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Digital Image Correlation to analyse stick–slip behaviour of tyre tread block ☆

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A B S T R A C T

Stick–slip behaviour is a common but not entirely understood tribological phenomenon. The sliding motion of a rubber sample was studied on a glass plate. The local sliding velocity field of the contact area was calculated by means of Digital Image Correlation and compared to the measured friction force. It was observed that the sliding of individual sipes nucleates from the side edge, whereas the sliding of a tread block propagates from the leading edge. Phase shifts between tread block detachments were observed. Furthermore, a velocity field for a precursor is presented which indicates only the local sliding of the contact without the triggering of a global detachment. The relevance of the result for rougher surfaces is discussed.

1. Introduction

Rubber friction is of the utmost importance in many applications, such as automotive tyres. In the rolling contact of the tyre, the continuous stiction-to-sliding transition in the contact area contributes significantly to the maximum achievable force level. In particular, in emergency braking the tyre operates at around an 8–10% slip ratio, resulting in a situation where the leading edge region of the contact patch clearly sticks to the road. As a result of the evolution of the deformation during contact, the rubber is later detached to sliding. Therefore, the detachment of the rubber contact is an interesting research topic; it has an obvious impact on e.g. braking performance of the tyre, tread wear and noise. In addition to the stiction-to-sliding transition of rolling contact, the rubber may enter a recurrent stick–slip motion, which inevitably has an important effect on the achievable tyre force.

Tyre grip and rolling resistance are traditionally controversial performance criteria because of the viscoelasticity of the tread rubber. Thus, any innovative ideas to improve the grip of the tyre without modifying the rubber compound can be utilised as alternatives to reduce the rolling resistance if the compound is adjusted to provide the same grip level as the original.

Optical methods are often used to study the contact between the rubber and the surface. For example, Roberts investigated the contact between smooth rubber and glass optically by means of optical interference [1]. In another study [2], the contact area of glass and hemispherical rough rubber was visualised by means of white light interferometry and the local velocity was calculated with Particle Image Velocimetry (PIV). In [3], the frictional stress distribution between a glass lens and rubber was determined from the inversion of the measured surface displacement field. The slip dynamics of a rubber–glass interface were studied in [4] and the surface displacement field during slip pulse propagation was determined and the contact between a glass hemisphere and a rough elastomer block was studied using Digital Image Correlation (DIC) velocimetry in [5]. It is also possible to study the rapid growth of cracks in materials by means of a high-speed rotating-mirror camera and DIC analysis [6]. The visualisation of the stick–slip phenomenon was recently reviewed in [7]. However, there are not many studies on the stick–slip phenomenon at a high sliding speed, especially if realistic vertical loads for automotive tyres are considered. In addition, there are very few studies where a planar rubber slider on a planar surface is analysed, a hemispherical slider on a plane being a more common approach. However, plane–plane sliding systems are very common in practice, e.g. in tyres, shoes, windscreen wipers [8], and seals.

An optical measurement system to study friction on transparent surfaces is introduced in this paper. An investigation is performed of how a sipe of the tyre tread block can vibrate in recurrent stick–slip motion. The velocity field of the sipe reveals the propagation of the detachment wave and shows how the detachment of one sipe may or may not lead to global sliding motion of the tread block. In addition, the behaviour of four individual tread blocks during stick–slip motion is explored and their contribution to the global friction force that is achieved is demonstrated.

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Some test parameter values produced clear precursors during the start of the motion of the sample and the contact phenomenon was analysed by means of DIC for this particular event. An aim is also to link observed phenomena to a more general tribological context than just the tyre friction as an application.

2. Methodology

2.1. Experiments

The measurements were conducted in a linear friction tester [9], where a rubber sample slides over a substrate. The substrate can be asphalt, concrete, ice, or glass. A glass plate was used in this research (Fig. 1). The load is applied by a pneumatic cylinder and linear motion is applied by a servo motor. The vertical and shear forces (F_z,F_x) acting on the sample are measured by a piezoelectric force sensor. As the sensor, sample holder, and rubber are moving, the sensor inevitably measures the inertial forces of this system. Because of the structure of the linkage, which allows vertical motion of the sample holder, the friction force has weak coupling to the vertical force, i.e. F_x results in a slightly decreasing F_z. This coupling has a stabilising effect on the stick–slip motion.

A high-speed camera was installed under the glass plate and the images that were captured were calibrated to metric scale with a calibration pattern (graph paper) over the surface of the glass.

The rubber sample (60×60 mm^2) was manufactured from a typical tread rubber compound (Shore A 55) and it was vulcanised in a mould. The sample has four individual tread blocks where each consists of five sipes (Fig. 2). The holes seen in the tread block are for studs, which were not used in this study. The height of the solid rubber under the tread block was 12 mm and the height of the tread block was 10 mm. The depth of the sipes was 6 mm.

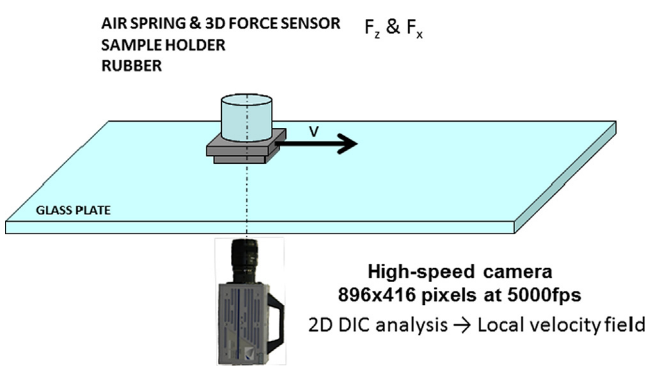

Fig. 1. Linear friction tester with in-situ high-speed camera.

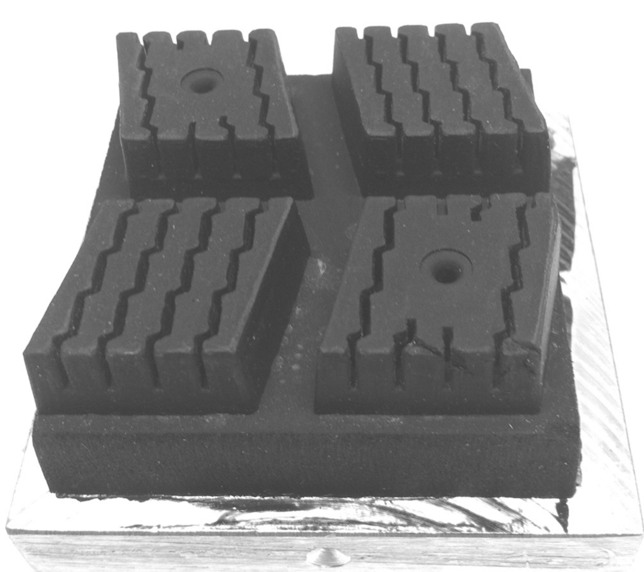

Fig. 2. Rubber sample used in the experiments.

2.2. Data acquisition and data processing

The force data were captured at 10,000 Hz and the image data at 5000 frames per second (fps). The data from two different sources were synchronised by stopping the data capturing at a common, previously defined, location available from the servo motor encoder of the linear friction tester.

The high-speed camera data were post-processed by Digital Image Correlation (DIC) in order to calculate the local velocity field of the rubber [10,11]. DIC calculates a cross-correlation of the subsets in the consecutive images. A shift indicating a peak cross-correlation is considered as a displacement of the subset between the images. The subset was 33×33 pixels for the tread block and 15×15 pixels for the sipe. In theory (based on optimal conditions [10]), one could reach an accuracy of 4 μm for the tread displacement and 8 μm for the sipe, but noise, distortion, and the non-optimal contrast within the subset substantially reduce the accuracy [11]. However, subpixel accuracy is clearly expected for this setup, where the length of each pixel is ~0.16 mm on the sample surface.

No additional markers on the rubber surface were needed to facilitate the DIC calculation. It was possible to measure the velocity of even individual sipes without any markers. If the markers were available, Particle Tracking Velocimetry (PTV) [12] might be a better alternative, because in DIC the “markers” should be randomly distributed. However, a network of dots has been used successfully to monitor an in-plane surface displacement field under torsion [13].

The high-speed camera also captured areas which were not in contact with the glass. Thus, the Region of Interest (ROI) was defined for the first image in the sequence and only the velocity of this area was calculated (Fig. 3). The ROI was shifted continuously on the basis of the DIC deformation field. Consequently, the ROI moved with the tread block or sipe when they were sliding. The fact that the ROI shifted along the deformation field serves as a rough validation of the DIC estimate for a particular image sequence (the ROI must overlay the same pattern at the end of the sequence).

The velocity for a small area of the sample holder was also evaluated with DIC, mainly for validation purposes (it should match the requested sliding speed of the linear friction tester).

The DIC method (as an optical method) is very favourable for rubber, because harmful reflections are absent. Meanwhile, the glass plate, as a sliding counterpart, may introduce reflections or patterns which do not move along the rubber. These effects occasionally appear in this specific measurement setup, but can often be eliminated by adjusting the lighting.

3. Results and discussion

3.1. Stick–slip dependency on load and sliding velocity

The tests were performed for three different loads and velocities, as shown in Fig. 4. The figure shows the friction coefficient (or, better to say, the normalised shear force) from a standstill situation to complete sliding. The 100-mm/s sliding speed does not show any high amplitude stick–slip on the observed length scale. The sliding friction coefficient μ_d is approximately 30% higher for 200 N than for a 600-N load. Additionally, some clear precursors or microslip can be observed [14–17], which are due to