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

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ABSTRACT

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.

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

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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 φ are governed by the following relation:

$$w(\varphi) = \frac{-\partial v(\varphi)}{\partial \varphi} \tag{1}$$

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 ith 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:

$$w(\varphi) = \sum_{n=1}^{i}[-nA_{n1}F_x\mathrm{Cos}(n\varphi) + nA_{n2}F_z\mathrm{Sin}(n\varphi)]$$

$$v(\varphi) = \sum_{n=1}^{i}[A_{n1}F_x\mathrm{Sin}(n\varphi) + A_{n2}F_z\mathrm{Cos}(n\varphi)] \tag{2}$$

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

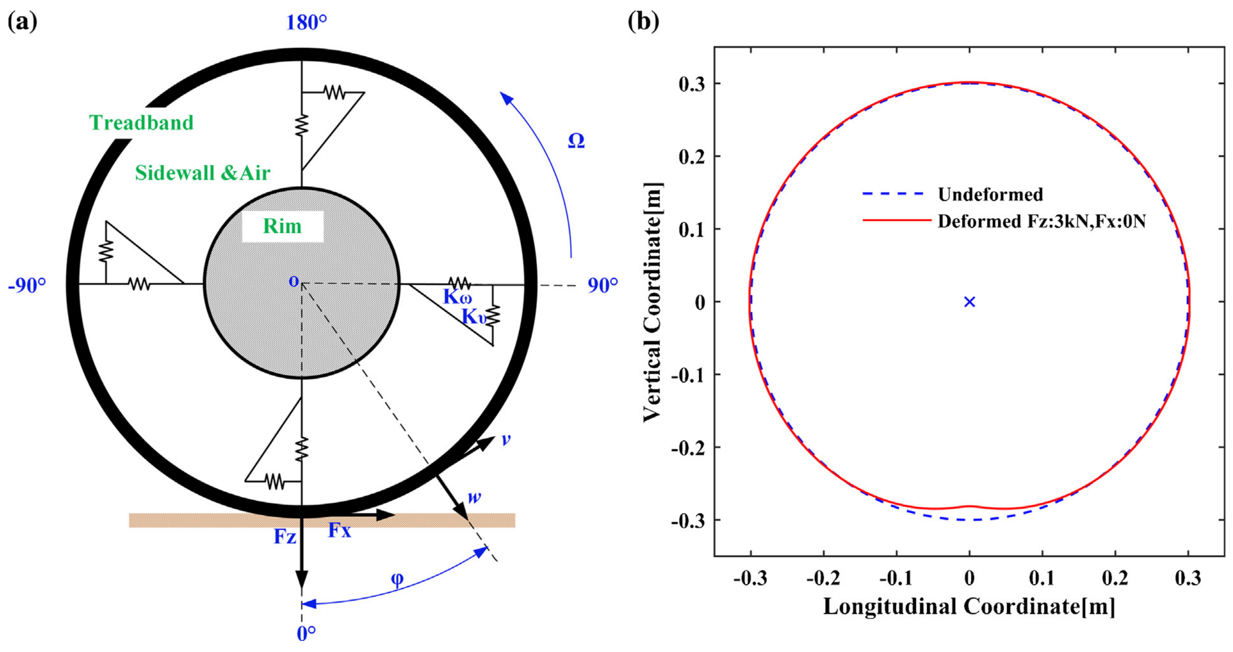

Fig. 1. (a) The flexible ring tire model; (b) simulated tire contours from the flexible ring model (inflation pressure: 2.2 bar).