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The in-plane deformation of a tire carcass: Analysis and measurement

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A B S T R A C T

The deformation of parts of a tire is the direct result of tire–road interactions, and therefore is of great interest in tire sensor development. This case study focuses on the analysis of the deformation of the tire carcass and investigates its potential for the estimation of the in-plane tire force. The deformation of the tire carcass due to applied steady-state in-plane forces is first analyzed with the flexible ring model and then validated through optical tire sensor measurements. Coupled deformations of the tire carcass in the radial and tangential directions are observed. This reveals a promising method for tire sensing applications in the estimation of the in-plane tire force, which relies only on direct measurements of the radial deformation of the tire carcass. Moreover, indicators are proposed to correlate the radial deformation of the tire carcass with in-plane tire forces.

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1. Introduction

The pneumatic tire has been an essential automotive component since its inception and plays a significant role in the safety, mobility, handling, comfort, and fuel economy of a vehicle. To alter vehicle states, all the desired forces and moments are generated through tire–road interactions, and therefore such interactions contain valuable information for the vehicle control system, such as Anti-lock Braking System (ABS), Adaptive Cruise Control (ACC), and Electronic Stability Control (ESC). However, since the tire acts as a passive component of the vehicle, this information is not directly accessible to the vehicle control system.

With the emergence of the tire sensor concept, it is expected that such a gap can be filled. A tire sensor system provides direct measurements of tire operating states such as tire component deformations, and then estimates vehicle states, including the friction potential [1], lateral force [2], and contact patch dimension [3]. Various tire sensors have been developed and demonstrated for research purposes [4–7]. However, before the tire sensor becomes commercially viable for production vehicles, several challenges, such as the data transmission and power management, need to be overcome. In addition, a more fundamental issue is the lack of clear physical mechanisms which are feasible as sensing principles. In other words, more work is needed to find simple and physics-based tire models that can form the basis for the onboard estimators required by tire sensor applications.

In this case study, the deformation of the tire carcass is investigated for the potential application of the estimation of the in-plane tire force. The deformation of the tire carcass due to applied steady-state in-plane forces are analyzed with the...
flexible ring model and validated through optical tire sensor measurements. Indicators based on the radial deformation of the tire carcass are correlated with the in-plane tire forces.

2. Analysis of in-plane tire deformation

2.1. Flexible ring tire model

It is generally accepted that a tire behaves in a similar way to an elastic ring under the influence of the excitation force in the low frequency range of 0–300 Hz [8–10]. Thus, the flexible ring model has been widely used to investigate in-plane tire behavior [11–13]. In this model, a tire is described as an elastic ring with parallel springs connected, in both the radial and tangential directions, to the rim, as shown in Fig. 1(a). For tire–road contacts, a single-point contact model for the vertical force \( F_z \) and longitudinal force \( F_x \) is used instead of a distributed contact model, as shown in other studies [11,12]. This is a simplification for measurements conducted on a curved surface, since the contact patch length is shorter than on a flat surface and the contact forces are distributed closer to the contact center. However, a distributed contact model, which is closer to real contact constraints, needs to be considered in the future studies.

Because of the high extensional stiffness of the modern radial tire, the middle surface of the tire carcass is assumed to be inextensible [14]. Hence, the radial deformation \( w \) and tangential deformation \( v \) of the tire carcass in a circumferential position \( \varphi \) are governed by the following relation:

\[
w(\varphi) = -\frac{\partial r(\varphi)}{\partial \varphi}
\]

The deformation of the ring is expressed in the modal expansion form, which assumes that the response of a complex linear multi-degree of freedom (MDOF) system can be represented as a weighted summation from the 1st mode shape until the \( i \)th mode shapes of the system. According to [14], the number of included highest mode \( i \) has a significant influence on the convergence of simulated deformations. In this case study, the first 50 mode shapes \( (i = 50) \) were included in the modal expansion form. The radial deformation \( w \) and tangential deformation \( v \) for the tire carcass read:

\[
w(\varphi) = \sum_{n=1}^{i} [-nA_{n1}F_z \cos(n\varphi) + nA_{n2}F_z \sin(n\varphi)]
\]

\[
v(\varphi) = \sum_{n=1}^{i} [A_{n1}F_z \sin(n\varphi) + A_{n2}F_z \cos(n\varphi)]
\]

where \( A_{n1} \) and \( A_{n2} \) are modal participation factors which are independent of the response position. The formulas for those factors are listed in Appendix A. The geometric and model parameters used in the simulation are listed in Appendix B. As

![Fig. 1. (a) The flexible ring tire model; (b) simulated tire contours from the flexible ring model (inflation pressure: 2.2 bar).](image)
shown in Fig. 1(b), the flexible ring tire model can be used to simulate and investigate the impact of tire forces on the contours and deformations of the tire carcass. Because of the inextensibility of the tire carcass, it is observed that the in-plane deformation has the following two features. First, the radial and tangential deformations of the tire are coupled. Moreover, the part of the tire which is not in contact with the road is also deformed and is influenced by the deformation of the tire in the contact zone.

2.2. Simulated in-plane tire deformation

Simulations are conducted with various wheel loads $F_z$ (from 1000 N to 5000 N) and inflation pressures $P$ (2.2 bar, 2.6 bar, and 3 bar) to analyze their influences on the in-plane tire deformation. The radial and tangential deformations at different circumferential positions are illustrated in Fig. 2. It is observed that both types of deformations are symmetric regarding the center position of the contact patch. The smallest radius, or, in other words, the largest radial deformation, occurs in the contact between the tire and road under the highest load and with the lowest inflation pressure. Meanwhile, the radius of the non-contact zone becomes larger with an increasing load. The tangential deformation for the circumferential position from $-180$ to $0$° points in the negative direction and alters its direction after the middle of the contact. This provides a physical explanation for the typical tire–road shear stress distribution observed in previous simulations and measurements [15].

Fig. 3 presents the in-plane deformations in both the radial and tangential directions for a rolling tire with four different braking forces in the longitudinal direction (from 0 N to 1500 N). An asymmetric pattern regarding the zero degree (the middle of the contact) can be observed for the deformations in both directions. The asymmetricity increases with an increase in the longitudinal force. Such changes in the radial deformation against the longitudinal force are primarily due to the aforementioned inextensibility of the tire carcass. Because of the inner pressure, the tire is a pre-stressed structure. The braking force applied in the tangential direction leads to an increase in the tensile stress of the tire carcass before the contact and a reduction after the contact. This observation is important, as the longitudinal force can be estimated purely on the basis of the radial deformation of the tire, which will be discussed later.

3. Measurement of in-plane tire deformation

3.1. Optical tire sensor system

To validate the simulation results from the flexible ring model, an optical tire sensor system was used to measure the deformations of the carcass under different in-plane tire forces. The tire sensor system was developed in the vehicle engineering group at Aalto University for studying tire–road interactions such as aquaplaning and rolling resistance. As shown in Fig. 4(a), the core sensing unit in this system is a one-dimensional laser triangulation sensor (Keyence IL-065). This sensor measures the distance $Z$ from the rim to the inner liner as it is fixed to the rim. For detailed specifications of the laser sensor, see [16,17]. The sensor rotates together with the rim while the tire is rolling. The power and multi-channel analog

![Fig. 2. In-plane tire deformations under different vertical forces with a rotational speed of 100 rad/s: (a) radial deformations and (b) tangential deformations.](image-url)
signal are transmitted to the sensor through a slip-ring device (Michigan Scientific SR10AW/T512). The circumferential position of the laser sensor is determined by an optical encoder (1024 counts/revolution, 0.35° resolution) within the slip-ring device.

As shown in Fig. 4(b), the instrumented tire was tested on a tire test rig with a 1219-mm diameter. The drum was covered with safety walk paper. Three tire forces and three moments can be logged by the force sensors. The wheel load was adjustable through hydraulic cylinders controlled by p/Q controllers. In addition, a hydraulic disc brake system was configured with different hydraulic pressures to generate various braking forces in the longitudinal direction, which were measured by the force sensors. In addition, to limit this study to in-plane tire deformations, the camber and slip angles were adjusted to 0°.
3.2. Deformation under vertical forces

As shown in Fig. 5, the measured radial deformations of the tire demonstrate a similar trend to the simulation results when the wheel load and inflation pressure change. Measured radial deformations with angular positions were first interpolated to \(N (N = 1000)\) equidistant circumferential positions between \(-180^\circ\) and \(180^\circ\). The mean radial deformation value \(w_{\text{laser,mean}}\) as an indicator, is calculated as follows:

\[
w_{\text{laser,mean}} = \frac{\sum w_{\text{laser}}(\varphi, -180^\circ \leq \varphi \leq 180^\circ)}{N}
\]  

where \(w_{\text{laser}}(\varphi)\) is the interpolated radial deformation at a specific circumferential position \(\varphi\). In other words, the mean radial deformation is an average of tire deformations in one full rotation, which include two deformations, the inward radial deformation due to tire–road contacts and the outward radial deformation due to tire structures. The mean radial deformation is plotted against the vertical loads and demonstrates a near-linear relationship for all the pressures that were applied. It can be seen that the inflation pressure has a significant influence on the radial stiffness, in addition to the contribution of the tire structure. In both, the high load and low inflation pressure cases, the observed smaller mean deformation values imply larger inward deformations (with a negative value) in the tire–road contact.

Fig. 5. Measured radial deformations of the tire under different vertical forces \((F_x; 0\ N, \text{inflation pressure: } 2.6\text{ bar})\) and at various inflation pressures (solid line: 2.2 bar, dashed line: 2.6 bar, and dashed-dotted line: 3.0 bar).

Fig. 6. Measured tire radial deformations under different longitudinal forces \((F_z; 3000\ N \text{ and inflation pressure: } 2.6\text{ bar})\).
3.3. Deformation under longitudinal forces

Fig. 6 compares the measured radial deformations under different longitudinal forces. As discussed in Section 3.2, the symmetricity of the radial deformation of the tire changes with the longitudinal force that is applied as a result of the pretension force and inextensibility of the ring structure. As a simple indicator, such asymmetricity can be measured by the difference between the mean measured deformation values before and after the contact, \( w_{\text{laser, diff}} \), which can be calculated as follows.

\[
w_{\text{laser, diff}} = \frac{1}{N} \sum w_{\text{laser}}(\varphi, -180^\circ \leq \varphi \leq 0^\circ) - \sum w_{\text{laser}}(\varphi, 0^\circ \leq \varphi \leq 180^\circ)
\]

(4)

The calculated mean value differences with negative values imply that the tire has a smaller radius before the tire–road contact. As shown in Fig. 6, the mean value difference has a linear relationship with the longitudinal forces and shows a dependence on the wheel load. The difference is larger at a higher load condition. The proposed indicator allows the estimation of the longitudinal force to be based solely on the radial deformation measurement.

4. Conclusions

In this paper, the in-plane deformations of the tire carcass are studied with tire model simulations and experimental tire sensor measurements. The flexible ring model was used to analyze the in-plane tire deformation under different vertical and longitudinal forces. The simulated in-plane tire deformations match the deformations measured through the optical tire sensor. Indicators from the optical tire sensor measurements are proposed and demonstrate good correlations with the forces applied to the tire. It is found that the radial deformation of the tire carcass provides information on both the longitudinal and vertical forces acting on the tire. This is mainly attributed to the coupled effect between the in-plane tire deformations caused by the inextensibility of the tire carcass in a modern radial tire. With this new finding, the radial deformation of the carcass can not only be used to estimate the vertical force acting on the tire, but also to estimate the longitudinal force acting on the tire, information which can be utilized to develop tire sensors for the estimation of tire forces or friction potential. From an industrial point of view, the laser sensor used in this study is more suitable for research and development purposes, due to its high cost. In practice, other non-contact measurement systems such as ultrasonic sensors and position sensitive detector (PSD) systems combined with light-emitting diodes (LEDs), with a simple principle and lower cost, are more promising solutions for the mass production.

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Appendix A.

Formulas for parameters of the flexible ring model.

- Pre-tension force in the carcass: \( \sigma_0 = p_0 b R + \rho A R^2 \Omega^2 \)
- Modal equivalent mass: \( m_\text{eq} = \rho A (1 + n^2) \)
- Modal damping factor: \( g_n = -4 \rho A n \Omega \)
- Modal stiffness factor: \( k_n = (E R/n^2/R^4 + \sigma_0^2/R^2)(1 - n^2) \)
- Modal participation factor 1: \( A_{n1} = 1/\pi \sqrt{(m_\text{eq} n^2 \Omega^2 + g_n n \Omega - k_n)} \)
- Modal participation factor 2: \( A_{n2} = n A_{n1} \)

Appendix B.

Geometric and model parameters of the tire used in the simulations.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Descriptions</th>
<th>Value</th>
<th>Parameters</th>
<th>Descriptions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>Carcass width</td>
<td>0.16 m</td>
<td>R</td>
<td>Tire radius</td>
<td>0.285 m</td>
</tr>
<tr>
<td>h</td>
<td>Carcass thickness</td>
<td>0.01 m</td>
<td>( k_w )</td>
<td>Equivalent radial stiffness</td>
<td>( 1.24 \times 10^5 ) N/m2</td>
</tr>
<tr>
<td>A</td>
<td>Cross-section area</td>
<td>0.0016 m²</td>
<td>( k_v )</td>
<td>Equivalent tangential stiffness</td>
<td>( 5.19 \times 10^3 ) N/m²</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Tire density</td>
<td>( 2.28 \times 10^3 ) Kg/m³</td>
<td>( p_0 )</td>
<td>Inflation pressure</td>
<td>2.6 bar</td>
</tr>
<tr>
<td>E</td>
<td>Carcass bending stiffness</td>
<td>1.41 Nm²</td>
<td>( \Omega )</td>
<td>Tire rotating speed</td>
<td>100 rad/s</td>
</tr>
</tbody>
</table>
References


