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Dynamic behaviour of a rolling tyre: Experimental and numerical analyses

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ABSTRACT

Based on the results of experimental and numerical analyses, the effect of rotation on the tyre dynamic behaviour is investigated. Better understanding of these effects will further improve the ability to control and optimize the noise and vibrations that result from the interaction between the road surface and the rolling tyre. Therefore, more understanding in the complex tyre dynamic properties will contribute to develop tyre design strategies to lower the tyre/road noise while less affecting other tyre performances.

The presented work is performed in the framework of the European industry-academia project TIRE-DYN, with partners Goodyear, Katholieke Universiteit Leuven and LMS International. The effect of rotation on the tyre dynamic behaviour is quantified for different operating conditions of the tyre, such as load, air pressure and rotation speed. By means of experimental and numerical analyses, the effects of rotation on the tyre dynamic behaviour are studied.

1. Introduction

Vehicle noise is one of the contributors to traffic noise. Recently a new vehicle noise regulation [1] has been adopted in the European Union. The regulation consists of a new test method and lower vehicle noise limit values. For M1a vehicles, representing the majority of the current car population, limits will be lowered in 3 phases from 72 dB(A) in 2016 to 68 dB (A) in 2024. Approximately 85 percent of the current car population does not fulfil the future vehicle noise requirements [2].

Tyre/road noise is one of the sources of vehicle noise and becomes important for driving speeds above 40 km/h for passenger cars and above 75 km/h for heavy trucks. The basic physical principles of tyre/road noise are well understood and documented [3]. Abatement of tyre/road noise at the source can be achieved through the development of low noise pavements and/or low noise tyres. This paper contributes to the development of low noise tyres by presenting a highly detailed FE model of a tyre in loaded and rotating condition. The model has been validated in the unloaded non-rotating operating condition.

The following paragraph gives an overview of the state-of-the-art *structural tyre models*. The models are briefly discussed in terms of applicability, capabilities and limitations.

A first class of models are *analytical models*. Analytical models are typically computationally very efficient. They are suitable for a general understanding of tyre dynamics. A first type of analytical model is the ring model consisting of a

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flexible 2D ring on an elastic foundation. This type of model is able to accommodate in-plane bending and longitudinal waves. Nowadays, ring models can be modelled in rotating condition, providing a basic understanding of Coriolis and Doppler effect [4]. Loading on the ground surface has typically been taken into account by means of a simplified spring contact system [5]. Another type of analytical model is the circular cylindrical shell model [6]. This type of model is an extension of the ring model to 3D, and therefore capable to accommodate cross-sectional waves (in the axial direction) as well. Typically, simply supported boundary conditions are applied to the tread band edges [7]. Recently, a circular cylindrical shell tyre model has been presented using free boundary conditions [8]. This model is no longer limited to zero radial displacement at the belt edges and thus results in a more accurate and complete prediction of the tyre modes. Alternatively, models with more advanced sidewall representations have been implemented. The sidewall has been modelled as a distributed stiffness [9,10] or as an explicit membrane model [11]. Both of the latter models have been validated by means of mobility measurements for the case of an unloaded non-rotating tyre. To the author's knowledge, a shell model that combines the effects of rotation, loading and frequency dependent material properties has not yet been published. A last type of analytical model is the plate model, consisting of a flat plate on a spring bedding [12]. This type of model is valid in the frequency range where curvature is no longer relevant [13]. It is more geared toward the prediction of radial and tangential vibrations at higher frequencies (up to 3 kHz) for which the accurate description of local deformations is important. As such the plate models are complementary to the previously discussed models. A plate model built up of two layers, representing belt and tread, with different isotropic material properties, has recently been implemented [14] and validated by means of point mobility measurements for the case of a non-rotating unloaded tyre for frequencies above 100 Hz [15]. Also anisotropic plate models exist, as for example presented in [16].

A second class of models are *finite element models*. Detailed finite element models are typically computationally very expensive. However, they allow accurate modelling on the premise of detailed material properties being available. Most state-of-the-art industrial models are based on the approach described hereafter. To compute the large tyre deformations in the stationary loaded rotating condition a nonlinear Augmented Lagrangian–Eulerian (ALE) approach is used, in which the rotating tyre is discretized by a fixed mesh through which the tyre material particles flow [17]. A complex eigenvalue analysis of the linearized system of equations allows us to decompose the model into its modal building blocks. This modal approach is based on earlier work on a rotating unloaded tyre [18,19]. Finally, to compute the small vibrations due to the road excitation a modal superposition is performed [20,21]. The model presented in this paper follows the just outlined procedure. Another finite element modelling approach consists of the transformation of the modal base of a tyre in loaded non-rotating condition to the rotating condition [22]. This modelling approach has been used to explain the phenomenon of eigenfrequency loci veering caused by the a-periodicity due to the tyre loading [23]. The waveguide finite element modelling approach has been successfully applied to reduce computational cost [24–26]. In this type of model the tyre cross-section is discretized by conventional finite elements. A wave equation describes the propagation around the tyre circumference. A special material condensation procedure is required to map the material properties to the cross-section mesh elements. Comparison of finite element and waveguide finite element model shows the need for a thorough material optimization of the latter type of model. Once optimized, the waveguide finite element model is well suited for parameter studies where the full capabilities of finite element models are not needed [27].

The paper is structured as follows. Section 2 explains the concept of dispersion diagrams for the characterization of the tyre dynamic behaviour and introduces a mode-numbering convention. Section 3 discusses the finite element model and the numerical computation procedure. Section 4 discusses the experimental configurations. The results from numerical and experimental analyses are presented in Section 5. Finally, the concluding remarks are given in Section 6. All analyses are performed for a smooth or slick tyre of size 205/55*R*16.

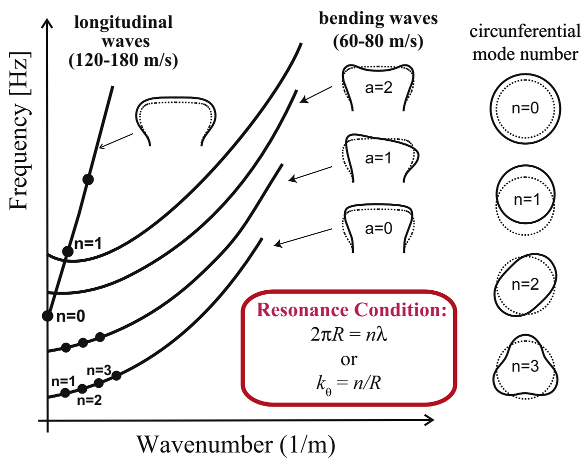

Fig. 1. Typical tyre dispersion curve (derived from reference [33]).