Internal Contour of a Tractor Tyre on Firm and Soft Ground

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The prediction of the forces and moments which a tyre can transmit to the ground requires precise knowledge of the contact area. At Hohenheim University, a laser measuring set was integrated into the existing single wheel tester. A laser sensor in the wheel allows the distance to the internal contour in the tread and in the sidewall area to be measured. Initial results show a significant deformation of the tyre even outside the contact area, which are not taken into account by existing models for contact area calculation.

Keywords
Tractor tyres, internal contour, laser measuring set, tyre deformation

Introduction

In recent years, the increasing vehicle masses of tractors and self-propelled machines have led to a more intensive consideration of the effects of the tyres and the ground. On the one hand, the design and the geometry of the tyres must be adapted to the increased demands with regard to efficiency and, hence, power transmission. On the other hand, compaction and damage to the soil are decisively influenced by the tyres used. For the evaluation of both criteria, the exact form and area of the contact zone between the tyre and the surface are of critical importance. At Hohenheim University, a laser measuring set was built into a tyre in order to enable the tyre deformation behaviour to be assessed precisely.

Theory

Knowledge of the precise contour of the contact area is important for the evaluation of the processes in the tyre and the resulting effects on power transmission. On a firm surface, such as asphalt or concrete, the contact area mainly depends on tyre deflection because the elasticity of the surface can generally be neglected. On soft ground, this simplification is no longer acceptable due to ground deformation and track formation. The deformation of the ground is composed of a plastic and an elastic component so that the subsequent measurement of ground deformation only partly reflects the momentary condition during the pass.
The rolling resistance of the tyre consists of an internal component caused by the flexing work of the tyre and an external component caused by ground deformation. A closer consideration of the forces at the wheel shows that the definition of the point of zero slip requires that the above-mentioned components be known. According to Grečenko [1], a wheel rolls without slip if the driving force corresponds to external rolling resistance. Since the direct measurement of external rolling resistance is impossible, internal rolling resistance on a firm surface and total resistance on a soft surface can be determined instead. Given the assumption that the internal component is equal on both surfaces, external rolling resistance can be calculated. This presupposes identical tyre deformation in both situations - an assumption which is to be examined more closely.
For a prediction of the forces which occur in the contact area, its shape must be known. Since the precise determination of the contour is already time consuming, the contour of the contact area is approximated by a rectangle or an ellipse in many models. The width of the tyre is assumed to equal the width of the contact area. This allows the problem of area determination to be reduced to a two-dimensional model of the tyre in the longitudinal and vertical direction. On a firm surface, the contact line of the tyre can be represented by a secant. On soft ground, it is generally approximated by the arc of a circle with an enlarged radius [2], a parabola [3], a spiral [4], or a combination of several elements (**figure 1**). The calculation of the contact length depends on numerous tyre- and ground parameters which are taken into account to a greater or lesser extent in the above-mentioned models. The contour is determined iteratively. The calculated contour allows the normal stress distribution to be calculated with the aid of Bekker´s pressure-sinkage relation [5]. Normal and shear stress is used for the calculation of the driving forces and rolling resistance.

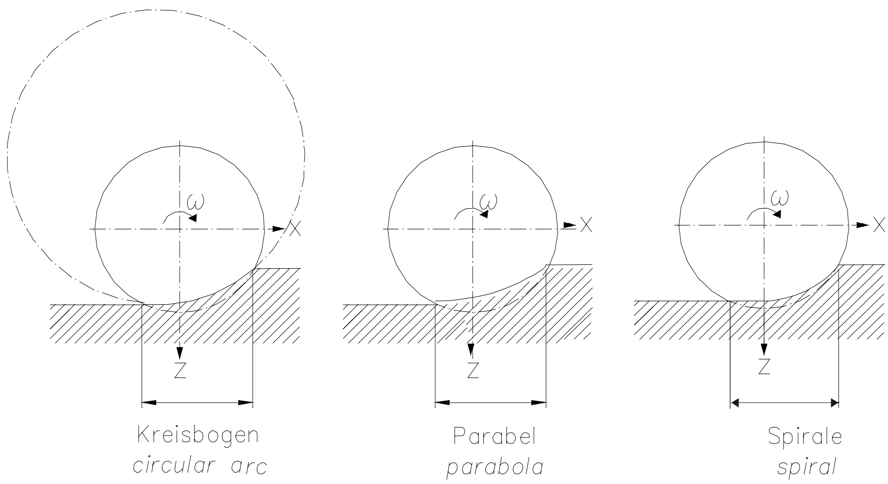

Figure 1: Tyre models from Söhne [2], Schmid [3] und Okello [4]

Measuring Method

For the investigation, the single wheel tester [6, 7] of Hohenheim University was used and extended. This measuring system provides good prerequisites for the measurement of the contact area because different tyre conditions, such as rolling under the influence of positive or negative longitudinal forces or lateral forces, can be simulated on different surfaces. Since measuring the external contour of the tyre during tyre-surface interaction requires very sophisticated equipment, a system for the measurement of the internal contour was developed, similar to the one in Kiel [8]. The interior of the 520/70 R 34 tyre used for this experiment provides enough space for the installation of a laser distance sensor. In order to avoid the sensor being damaged during the mounting of the tyre, the sensor is installed after the tyre has been mounted. The wheel rim shown in **figure 2** was provided with assembly openings. The laser sensor, a stepper motor, and an rotary encoder are mounted on a carrier. The stepper motor allows the laser sensor to be swivelled laterally to the direction of travel by an angle ß of up to ± 85°. The carrier is mounted on the rim and rotates with the tyre. In addition, a pressure sensor was installed in the rim in order to measure the precise inflation pressure. A slip ring is used to transmit the measurement signals for data registration. The torque angle position δ of the measuring wheel is established with the aid of the existing rotary encoder. Additionally, a proximity switch was installed in order to define the zero position of the measuring wheel.

Especially if the wheel runs with a side slip, significant shifting of the tyre must be expected, which the laser system allows to be measured only to a limited extent. Due to the system design, the laser distance sensor measures the distance to the internal contour of the tyre without taking a possible translational movement of the measuring point into account. Other systems, which consist of springs and wire strain gauges, consider this area shifting [9]. However, these systems have the disadvantage that only one measuring point can be measured stationarily, i.e. variation requires time-consuming shifting of the measuring point.

Measurements were taken stationarily and during the ride. During the stationary measurements, the laser sensor was swivelled with the aid of the stepper motor in order to record the lateral profile of the tyre. For the individual measurements, the wheel was turned into different positions, providing a profile of the entire

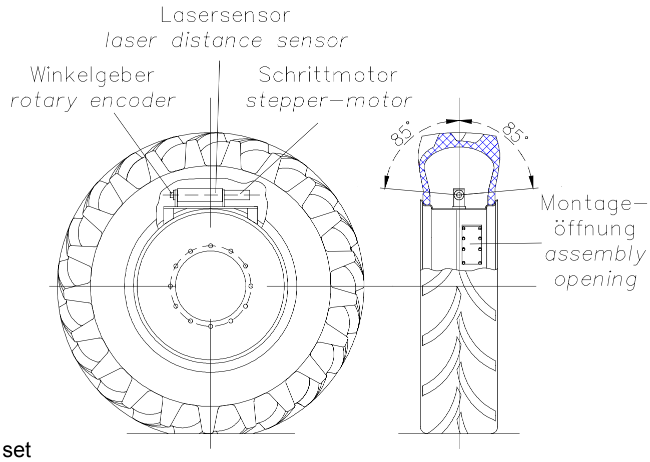

Figure 2: Laser measuring set

contact area. For the ride measurements, the laser was fixed in the position ß = const., and the distance signal for several revolutions was measured. Subsequently, the swivelling angle ß was varied so that the measurements included both the contact area and the sidewall. Measurements were taken both on firm and soft surfaces. For this purpose, a soil bin filled with sandy loam was used.

Results

Stationary Measurements

As inflation pressure increases, the unburdened tyre shows a greater tyre radius. In contrast to the very clear bulging of the centre of the cross ply tyre measured in reference [8], the internal contour of the radial tyre shows that the tyre radius increases only slightly by a few millimetres. The relatively stiff belt of the tyre prevents stronger deformation of the tyre centre, while a cross ply tyre permits greater deformation due to the winding pattern of the carcass.

Figure 3 shows the comparison of several stationary measurements on a firm and a soft surface for different wheel loads. The real distance of the laser from the internal contour is shown in both the Z- and the Y-direction. Growing wheel load leads to greater tyre deflection and increasing flattening of the contact area. Flattening and deflection are greater on the concrete surface because the length of the contact patch is smaller. Measurements on a firm surface have shown that the position of the lugs becomes detectable at the internal surface of the tyre. The pressure of the lug leads to carcass deformation. In the central area, the contour therefore does not run parallel to the horizontal road surface. Instead, it is curved at -200 mm to -100 mm. At higher inflation pressures, this effect becomes even more pronounced. This is caused by the smaller number of lugs in the contact area, which leads to a reduced contact patch. Due to the increasing bulging of the sidewall at higher wheel loads, poor reflection of the laser beam at the inner wall of the tyre causes faulty signals.

The results outside the contact area generally show symmetrical behaviour in the sections which enter and leave the contact area. Among other factors, deviations are caused by the moving direction of the lugs. When the lug enters the

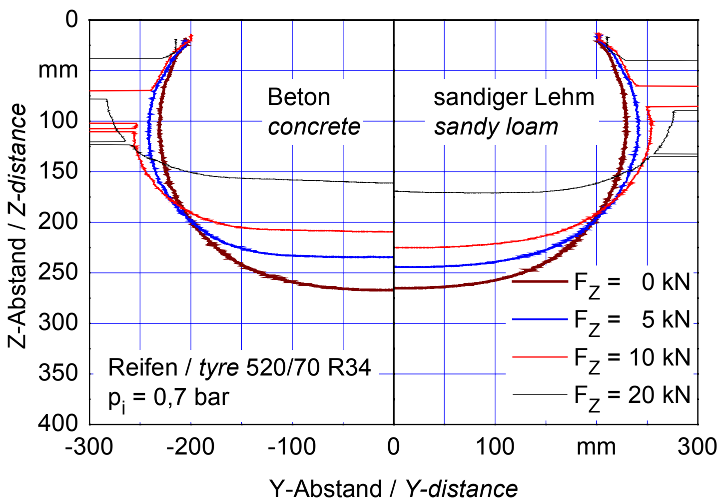

Figure 3: Internal contour of the tyre in lateral direction

contact area, it is subject to forces acting upon its centre, while the outer part of the lug leaves the contact area last. The deformation of the internal contour is influenced by this effect and explains the deviation.

Ride Measurements

The real contour determined during a ride measurement is shown in **Figure 4**. The internal contour shows the measured distance of the laser for one wheel revolution on soft ground. The circular, unburdened contour of the tyre is shown as a broken line. Based on the internal contour, the expected shape of the external contour was established. For this purpose, the elasticity of both the tread in the radial direction and the lugs is not taken into account. For the consideration of the contact area, generally the front- and the rear angle Θ_1 and Θ_2 are employed, which characterize the entrance- and exit point of the contact area. Theoretically, the front angle can be calculated using the sinkage of the tyre. The elastic redeformation of the ground makes a precise determination of the rear angle more difficult. Since the elastic component is small, it is neglected by approximation.

If the contour within the contact area is compared with the theoretical approaches, the individual models exhibit only slight differences. **Figure 5** shows the deviations of the circle- and parabola contour from the measured contour within the contact area. Due to the relatively large diameter of the tractor tyres in comparison with the contact area, the contour within the contact area constitutes only a small portion of the entire circumference. This part of the contour can be well approximated by circle arcs as well as parabolas or spirals.

However, the relatively stiff belt of the tyre causes tread deformation even outside the actual contact area. The pre-deformation of the tyre results in a shifting of the entrance point of the tyre into the contact area so that the real front angle Θ_{1R} is larger. In the shown case, the contact length diminishes by 12.5%, provided the rear angle Θ_2 remains constant.

In the known theoretical approaches for the determination of the contact area, the tyre outside the contact area is approximated by the unburdened radius r_0. **Figure 6**, however, shows that this is only a rough approximation. A comparison with the unburdened distance l_0 of the laser sensor shows the shifting and deformation of the internal contour over the entire circumference. In the upper part of the tyre, the contour is almost constantly shifted outwards. In the range from δ = 90° and δ = 270°, additional rising of the internal contour can be observed. The angles δ_1 and δ_2 characterize the subsequent deformation of the tyre due to the contact pressure in the contact area. This range comprises a pre- and post-deformation zone outside the contact area. The intensity of the pre- and post deformation of the tyre depends on the load and is more pronounced as total deformation increases. For this reason, tyre deformation can only insufficiently be described with the aid of the front- and rear angles shown in Figure 4.

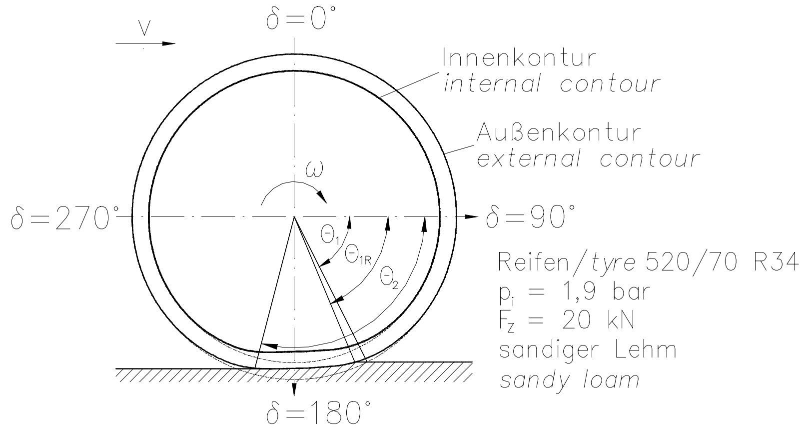

Figure 4: Deformation of the tyre in longitudinal direction

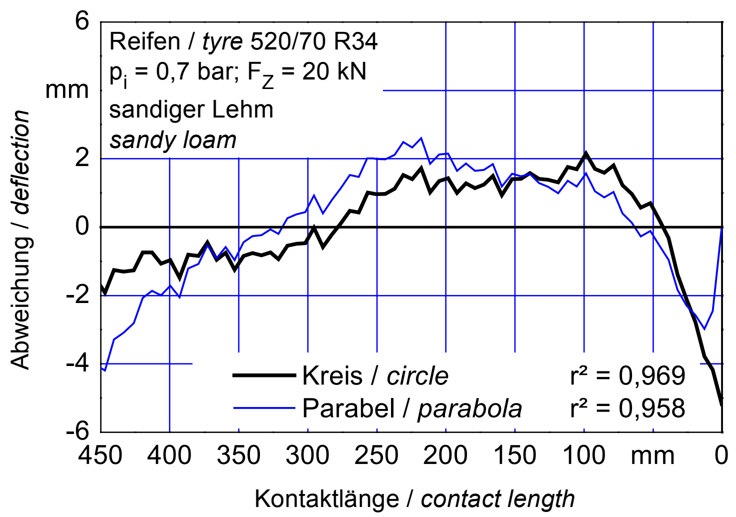

Figure 5: Difference of the alternate models to internal contour

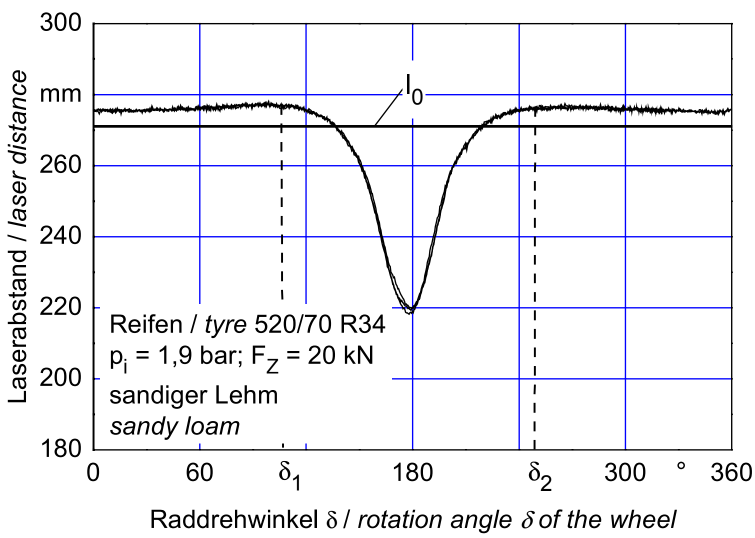

Figure 6: Difference of the internal contour to the distance l_0 of the unburdened tyre

Furthermore, it has been established that deformation is not symmetrical. Especially on soft ground, but also on a firm surface, deformation is stronger in the entrance zone than in the exit zone. This applies both inside and outside the contact area.

In addition to the measurements in the tyre centre, the sidewalls were examined. As already shown in Figure 3 for the stationary measurements, widening occurs in the area of the contact patch. In comparison with Figure 6, this results in the opposite behaviour. The distance in the contact area is enlarged, while in the pre- and post-deformation zone outside the contact area the sidewall is shifted slightly inwards.

Comparison of Stationary and Ride Measurements

If the distance of the laser sensor in the tyre centre is compared during stationary and ride measurements on a firm surface, the results prove to be nearly identical. An increase in the rolling radius and the tyre circumference, which was to be expected for higher driving speeds [10], was not proven. The reasons for this result must be seen in the low driving speed during the ride measurements.

A comparison of the measurements on a soft surface shows greater deformations in the area where the tyre enters the contact patch during wheel ride measurements. During the stationary measurements, a steady state condition is reached after ground consolidation is completed so that a comparison does not yield meaningful results. During ride measurements, the rolling wheel meets with stronger ground resistance. At the same time, the tyre centre is subject to stronger deformation, and the sidewall is deformed outwards to a greater extent.

Determination of the Rolling Radius

The measured contours in the contact area show the problems of rolling radius determination. Different definitions of the rolling radius provide different results. The moment radius, for example, is not measured at the wheel centre, but at a point offset by the lever arm of the wheel load [7]. The result differs from the geometric determination of the rolling radius based on the rolling circumference of the tyre. The measured internal contours show that, depending on the point of application, altered values for the distance of a contact point from the wheel centre are obtained.

Ride Measurements with a Wheel with Side Slip

Ride measurements were taken for a side slip angle of $\alpha = 15°$, and the distance of the laser measuring set to the internal contour was recorded from different swivelling angles ß (**figure 7**). During these measurements, the laser sensor is swivelled towards the outer side of the curve. **Figure 8** shows the rolling lines of the wheel with side slip at different angles of the laser sensor in comparison with the unsteered wheel. The real distance of the internal tyre contour from the laser sensor is shown with the distance l_0 of the unburdened tyre serving as reference. During the vertical distance measurement (ß = 0°), the tyre deflects more when the wheel is turned to one side. This result is also confirmed by the measurement of the rolling radius during the measuring ride. Measurements outside the tyre centre (ß = 20°; 40°; 60°) clearly show that the tyre

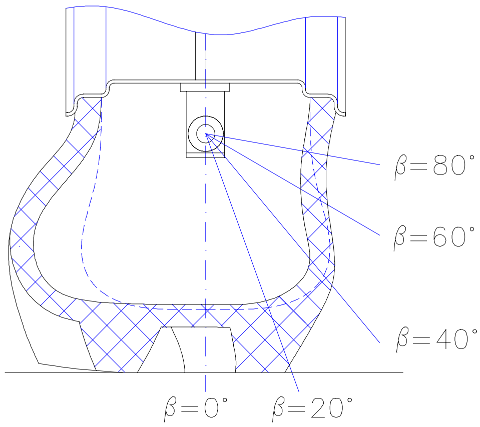

Figure 7: Measurement of the internal contour of a tyre with side slip

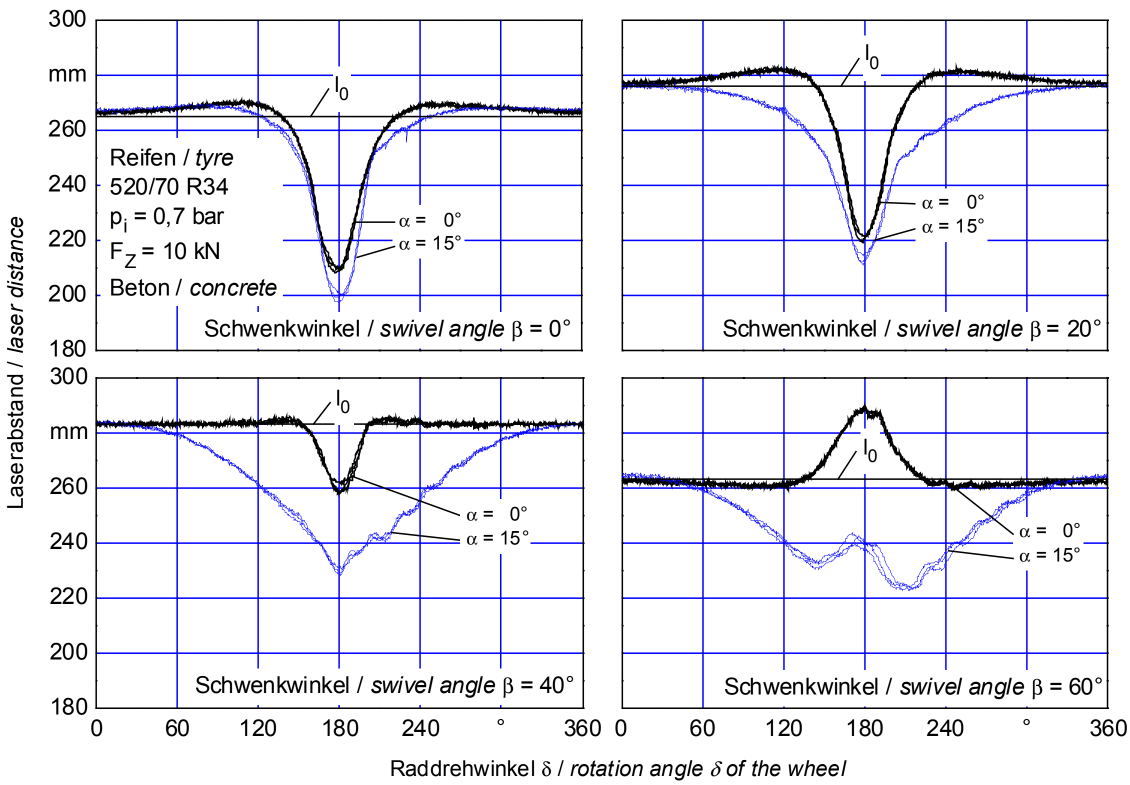

Figure 8: Influence of slip angle α on the deformation of the tyre

contour in the areas where the tyre enters and leaves the contact patch are no longer symmetrical. Wave formation in the exit area indicates compression of the tyre. In addition, the reduction of the distance to the tyre sidewall caused by the effect of the lateral force is clearly visible. In a wheel with side slip, the deformation of the tyre sidewall extends over almost the entire circumference. The widening of the sidewall in the contact patch area is reduced by overlaid shifting. In the sidewall area, the contour in the zone where the tyre enters and leaves the contact patch is not symmetrical either. The stronger deformation in the exit area may be caused by the geometry of the tread because the lugs are subject to greater loads in the outer area when leaving the contact patch and can thus exert stronger inward pressure on the sidewall.

Conclusions

The measurements show that the conventional models for the simulation of the tyre contour do not sufficiently consider the real deformation of the tyre because the tyre not only deforms in the contact area, but nearly over the entire circumference. A comparison of ride measurements on soft and firm ground yields different results. On a soft surface, the tyre is deformed less. This result shows that internal rolling resistance on firm and soft ground is not identical, even if the other parameters are the same. The determination of the internal rolling resistance component on a soft surface remains problematical. Resorting to rolling resistance on a firm surface causes the internal rolling resistance component to become too big, which aggravates the well-known problem of determining the point of zero slip [11]. Future models should take the state of deformation of the tyre into account and allow the internal rolling resistance to be calculated.

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