methods include the classical approach of stress measurement through strain gauged pins [11], but also innovative approaches, one of them involving piezoelectric force transducers and the other using accelerometers.

The measurement of tyre-road contact stress distributions is a difficult task, as the contact patch should not be altered by the existence of a measuring device between tyre and road. Therefore, such measuring device must be placed either in the road surface or in the tyre tread. In both cases, the rolling conditions are modified to some extent. However the design of test rig must be such that the influence on rolling conditions is kept to a minimum. The stress distributions are strongly influenced by many sets of factors, some of which are determined by tyre design and construction (radial or bias, tread design, tyre dimensions, etc.), and others by exploitation and rolling conditions (inflation pressure, vehicle speed, tyre vertical load, slip angle, etc.) [12]. So far, there are no measuring rigs able to measure stress distributions taking into account all parameters. Most of the existing test rigs are designed for indoor measurements, many of them using strain gauged pins for measuring tri-axial stresses. Such rigs equipped with a single strain gauged pin were used by Seitz [9] and Lippmann [6]. For rolling tyre, tri-axial stress distributions were measured only on a longitudinal strip of the contact area at a time. Other rigs comprised a transversal array of strain gauged pins, such as those developed
by Howell [5] and Pottinger [7]. The transversal arrays had gaps between the pins, which did not allow covering the entire width of the contact patch at a time. Regardless of the number of pins, a small interstice must exist between sensing element and surrounding bed or drum, which somewhat alters the nature of contact. Rig design must take into account that this interstice should be as small as possible.

Few of the existing test rigs are designed for outdoor measurements, such as the complex one developed by De Beer [4]. It allows measuring tri-axial stress distributions for all the tyres of a truck or trailer at a time. The shape and arrangement of pins alters the nature of contact. Measurements can only be performed at low rolling speed.

There is also another method of measuring normal stress in the tyre-road contact patch, using printed circuit technology to create resistive, capacitive or piezoelectric small sensors [8]. The method offers very good resolution. However, it can only be used in static or quasistatic conditions and measures only the distribution of normal stress.

Very few measuring devices are embedded in the tyre tread. The Technical University of Darmstadt developed a measuring device using four Hall sensors embedded in the tyre tread [10]. Tyre deformation was measured under real rolling conditions, even at higher speed. However, the device can measure tyre deformation in only one small contact patch portion of and tyre structure is locally altered.

For measuring tyre-road contact stress distributions, indoor and outdoor test rigs were developed at the University POLITEHNICA of Bucharest. The indoor movable bed rig has an array of force transducers able to measure the shear stresses across the contact patch of a free rolling tyre at low speed [1]. The first outdoor rig was developed for measuring tri-axial stress distributions using a short array of strain-gauged pins [2]. The experiments can be performed for passenger car tyres and truck tyres, in free rolling, traction or braking conditions. The distance between two adjacent pins is a fraction of millimetre. The limited number of pins of this first rig does not allow covering the entire width of contact patch at a time. A new outdoor rig which eliminates this drawback was developed [3].

Many test rigs equipped with strain gauged pins allow measuring the tyre-road stress distributions in static conditions or at low rolling speed. Increase of rolling speed leads to difficulties or to impossibility of measuring stress distributions with several existing test rigs. In this paper, the authors aim to investigate the use of other possible methods of measuring stress distributions besides the strain gauge method. Four prototypes of installations using three measuring principles will further be presented. The viability of these methods will be discussed.

2. Methods for Contact Stress Measurement

2.1. Strain Gauge Instrumented Pins

Two types of strain gauge instrumented pins were designed and manufactured. One of the two types of pin was already used in the first outdoor rig [2]. The dimensions of each type of pin were optimized by FEM analysis. Several requirements were taken into account in the design stage. Each prototype consists of a single metal pin which measures tri-axial forces applied on a square with 10 mm side length, placed in the tyre-road contact patch. Each prototype can be used for measuring contact stress of passenger car and truck tyres, in free rolling, traction, braking, as well as static conditions. The prototypes are designed for outdoor mounting in the road surface, as shown in figure 1.

The distance between the active head and the surrounding area is a fraction of millimetre. For each pin type, measurements were performed in real rolling conditions, using passenger car tyres with tread pattern. Free rolling, traction and braking tests were performed. Various types of vehicles and tyres were used. Samples of tri-axial stress distributions measured as forces applied on one square centimetre are presented in figure 2.
Figure 1. Strain gauged pin prototype placed in the road surface.

Figure 2. Distributions of tri-axial forces measured with type I strain gauged pin (left) and with type II strain gauged pin (right).

These distributions were measured in free rolling conditions on a longitudinal strip of the contact patch area. Sets of measurements in which the pin was in contact with an entire tread block were chosen. The main interest was interpreting the shape of curves, regardless of tyre type or wheel lateral position relative to the strain gauged pin. The analysis of results shows that the shape and magnitude of curves corresponds to the results published in literature. The results obtained using the two pin prototypes are almost similar, which validates each of the prototypes for future applications in a complex transducer. Both prototypes can measure both in static and dynamic conditions. Analysis of curves measured at higher speed shows a delayed return to unloaded position of each instrumented pin due to data acquisition system setup.
2.2. Instrumented Pin with Piezoelectric Force Sensors
An instrumented pin with piezoelectric force sensors was designed and manufactured, as the measuring component of a transducer mounted in the road surface. The metal pin head has a square shape with 10 mm side length, placed in the tyre-road contact patch. A special requirement for the transducer design was that the contact between tyre and road is least altered. Therefore, the distance between the active head and the surrounding area is a fraction of millimetre. The pin was equipped with a piezoelectric force sensor for each measuring direction (normal, longitudinal and lateral), according to the CAD model shown in figure 3.

![Figure 3. CAD model of the instrumented pin with piezoelectric force sensors.](image)

The piezoelectric force sensors were chosen so that they have low frequency response, small dimensions and measuring ranges adequate for truck tyres contact forces. This type of transducer does not measure the distributed forces in static conditions. The measuring rig containing an instrumented pin with piezoelectric force sensors is shown in figure 4. The measuring system, presented in this figure in laboratory conditions, is designed for working outdoors in real rolling conditions.

The transducer containing an instrumented pin with piezoelectric force sensors was used to perform measurements in real rolling conditions, for passenger car tyres with tread pattern. Free rolling tests were performed, as well as traction and braking. Various types of vehicles and tyres were tested. Samples of tri-axial force distributions measured in free rolling conditions on a longitudinal strip of the contact patch area are presented in figure 5.

The analysis of results shows that distributed forces in the tyre-road contact patch can be measured using an instrumented pin with piezoelectric force sensors. The method proved viable for usual rolling speeds. Also, limitations of this method appeared at speeds below 1 km/h, at which signal magnitude decreases, because of the sensitivity of piezoelectric sensors.
Figure 4. Instrumented pin with piezoelectric force sensors mounted in the transducer.

Figure 5. Distributions of tri-axial forces measured using piezoelectric force method.

The shapes and magnitudes of force curves are confirmed by comparison with the curves obtained using strain gauge instrumented pins. It can be noticed that the peak of vertical force distribution is shifted towards the leading edge of the contact patch, in respect to the curves shown in Figure 2. Also, the comparison shows that the curve slope near the leading edge of the contact patch is higher for piezoelectric instrumented pin than those of strain gauged pins. The longitudinal force distribution is more similar to a polygonal shape in the case of piezoelectric method. These aspects can be determined by the accuracy of high frequency behaviour of piezoelectric force sensors.

The method using piezoelectric force sensors is not suitable for developing an array of adjacent instrumented pins covering the entire width of the contact patch, because of the space required by an actual instrumented unit.
2.3. Tri-Axial Accelerometer Instrumented Pin

Tyre-road contact is a dynamic phenomenon, in which forces are applied with shock in the contact patch. Consequently, a stress measuring method was developed using a special metallic pin equipped with a tri-axial accelerometer and placed in the road surface. The design requirements for the pin were the same as for the instrumented pin with piezoelectric force sensors.

The tri-axial accelerometer was chosen so that it has low frequency response, small dimensions and measuring range adequate for contact patch accelerations, which can have high values due to the tyre-road impact. This type of transducer does not work in static conditions. The measuring system was designed for working outdoors in real rolling conditions, for passenger car tyres, in free rolling, braking and traction conditions.

A multi-channel data acquisition system was developed and specially designed LabVIEW applications have been used for data acquisition and for obtaining distributions of tri-axial displacements by integration of accelerations measured on all three directions, such as the detail in figure 6.

Figure 6. Detail of LabVIEW application for integration of accelerations on three directions.

Various types of vehicles and tyres were tested. Figure 7 shows an example of data acquisition of pin accelerations on all three directions due to the tyre-road contact. The pin impact at the leading edge of the contact patch and the pin release at the trailing edge are clearly visible in figure 7, especially on the vertical direction, where larger forces are applied. The first impact is followed by vibration phenomena, mainly due to pin resonance.

The measured accelerations were integrated two times each, to obtain the pin displacements on the x, y, and z directions. The integration calculi have to be carefully made for decreasing the errors. The displacement results are presented in figure 8. Displacement shape on Z direction presented in figure 8 has a good correlation with the force graph measured using piezoelectric force method shown in figure 5.

Although the shapes of the X and Y displacement are relatively in accordance with results obtained through strain gauge instrumented pin method, their magnitudes are very small. The explanations are: very small shear stresses in the tyre-road contact patch, and a partially inadequate pin design for this application. In the future, a new pin design will be elaborated for enhancing the results accuracy. Also, a dynamic calibration will be performed for computation of force distributions.

The results are encouraging and it is necessary to continue the investigation of stress distribution through acceleration method. It is noted that this method could involve accelerometers placed in the road, but also in the tyre carcass. In this case, important information regarding contact patch phenomena could be obtained for enhancing the vehicle safety.
3. Conclusions
Three methods of measuring tri-axial stress distributions in the tyre-road contact patch have been investigated: strain gauge method; force sensing technique; acceleration measurements. The validity of each of the three methods is proved by the experimental results. For each mentioned method the main advantages and drawbacks were underlined. For all methods, the shapes and magnitudes of tri-axial stress (force or displacement) distributions are similar to those published in literature.

The results obtained using the two strain gauged pin prototypes are quite similar. Both strain gauged instrumented pins can measure in static and dynamic conditions. Comparative analysis of curves measured at higher speed by different methods shows a delayed response of each strain gauged pin, leading to a shift of the peaks and decrease of curve slopes. On the other side, fast response of instrumented pin is obtained when using methods based on force and acceleration measurements.

Figure 7. Data acquisition of pin accelerations on all three directions during tyre-road contact.

Figure 8. Pin displacements on three directions obtained by integration.
The method using piezoelectric force sensors is not suitable for developing an array of instrumented pins covering the entire width of the contact patch, because of the space required by an instrumented unit.

The stress distributions could be also obtained starting from measuring accelerations of an instrumented pin. An intermediary step consists of obtaining the pin displacements through integral calculi, but errors could appear. Good correlation occurs between the displacement curves and the force graph measured through piezoelectric force method. A new pin design is necessary, and a dynamic calibration has to be performed for acceleration instrumented pin.

The investigation of phenomena in the tyre-road contact patch with accelerometers placed in the road, but also in the tyre carcass, is capable of offering valuable information for enhancing the vehicle safety.

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