NOVEL EXPERIMENTAL CHARACTERIZATION OF THE TIRE-PAVEMENT SYSTEM

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ABSTRACT

The knowledge of contact parameters in tire-pavement systems, represents a critical factor in many issues related to the assessment of both pavement damaging (where the contact area and pressure distribution assume the role of input boundary condition) and tire tread performances. Nevertheless, it is remarkable the lack of high-accuracy experimental techniques able to supply such critical information, being the most widespread methods (such as VRSPTA or other commercial pressure-sensitive devices) characterized by a relatively low spatial resolution level. In order to partly overcome such drawback, the present study proposes a novel approach to investigate tire-ground system that exploits the property of high-frequency ultrasonic waves to be differently reflected by a contact interface depending on its stress state. The application of this non-invasive method allows to obtain in real time graphic maps of contact conditions as well as quantitative information as regards geometric features of the contact area (i.e. size and shape) and contact pressure distribution values (after suitable post-processing procedures) with a resolution up to 0.1 mm. In order to quantitatively assess the reliability of the ultrasonic technique, a number of laboratory tests were carried out for the case of the contact of a motor-bicycle tire on a rigid surface under different conditions as regards inflation pressure and applied load. For each tested case, the raw ultrasonic reflection data were converted into graphic maps that display the contact area features and, at the same time, contain information about magnitude of contact pressures. The preliminary results are quite encouraging and let us foresee a future use of this method to support and improve numerical simulations of tire-ground contact and to evaluate the performance of new and existing road pavements thus supporting the reliability of their design and the management process during their life-cycle.
Keywords: tire-pavement contact, experimental, ultrasonic waves

1. INTRODUCTION AND PURPOSES OF THE STUDY

A significant number of key issues related with road transport, from pavement failures to vehicle performance and energy consumption, are strictly related to phenomena which originates at tire-pavement interface. Despite the importance of such system, the amount of available information about main contact parameters still cannot be considered fully satisfactory, mainly because its inaccessibility makes it quite difficult to investigate it with most experimental techniques.

Past studies showed that it is relatively easy to characterize the tire-pavement contact in terms of size and shape of nominal contact area, even when simple approaches are employed. In 1974, Yeager investigated about hydroplaning by taking pictures of the contact patch for a tire pressed against a transparent support with a camera located under the plate; a similar approach was later employed by Yong et al. (1980) to develop an analytical model able to predict the tire deformation and the resultant energy loss.

The use of tracing media (e.g. ink and carbon paper) aimed to obtain prints of the contact patch to visually check its shape and also extract quantitative information about its size (e.g. overall contact area and length of its axes) has been extensively carried in the last two decades, and results of such measurements are reported for the contact of both tractor (Plackett 1984, Upadhyaya and Wulfsohn 1990, Lyasko 1994) and off-raod tires (Grečenko 1995).

It is noteworthy that most of the aforementioned methods are unable to supply information on contact pressure distribution, as they only allows to estimate the average contact pressure by dividing the applied load by the measured area. Thus, it appears essential to have available experimental methods by which to measure normal and shear stress so as to integrate the two kinds of data and collect more detailed knowledge on the whole contact phenomenon. Early experiments aimed at measuring contact stresses in a tire-road system were carried out in 1941 by Markwick and Starks, who developed an ingenious system based on a sort of electrical resistance strain gage; with this system they were able to reproduce both normal and shear stress profiles along the major and minor axes of the contact ellipse.

Yeager (1974) used 0.5” diameter triaxial load pins to measure the forces acting on the contact area at discrete locations. Marshek et al. (1986) employed a pressure-sensitive film to investigate contact between a truck tire and a rigid surface; they assessed the influence of tread pattern, tire inflation pressure and axle load on size and shape of the contact area and contact pressure distribution.

Tielking and Abraham (1994) built a plate on which a movable shoe with 10 load pins was mounted, thus providing contact pressure profiles at various transverse locations. De Beer et al. (1997) developed the ‘Vehicle-Road Pressure Transducer Array (VRSPTA)’ which basically consists of an array of triaxial strain gauged pins mounted on a steel plate fixed on an actual road surface. With this system they were able to measure simultaneously vertical, transverse and longitudinal contact stress on a whole contact patch with a resolution of about 17 mm for slow moving wheels (25 km/h maximum).

Measurements of normal, longitudinal and lateral shear stresses were recently reported by Hall et al. (2003), who performed experiments under static and dynamic conditions with a rolling drum and a flat bed testing machine to characterize contact patch behaviour for different external conditions as regards applied load, slip and camber angle.

From the analysis of the literature, it appears evident that most methods capable of displaying and monitoring the evolution of contact area geometry have little (or no) capability of reproducing contact pressure distribution. The only exception is represented by commercial pressure-sensitive films (such as Fuji Prescale) but, apart from cost, this method requires long and painstaking procedures in the preparation of the test and the processing of data. Moreover, each test requires the loading and unloading of the components, and this means that the evolution of the contact parameters cannot be followed in real time while the external conditions have changed.

Finally, it is to be recalled that this kind of film works properly only in a well determined (and usually narrow) range of contact pressures, and the error in their estimation can be up to 20% unless some sophisticated (and expensive) devices are used for densitometric analysis,

On the contrary, most devices used to measure stress state are basically built by assembling a number of uni- or multi-axial force transducers that must necessarily be placed in single discrete locations of the contact area. This fact results in a limited resolution of pressure distribution data, and thus the integration of such measurements with a 'traditional' technique capable of displaying size and shape of the contact area appears to be essential.

On the basis of the aforementioned considerations, in this study we propose the application of an ultrasonic, non-invasive technique to investigate the contact between a tire and a rigid surface. As shown in detail below, this method exploits the properties of high-frequency ultrasonic waves to be differently reflected by a contact interface depending on its stress state. Thus the ultrasonic reflection can be graphically processed in real time to build 'contact maps' that display size and shape of the contact area and supply preliminary qualitative information about contact pressure distribution. Quantitative measurements can then be performed starting from the raw ultrasonic data by means of a calibration process.

The method was applied to the contact of a motor-bicycle tire with a rigid plastic surface. Tests were carried out by varying both the load applied and the inflation pressure and for each case a contact map, including contact pressure values, was obtained. Furthermore, to assess the reliability of the technique, the ultrasonic results were compared with those obtained by means of a commercial pressure-sensitive film.

2. ULTRASONIC CHARACTERIZATION OF CONTACT: BASIC PRINCIPLES

Ultrasonic waves are currently used in a wide range of engineering fields as one of the most useful non-destructive testing technique; this method allows detection of flaws inside materials due to reflection and scattering phenomena which originate when the beam interacts with the surface of separation between two media having different acoustic properties.

Nevertheless, in late '50s (Krachter 1958) it was observed that high frequency ultrasonic beams are also characterized by the interesting property to be differently reflected (and transmitted) by a contact interface according to its stress state.

In particular, for the ideal case of perfectly adhesion between two media characterized by a certain value of acoustic impedance Z_i, the reflection coefficient R is load-independent and expressed by the following relationship:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad \text{(Eq. 1)}$$

However, engineering contacts are usually far from the ideal hypothesis of perfect adherence and, most likely, they can be considered as a sequence of parts in contact (the Real Contact Area, RCA) and voids that act as reflectors of sound energy due to the fact that only a negligible part of ultrasounds can be transmitted across a solid-gas boundary.

This means that in a real situation the coefficient of reflection is no longer independent of the applied load since an increase in contact pressure will result in a reduction of the number and size of the interface gaps. In particular, since the continuity of the interface improves as the RCA increases, a smaller part of the ultrasonic waves will be reflected, and thus the observation of a decrease in the amplitude of the reflected signal denotes a better contact state.

By expressing the coefficient of reflection (R) as a ratio of the amplitude of the incident wave (H_0) in absence of load (or outside the contact region) and the amplitude of the reflected wave for a certain applied load i (H_i) as follows:

$$R = \frac{H_i}{H_0} \qquad \text{(Eq. 2)}$$

we have a parameter for which the quantitative analysis of its variation allows assessment of the better or worse level of contact between the two parts. In particular, the process extremes occur:

1. *maximum: when the reflection coefficient R is 1*

In this case no energy is transmitted through the interface (i.e. no contact exists or the external load is null)

2. *minimum: when the value of R (<1) is given by Eq. 1*

All the energy is transmitted through the interface, implying that each point of the two surfaces is in perfect contact (ideal situation). In the case of a homogeneous contact (e.g. steel-steel, easy to find in most mechanical contacts) this value is 0; when different materials are coupled we expect to find values of R>0 depending on the acoustic impedance values of the contacting bodies. It is to be noted that the contact of similar materials (in terms of acoustic features) is easier to investigate with this technique, since the variation in amplitude of the wave reflected by the interface is more relevant with respect to cases in which the significant difference of acoustic impedance makes the reduction of the reflection hardly detectable even when the contact is almost perfect.

Such properties can be exploited to reproduce (and measure) the nominal contact area features: in this case it is relatively easy to determine the size and shape of a contact patch since it is sufficient to discriminate the point at which a complete ultrasonic reflection occurs (i.e. no contact is present) from the points at which the same parameter assumes a value lower than unity.

The method can also be employed to estimate the contact pressure distribution, but it must kept in mind that the reflection from the interface is affected not only by the contact state, but also by the frequency of the incident wave and surface roughness. Thus, the transformation of raw ultrasonic data into actual contact pressure values requires a preventive calibration process in which an empirical 'reflection vs. pressure' relationship is established on the basis of experiments carried out on known contact situations (e.g. Hertzian or numerically solved). The results can then be transferred to an unknown contact geometry (regardless of the kind of existing pressure distribution), being careful to keep all the above variables unchanged.

Practical examples of such procedure has been recently proposed by Pau and co-workers for wheel-rail systems (Pau et al. 2001) as simple sphere-plane contacts (Aymerich et al. 2003) while Dwyer-Joyce and Drinkwater (2003) investigated contact stresses in machine elements and joints. These experiences have confirmed the reliability and usefulness of the ultrasonic method as a simple, rapid and reliable technique for determining contact pressure variations in both metallic and non metallic interfaces.

3. MATERIALS AND METHODS

3.1 Tire-ground contact

A 2 3/4-16 43J motor-bicycle tire (Vee Rubber International Co. Ltd., Thailand) characterized by a tread consisting of grooves in a zig zag pattern, was mounted on a 16" wheel and housed inside a simple aluminium frame as shown in Fig. 1.

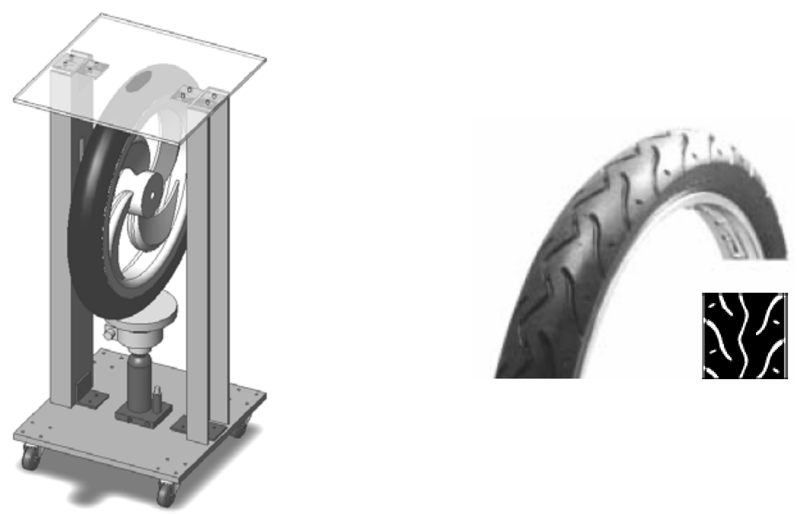

Figure 1 Tire-plate contact. Left: arrangement of the components for the ultrasonic analysis, Right: tire tread pattern

A hydraulic jack and a load cell were placed under the wheel to apply and monitor the applied load respectively, while the upper part of the wheel was put in contact with a PolyMethylMethAcrylate (PMMA) rectangular plate having a thickness of 7.5 mm.

This material was chosen for its acoustic properties, which are similar to rubber , thus ensuring a good dynamic range for the ultrasonic amplitude variations.

A small plastic container filled with water was placed on the other side of the PMMA plate in such a way as to ensure optimal transmission of the waves from the transducer to the contact region.

The tire, which was inflated to pressures of 200, 250 and 300 kPa, was loaded with a load varying from 600 N to 1200 N (in steps of 200 N), thus achieving an estimated average contact pressure in the range of 0.35-0.40 MPa

3.2 The ultrasonic set-up

One of the strongest points of the ultrasonic method is that no special equipment is required to perform a contact analysis; it is possible to employ a common ultrasonic pulser/receiver (of the kind used for routine NDT tests) coupled to an appropriate transducer. In this study, a 10 MHz longitudinally focused immersion probe was used as it gives the best compromise in terms of spatial resolution of contact maps and penetration power in the PMMA layer. The probe, which is immersed in water at a suitable distance to focus the ultrasonic beam exactly on the contact area, is moved by a three-dimensional scan system and connected to a Panametrics 500PR 25 MHz pulser/receiver; the ultrasonic signal received from the contact interface is constantly monitored on a Tektronix TDS3012B 100MHz digital oscilloscope. As the transducer is scanned over the potential contact region, the values of the ultrasonic reflection are stored in text matrices for further post-processing procedures.

Both the scan system and the detector are controlled by a PC with house-made software built in the LabView environment which allows:

- acquisition from the oscilloscope (and storage in a file if requested) of either the amplitude or the whole ultrasonic signal (via Ethernet connection);
- control of the probe movement in real-time by means of user-defined sequences;
- processing of ultrasonic data in real time by graphically displaying them as 'contact maps' in a false-color scale.

For each load step, ultrasonic scans were performed on 50x150 mm rectangular regions, with 0.25 mm (fine map) or 1 mm (coarse map) steps, thus obtaining matrices composed respectively of 120000 and 7500 terms, in which the generic a_{ij} term represents the amplitude of the ultrasonic reflection from the interface at a given point.

The subsequent graphical post-processing of the matrices allows preliminary evaluation of the contact conditions; the regions in which the coefficient of reflection is lower are related to better contact conditions, while as we move towards the edge of the contact area the reflection increases up to the unity value which corresponds to absence of contact.

Transformation of the raw ultrasonic data into contact pressure distribution was carried out by means of a preventive calibration procedure (as previously mentioned) which resulted in an empirical 'reflection vs. pressure' relationship established on the basis of experiments carried out on a known contact situation (in our case a Hertzian sphere-plane contact). Once obtained, the calibration curve was transferred to the tire-ground reflection matrices thus converting them into contact pressure maps.

3.3 The pressure sensitive film

A commercially available pressure sensitive film (Fuji Prescale, Fuji Co. Tokyo, Japan) was used to assess the reliability of the ultrasonic results; this is a kind of film widely used especially in biomechanics (in critical situations such as contact problems in human joints), which allows the measurement of nominal contact area and contact pressure through a system of small microcapsules filled with liquid (2-25 μm diameter) included in (two-sheets type) or coated with (mono-sheet type) a polyester base and a color-developing layer.

Once the film is placed between the two contacting surfaces and load is applied, the microcapsules break and the color-forming material reacts with the color-developing material, thus originating the presence of red patches on the film. A proper analysis of color intensity can be carried out either by a simple visual comparison with a reference table provided by the manufacturer or by using a more sophisticated (and expensive) densitometric analysis system such as Fuji FPD-901, which automatically converts the tones of red into pressure values.

Although the system is quite simple to apply and the qualitative assessment of contact parameters almost immediate, a detailed quantitative analysis of such parameters appears to be more complicated and requires the use of a suitable scanning system and image analysis software.

In our tests, cuts of Fuji Prescale Ultra Super Low film (LLLW, two-sheet type, pressure range 0.2-0.6 MPa) were interposed between the tire and the plate and the load was applied according to manufacturer's instructions for so-called 'continuous pressure' (the desired load is reached in a time of 2 minutes and then maintained for an additional 2 minutes). The impressed film was digitized by means of a 2400 dpi optical scanner, thus obtaining a 8-bit gray level picture (0=black, 255=white) from which to extract the necessary information about size and shape of the contact area. A fresh (not impressed) cut of film was scanned together with the results of the tests and its value of gray was assumed as the reference standard for the zero pressure value.

To obtain pressure maps from the film, a density calibration procedure was established: both the reference density table and the 'density vs. pressure' curve (supplied by the manufacturer) were digitized using the same parameters as the tire-plate acquisitions, and the density index was translated into gray level using the public domain software ImageJ (National Institute of Health, USA). Since each density index is related to a certain value of contact pressure, it is possible to build a 'gray level vs. pressure' calibration curve which can be input in the software. Following this procedure, the original film scans were converted into pressure maps.

4. RESULTS AND DISCUSSION

4.1 Ultrasonic tests

As previously mentioned, the data collected from the ultrasonic analysis can be graphically arranged by establishing a correspondence between the value of the reflection coefficient and a color on a map. In such a way, it is possible to both visualize the shape of the contact region and measure the main geometrical parameters of the patch. The typical processed output of the ultrasonic tests is shown in Fig. 2: the contact area, which appears elliptical in shape, is characterized by the highest values of the ultrasonic reflection (the red regions) where no contact is present, namely outside the contact area and in the tire groove locations. The lowest reflection values, which correspond to points at which contact pressure is higher, are mostly located along the major axis of the ellipse and around the groves, as expected for the presence of edge effects.

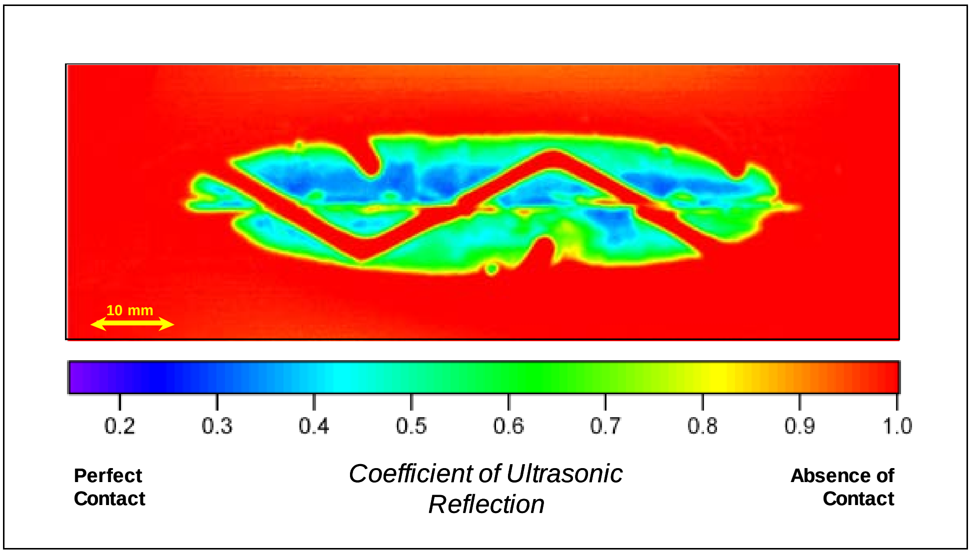

Figure 2 Graphic processing of ultrasonic refection data for a tire-plate contact (applied load 600 N, inflation pressure 250 kPa)

The evolution of the tire-ground contact area for a fixed inflation pressure (250 kPa in this case) and increasing load is reported in Fig. 3: it is clearly evident that the ultrasonic technique is able to faithfully monitor variations in the contact patch caused by changes in external conditions.

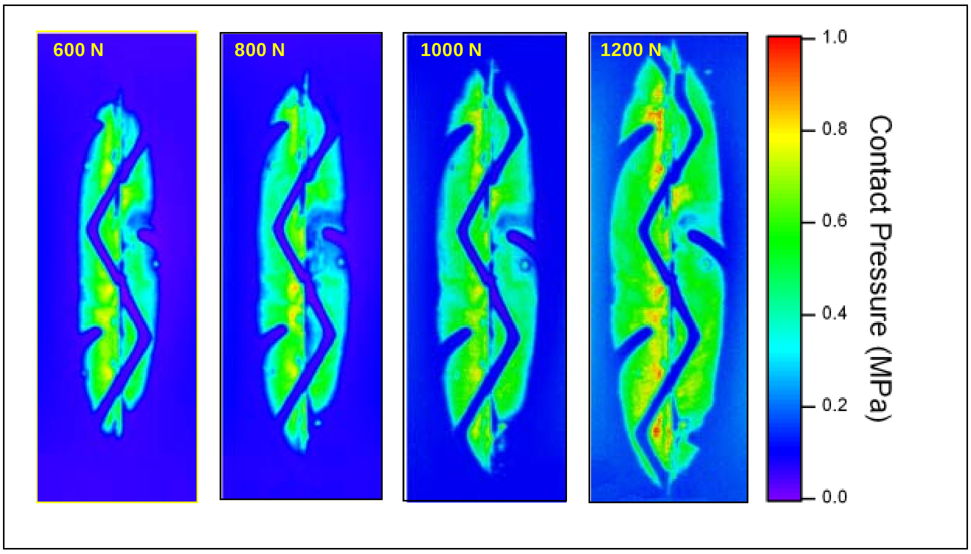

Figure 3 Ultrasonic maps of contact: evolution of the contact ellipse for increasing applied loads (inflation pressure 250 kPa)

4.2 Pressure sensitive film results and comparison between the two experimental techniques

In Fig. 4 are reported the scan of the pressure-sensitive film obtained for some of the cases tested.

The high-resolution digital reconstruction clearly shows the granular nature of the film, which appears as discrete microstains. This peculiarity, which allows observation of significant oscillations in gray density (and thus in contact pressure) values, was previously observed and investigated by Hale and Brown (1992). Nevertheless, despite these problems of accuracy at the microscopic scale, the global performance of the pressure-sensitive film was found to be in agreement with previous tests reported in the literature. In fact, the average estimated error, which was calculated by integrating contact pressure over the whole scan area and comparing it with the applied load, was +8%.

A comparison between the values of the tire-ground areas measured with the two experimental techniques employed is summarized in Fig. 5. From the diagram we can see a good qualitative agreement of the curves while, from a strictly quantitative standpoint, the average difference between ultrasonic and pressure-sensitive areas was calculated at +15% (i.e. ultrasounds tend to overestimate the area compared with the pressure-sensitive film).

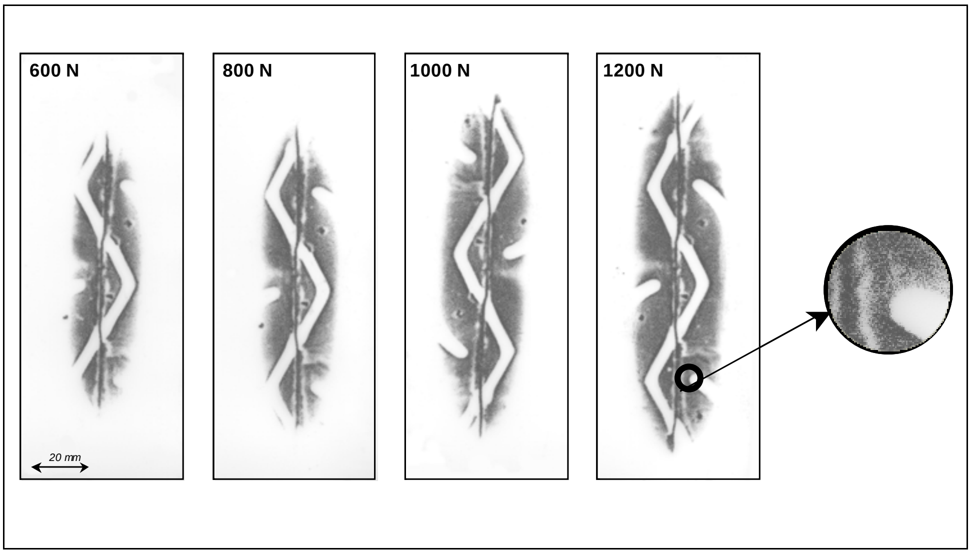

Figure 4 Evolution of the contact ellipse for increasing applied loads as obtained from the pressure-sensitive film tests (inflation pressure 250 kPa) Right: magnification of a detail of the results.

A possible reason for this difference can be found in the fact that the contact area calculation performed on the basis of the pressure-sensitive film data was performed by selecting the points as belonging to the ellipse axes, within the allowable range of measurement declared by the manufacturer (i.e. 0.2 MPa as the lower threshold). This fact may lead to underestimating their actual lengths, because it may be that points at which the contact pressure is lower than 0.2 MPa are actually still part of the axes, but since under this threshold the error cannot be controlled, it is necessary to exclude them from the computation.

Another possible source of difference in the experimental measurements is related to the size of the ultrasonic beam which, in our case, was calculated for a steel target test.

Although further investigations are required to quantitatively verify this hypothesis, it is likely that the PMMA plate (since the longitudinal speed of the waves was lower than in steel) alters the beam size so as to make it larger than expected, thus slightly increasing the overestimation effect.

5. CONCLUSIONS

The present study investigated the feasibility of application of a non-invasive experimental method based on ultrasonic waves as a tool suitable in characterizing the contact between a tire and a rigid surface.

Laboratory tests were carried out on the case of a motor-bicycle tire in contact with a rigid plastic plate while varying external conditions such as applied load and inflation pressure. The possible contact region was scanned with 10 MHz frequency longitudinal ultrasonic waves and the reflection from the interface, which is known to be related to the normal contact stress, was acquired and transformed into contact maps.

The graphic processing of the raw reflection data, produces in real time the shape of the nominal contact area and provides a preliminary qualitative distribution of contact pressure, the regions characterized by a lower coefficient of reflection being the ones most stressed.

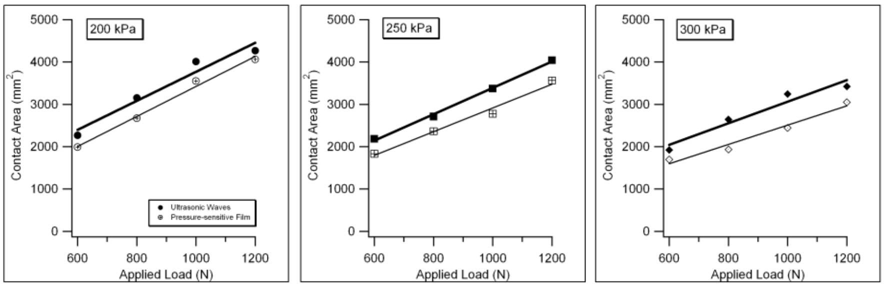

Figure 5 Comparison between the contact area values obtained from ultrasonic and those from pressure-sensitive film tests

Further post-processing procedures, which involve the use of common image processing software and a dedicated calibration process, make it possible to calculate the length of the contact ellipse semi-axes, the overall contact area value and the contact pressure distribution on a point-by-point basis.

The results was also compared with another experimental technique (namely a commercial pressure-sensitive film) so as to establish the quantitative reliability of the ultrasonic measurements and a fairly good agreement was found between the two methods, thus confirming the validity of the ultrasonic approach. Nevertheless, it is to be noted that at present the method is in practice restricted to the laboratory and has been tested only in static conditions; in any case it is not unrealistic to foresee possible future applications even under rolling contact conditions.

In conclusion, it is possible to state that the ultrasonic method may be useful in obtaining high-resolution maps of tire-ground contact pressure distribution to experimentally verify the efficiency of new tire designs, to better understand the mechanisms of failure of road pavements and, in general, to give strong support to numerical simulations in investigating tire-ground contact when external conditions are either unpredictable or difficult to be modelled.

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