Local Effects Between the Tyre and the Road

The tyre is the integral part of the vehicle that transmits all normal and tangential forces between the vehicle and the road. The tyre tread block is the only tyre component that is in direct contact with the road surface and is thus of special interest. However, the contact situation between the tyre and the road is a very complex one, and therefore all its details are usually unknown. The Institute of Dynamics and Vibration Research at Leibniz University Hanover (Germany) and the Insitute of Machine Elements, Design and Production of the Technical University Freiberg (Germany) investigate the local contact phenomena in the tyre/road contact and developed a modular model that describes the dynamic behaviour of tyre tread blocks, taking into account the contact effects.

1 Introduction

The interaction between the tyre and the road is very complex and highly nonlinear. The mechanical behaviour of the tread block in contact with the rough road surface predefines the contact situation between the tyre and the road. The road surface is composed of stones, sand, filler and binder and therefore comprises a large range of surface wavelengths that directly influence the tyre's performance. In the rolling process of the tyre, the contact between the tread block and the road surface is characterised by a dynamic sequence of loading and unloading, with alternating local sticking and sliding phases, particularly in the trailing contact zone. Especially under braking and cornering manoeuvres, the contact regions with a local sliding motion of the tread block on the road surface increase significantly. Due to the rolling motion of the tyre, the contact of an individual tread block can be seen as a chronology of recurring single contact events.

The surface texture of the road surface leads to a contact situation with local contact regions that only exist at the highest surface asperities [1]. Therefore, the area of real contact is only a fraction of the nominal contact area, which leads to high local contact pressure and therefore to large local deformations [2]. The area of real contact depends particularly on the surface texture of the road, as well as on the material properties of the contacting bodies and on the effective load. For the experimental investigation of the local contact spots, a pressure-sensitive film is used. If pressure is applied to the film, microcapsules break and a chemical reaction generates a colour impression that is proportional to the local contact pressure in the respective limited measurement range. The large range of surface wavelengths of the road leads to a large range of the local contact pressure between the tyre and the road. Therefore, pressure-sensitive films with different measurement ranges are used to identify the normal contact pressure over a wide range. The single measurement results are combined, thus yielding an integrative impression of the local loads.

As an example, **Figure 1** shows a measured normal contact pressure distribution between a quadratic tyre tread block and a concrete road surface with a nominal contact area of 225 mm² under a nominal contact pressure p_N of 0.3 N/mm². The contact situation leads to local pointwise contact regions and a small percentage contact area. A maximum local normal contact pressure of more than 10 N/mm² can be identified, which is at least more than a factor of 30 of the nominal contact pressure.

2 Experimental Investigations

2.1 Investigation of Local Contact Phenomena

As the load applied to the tread block increases, the rubber material is pressed more and more into the road surface. Two different contact phenomena can be observed. Firstly, the number of the local contact spots increases as the normal load increases. Secondly, the area of real contact at the existing contact spots is enlarged.

The contact stiffness c_N describes the resistance to the penetration of the soft tread block layer into the rough road sur-

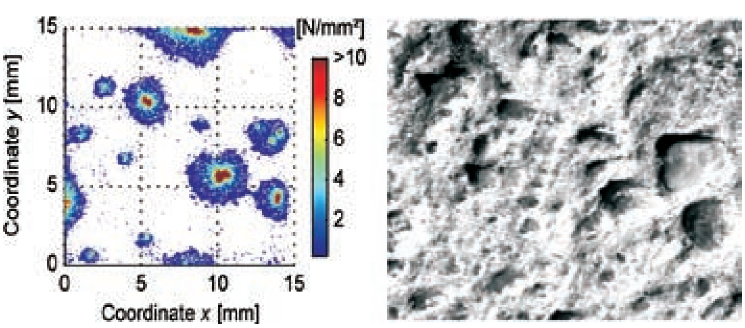

Figure 1: Measured normal contact pressure distribution of a tyre tread block under a static normal contact pressure p_N of 0.3 N/mm² (left) and a corresponding section of the concrete surface (right)

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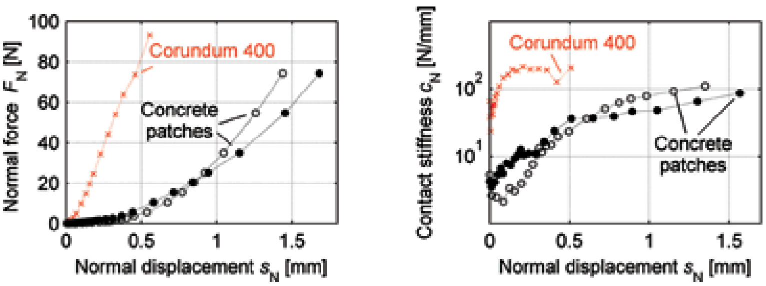

Figure 2: Measured static normal force/displacement relationships due to the interaction between the tread block and different rough surfaces (left) and the related normal contact stiffness/displacement relationships (right)

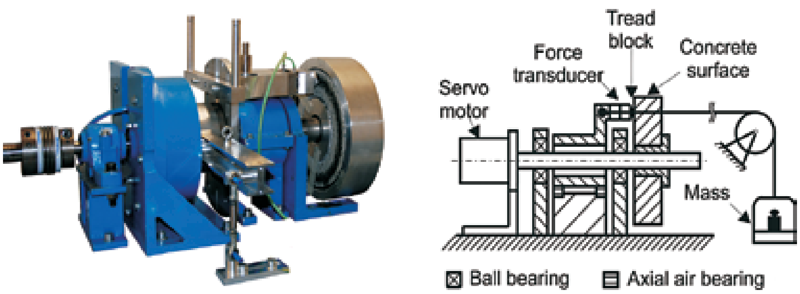

Figure 3: Tribometer test rig for sliding friction measurements between tyre tread blocks and road surfaces (left) and basic sketch of the tribometer test rig (right)

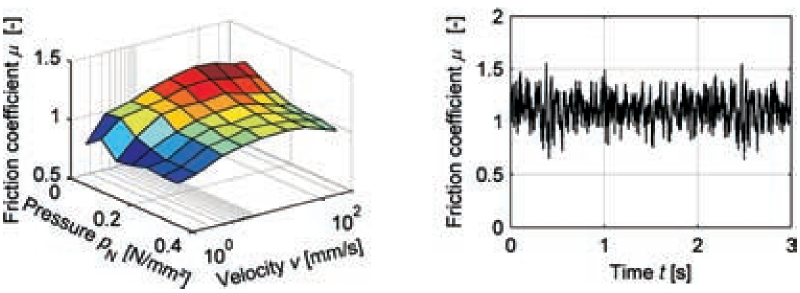

Figure 4: Measured steady friction characteristic of a sliding tyre tread block on a dry concrete road surface (left) and measured friction coefficient μ (t) under a nominal contact pressure p_N of 0.3 N/mm² and a sliding velocity v of 300 mm/sec (right)

face. Due to the rolling motion of the tyre, the single tread blocks interact periodically with the road surface. At the beginning of a penetration process, only a few asperities interact with the tread block. An increasing load leads to a large increase in the local contact pressures and high local displacements can be observed, resulting in a small contact stiffness c_N. With an increasing number of junctions, the same increase in the normal load leads to a comparably small increase in the local pressure and therefore to smaller displacements, resulting in a higher contact stiffness. The normal contact stiffness c_N is mathematically defined as the ratio of the applied normal force increment ΔF_N and the normal displacement increment Δs_N of the upper tread block surface.

Figure 2 left shows the measurement of normal force/displacement relationships of a tread block in interaction with different patches on the concrete surface and on a corundum surface grit 400. The cleft surface texture leads to distinctive non-linear relationships, which indicate a non-linear contact stiffness, Figure 2 right. The surface texture of the corundum surface is characterised by surface wavelengths especially in the microtexture range, which results in an almost linear force-displacement relationship and a constant contact stiffness from a certain normal displacement s_N of 0.05 mm on indicating the maximum roughness depth.

2.2 Tribometer Test Rig

In the contact zone between the tyre and the road, contact regions with local sliding friction between the tread block and the road surface can be observed. At the Institute of Dynamics and Vibration Research (IDS), of the Leibniz University Hanover (Germany), a tribometer test rig was developed to analyse sliding friction processes, **Figure 3**. Precise weights are used to press the tread block with a given nominal contact pressure p_N onto the rotating friction disc. Typical friction surfaces are a concrete road, a stone mastic asphalt or corundum with different types of grit. Force transducers are placed near to the contact to measure the dynamic normal and tangential contact forces. The set-up is mounted on air bearings to avoid dry friction between the test rig components and to measure smallest contact forces accurately. The relative velocity v between the tread block and the friction surface can be continuously varied between 0.1 mm/sec and 3000 mm/sec.

2.3 Mechanisms of Rubber Friction

According to Kummer [3], rubber friction can be divided into four general mechanisms: hysteresis, adhesion, cohesion and viscous friction. The appearance of the single friction mechanisms strongly depends on the contact situation: for instance, on the topography of the friction surfaces, the material properties and the existence of a lubrication film. The steady friction characteristic depends on different contact parameters, for example the relative velocity v, the contact pressure p_N, the ambient and contact temperature, the geometry of the tyre tread block and the road texture.

Figure 4 left shows the measured steady friction characteristic of a tyre tread block sliding on a concrete road surface under a variation of the contact parameters v and p_N using the tribometer test rig. The sliding friction process is measured within a defined sliding distance s, and a mean value of the friction coefficient is specified for each contact parameter combination. The friction characteristic shows a distinctive maxi-

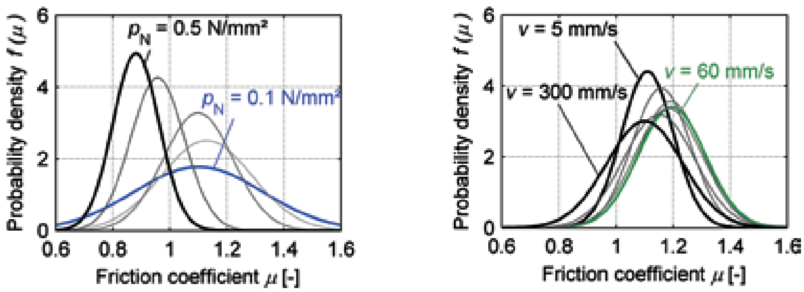

Figure 5: Normal probability density functions $f(\mu)$ of the measured friction coefficient $\mu(t)$ as a function of the nominal contact pressure p_N under a sliding velocity v of 300 mm/sec (left) and as a function of the sliding velocity v under a nominal contact pressure p_N of 0.3 N/mm² (right)

mum with regard to the relative velocity v. This effect can be assigned to the hysteresis friction mechanism [4]. The friction coefficient μ decreases with increasing normal contact pressure, which is often observed in experimental friction studies.

2.4 Friction Characteristics

The friction process of a sliding tyre tread block is a stochastic one. Figure 4 right shows the sliding friction process $\mu(t)$ of a tyre tread block on a concrete road surface with a nominal contact pressure p_N of 0.3 N/mm² and a sliding velocity v of 300 mm/sec. The analysis of the statistical parameters kurtosis and skewness of the distributed friction values offers a strong correlation to a Gaussian distribution [5].

The normal probability density function $f(\mu)$ includes information about the mean value of the friction coefficient and the standard deviation of the distributed measuring value. The distribution of the measured friction coefficient $\mu(t)$ is analysed for a variation of the contact conditions. **Figure 5** left shows the normal probability density functions $f(\mu)$ of the measured friction coefficient $\mu(t)$ as a function of the nominal contact pressure p_N for a sliding velocity v of 300 mm/sec on the concrete surface. The investigations show the well-known tendency of a decreasing mean friction coefficient μ with an increase in the normal contact pressure p_N. The second effect that can be observed offers a decreasing standard deviation of the distributed measured value with an increase in the nominal contact pressure p_N.

Figure 5 right shows the normal probability density functions for a nominal contact pressure p_N of 0.3 N/mm² as a function of the sliding velocity v. The typical elastomer friction effect, namely a distinctive maximum value for the mean friction value as a function of the sliding velocity v, can be detected explicitly at a velocity v of 60 mm/sec. The standard deviation of the distributed friction coefficient $\mu(t)$ rises with increasing sliding velocity v. This effect appears due to the enhanced excitation of the tread block as a consequence of the distinctive macro-texture of the concrete road surface.

2.5 Wear Process

In the sliding friction process of the tyre tread block on the rough road surface, wear occurs and changes the geometry of the tread block, which in turn influences the contact situation. **Figure 6** left shows a detail of a tyre tread block surface after handling manoeuvres and visualises the effect of wear on the local contact situation. One condition for wear generation is relative motion between the tread block and the road surface. At the beginning of the friction process, a lip is observed at the leading edge of the tyre tread block [6].

This contact situation results in a higher local contact pressure at the leading edge, also resulting in higher contact temperatures that can additionally increase local wear effects. After a certain sliding distance s, a homogenised contact pressure distribution leads to a larger area of real contact, as well as a smaller local contact pressure and a steady wear rate that mathematically describes the mass loss of the rubber material per sliding distance [7].

The wear effects are studied for a tread block sliding on a concrete surface at a sliding velocity v of 300 mm/sec under a variation of the nominal contact pressure p_N, Figure 6 right. At the beginning of the sliding motion, a high wear rate η can be observed, due to the described edge effect. After a sliding distance s of approximately 100 m, an almost constant wear rate η is reached, which indicates a steady process. The nominal contact pressure p_N has a strong influence on the steady wear rate, which increases as a higher load is applied to the tread block.

3 Simulation

Most scientific tyre research has been performed by simulation of the whole tyre body using finite element calculations. These models are characterised by a very high number of degrees of freedom. To solve the numerical problem of a rolling tyre, the tread pattern in contact with a discretised road surface texture and the parameter-dependent friction characteristic are usually neglected with regard to the computational efficiency. Extensive three-dimensional quasi-static finite ele-

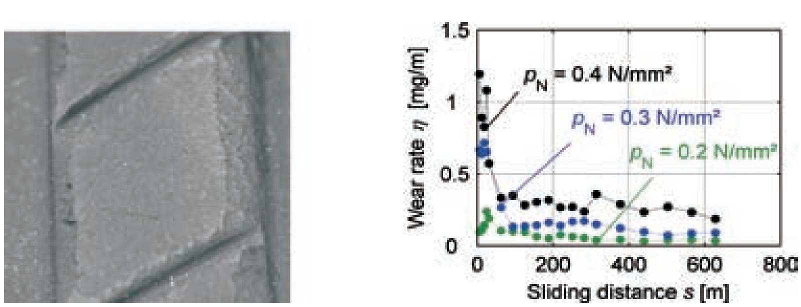

Figure 6: Detail of the tyre tread surface after handling manoeuvres (left) and measured wear rate $\eta(s)$ of a sliding tread block on a concrete road surface with a sliding velocity v of 300 mm/sec under a variation of the nominal normal contact pressure p_N (right)

ment calculations of tread blocks for the simulation of local wear and contact temperatures are presented in [8].

3.1 Dynamic Tread Block Behaviour

Here, a fast and efficient model for the prediction of the dynamic tread block behaviour is presented. Such a model has to consider the influences discussed above, which include the tread block dimensions and material properties, the local friction characteristic, the surface roughness and wear effects. The basic idea of the model is to separate the structural mechanics and the complex contact mechanics shown above. This is achieved by dividing the complex problem into smaller sub-problems. The dynamic description of the tread block and the contact phenomena observed by measurements are treated in the model as modules [7]. **Figure 7** illustrates the concept of the dynamic model.

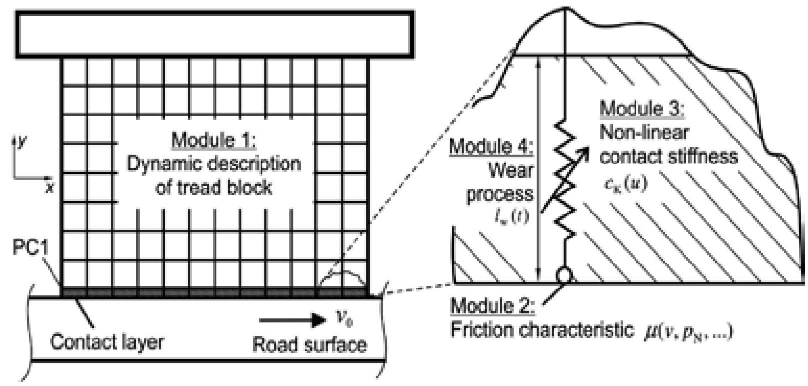

Figure 7: Dynamic tread block model (left) considers different contact phenomena modularly to predict the dynamic behaviour of a tyre tread block in sliding contact; sub-model of a single point contact of the contact layer (right)

3.1.1 Module 1: Dynamic Description of the Tread Block

The block geometry and the material properties of the tread block are considered by a plane finite element model that covers structural effects such as inertia, elasticity and damping. Transient process as well as high-frequency vibrations, which occur for example in the case of tyre squeal or during ABS braking lead to permanently changing contact situations within the contact area between tyre and road which influence the transmittable forces. Hence follows the demand to calculate dynamic processes and vibrations efficiently in the model in the high frequency range which requires a reduction in the number of degrees of freedom of the finite element model. This is achieved by the Craig/Bampton reduction, which is well-known in the field of structural dynamics. The method can be interpreted as a combination of static and modal condensation. The normal and tangential contact forces are treated as external forces of the tread block module, which are gained from point contact elements coupled to the block layer.

3.1.2 Module 2: Friction Characteristic

Within the tread block model, the local friction characteristic is applied to every point contact. The measurements presented above show a large effect of the contact parameters on the friction characteristic of the sliding tyre tread block. In the case of a concrete surface, the friction coefficient shows a strong dependency on the relative velocity. Experiments were conducted on the tribometer test rig to obtain the friction characteristic on the concrete road surface, Figure 4 left and **Figure 8** left. The shape shows a maximum at 40 mm/sec to 60 mm/sec. An approximation function, which is also shown, is used as input for the simulation. An influence of the normal pressure on the coefficient of friction is neglected here, but it can easily be included in the model.

3.1.3 Module 3: Non-Linear Contact Stiffness

The observed non-linear force/displacement relationship due to the contact with the rough road surface is modelled by non-linear springs, which are coupled to every contact node of the tread block module. The entire model can thus be interpreted as a connection of block elasticity and contact stiffness. Experimental data is again used to approximate the normal force/displacement characteristic of the whole tread block gained from measurements of the tread block interacting with the concrete road surface, Figure 2 left and Figure 8 right.

3.1.4 Module 4: Wear

Wear changes the tyre tread block geometry and is covered by giving the non-linear springs a variable length without changing their stiffness. The decrease in the spring lengths represents the wear and depends on a wear law that is approximated in proportion to the local frictional power.

Since the contact properties with the friction characteristic and the non-linear contact stiffness are already described by the contact layer, it is possible to model the rough surface as a smooth surface in the simulation, which allows

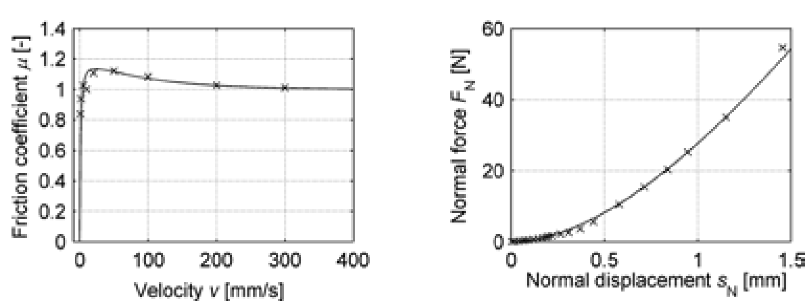

Figure 8: Measured and approximated friction characteristic μ (v) of a sliding tyre tread block on a concrete road surface under a nominal contact pressure p_N of 0.2 N/mm² (left); measured and approximated normal force displacement relationships (right)

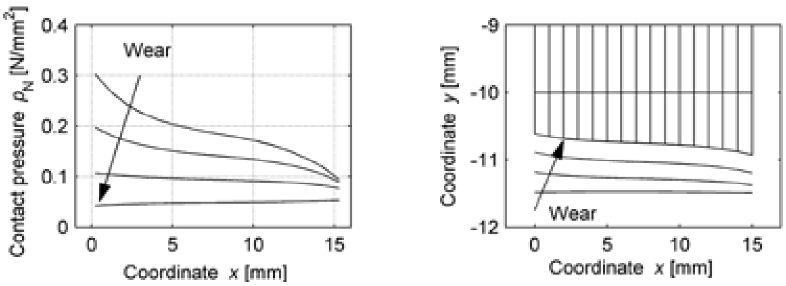

Figure 9: Influence of local wear effects on the contact pressure distribution of the sliding tyre tread block (left) and simulated worn shape due to local wear (right), leading edge at x=0

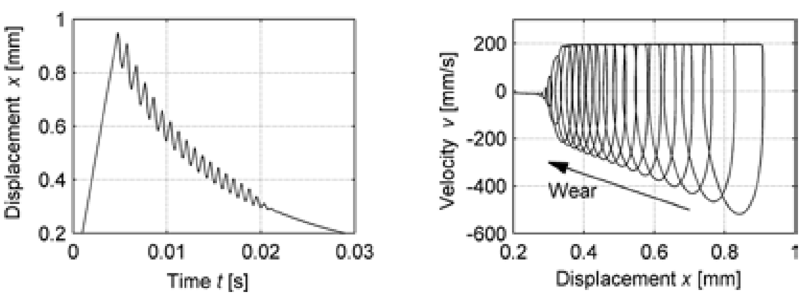

Figure 10: Wear-induced change in the dynamic tread block behaviour; displacement of the leading edge versus time (left) and corresponding phase plot (right)

a simple and fast contact algorithm. Simulations are performed with the approximated contact parameters described above. The simulated normal contact pressure distribution is shown in **Figure 9** left. The simulation demonstrates the in the measurement part mentioned edge effect with a higher contact pressure at the leading tread block edge. After a certain sliding distance with local wear, the maximum local contact pressure decreases at the leading edge. The typical S-shape is also simulated after a certain sliding distance, which can also be observed in the measurement results, Figure 9 right.

For a sliding velocity of 200 mm/sec, stick-slip vibrations occur. **Figure 10** left depicts exemplarily the displacement in x-direction with respect to time of the first point contact which is at the leading edge and labelled PC1 in Figure 7. In the simulation, a fixed normal displacement is used, which leads to a normal pressure of 0.2 N/mm² at the beginning of the sliding process. With increasing time, the amplitudes decrease and finally even cease due to wear. For the illustration of this effect, a very high wear rate was set in the simulation. Figure 10 right shows the respective phase plot for the point contact PC1. The model also provides the corresponding reaction forces to the fixed support, which represent the excitation forces to the tyre body [8]. It can be concluded that the local wear has an influence on the dynamic behaviour of the entire system.

4 Conclusion

The tyre is the integral part of the vehicle that transmits all normal and tangential forces between the vehicle and the road. The interaction between the tyre and the road is very complex. The contact of a tread block with the rough road surface leads to a small real contact area, high local contact pressures and the described non-linear contact stiffness. The sliding friction process of a tread block on a concrete surface is investigated with a tribometer test rig. Measurements indicate that the friction coefficient and the wear process strongly depend on the nominal contact pressure and the sliding velocity. The presented model allows a prediction of the dynamic tread block behaviour under consideration of the experimentally observed contact phenomena.

The efficient calculation procedure can be used as a basis for the simulation of the frictional behaviour of real tread patterns.

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