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Dynamic computations of nonlinear beams in contact with rough surfaces

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Abstract

We present computations of a two-dimensional nonlinear ring in contact with a rough surface for the analysis of tire dynamic behaviour at low frequencies in both non-rolling and rolling conditions. For the ring, the assumptions of a Timoshenko beam and finite displacements are considered to build the model. The analytical formulation is established successfully in linear/nonlinear static and dynamic states in non-rolling and rolling conditions using an Arbitrary Lagrangian Eulerian approach. Then, the contact with a real road is introduced. In particular, the calculation of the contact is divided into a non-linear stationary analysis followed by a linear dynamic calculation. The validation of this model is successfully done by comparisons with test results like rolling on simple shapes or with Abaqus computations.

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Keywords: tire; vibration; non linear; beam; noise; contact; rough surface

1. Introduction

The interior noise of vehicles has an important source coming from tires in the low frequency range, typically up to 400Hz. For these frequencies the rolling noise is mainly due to tire vibrations. These vibrations are themselves created by the unsteady contact between road asperities and the tire tread pattern. For predicting this noise generation a tire model is necessary. In the past, various tire models have been developed focusing on different aspects of the problem.

A first class of models is the two and three-dimensional circular ring models. For instance Böhm [1], Heckl [2] and Kropp [3] have modelled the tread as a circular Euler-Bernoulli beam. Sidewalls are represented by radial and tangential springs. This model takes into account the effect of the internal pressure and is linear. These circular ring models are very useful for analysing the radial vibrations of tires for low frequencies. Several authors added the effect of rotation, see for instance Meftah [4], Périsse [5] and Campanac [6,7]. In addition, Huang [8] has analysed

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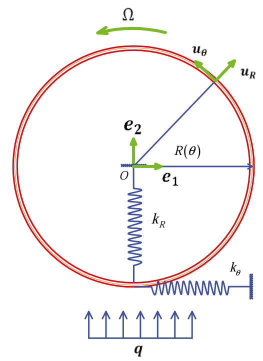

Fig. 1. Description of the circular ring model

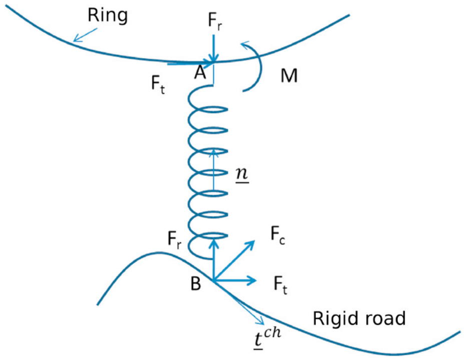

Fig. 2. Contact forces

the rotating ring model under a suspension system. So, two-dimensional circular ring models allow the modelling of the dynamic behaviour of tires for low frequencies [0-400Hz] and analytical transfer functions can be obtained to deal with contact problems. All these models are linear and do not allow to consider, for instance, the influence of the vehicle load or nonlinear material behaviours on tire vibrations. For higher frequencies, plates models were developed by [9–12]. Regarding three-dimensional numerical models, Fadavi [13] and Brinkmeier [14] used Abaqus to model a tire. Another possibility is to use waveguides as in Waki [15] or Duhamel [16,17].

Often, authors have neglected the quasi-static deformation of tires and confused the stationary configuration with the configuration of reference. Under the load of the vehicle and the effect of the air pressure, tires undergo nonlinear deformations. It is thus necessary to distinguish the non-deformed and deformed configurations. This configuration is not known and is obtained by solving the equilibrium equations in stationary regime. This point was for instance developed by [18–20] which used a FEM model for computing the response of tires including the quasi-static deformation and gyroscopic effects. However, these FEM models leads to heavy computations.

This paper aims at developing a nonlinear circular ring model with a good representation of shear deformations to get a mostly analytical model able to estimate the influence of non linearities and to use it for solving contact problems with a rough surface. The structure of the paper is the following. In section two a Timoshenko beam model including shear and rotating effects with large deformations is considered. In section three the contact model is developed. Finally, in section four, examples and validations are given before a conclusion.

2. Beam in finite transformation

The description of the circular ring model representing a tire is illustrated in figure (1). The tread is described as a circular beam. The sides are modelled using radial and tangential springs with respective stiffness k_R, k_θ. The pressure is modelled as a uniform load on the ring. The circular ring has a radius R, a straight section A and a thickness e. The beam is assumed very thin with $\frac{e}{R} \ll 1$.

Each material point in the rotating configuration is defined by two variables (z, θ) in the polar coordinates defined by $(\boldsymbol{u}_R, \boldsymbol{u}_\theta)$ with z varying in the range $[-\frac{e}{2}; \frac{e}{2}]$ and θ in $[0; 2\pi]$. In the rotating configuration, a material point can be represented in the following way:

$$\boldsymbol{OP} = \boldsymbol{OS} + \boldsymbol{SP} = (R + z)\boldsymbol{u}_R \tag{1}$$

with S is a point on the neutral fibre of the beam. S and P belong to the same section. Four configurations are defined: the reference configuration, the rigid rotating configuration, the stationary configuration (rolling on a flat road) and the final configuration (time dependent vibration of the ring). They are referred in the following with indices 0, r, s and t respectively. By switching to the stationary configuration, a displacement field is applied so that $P \to P'$ and $S \to S'$. Point S moves to point S' by two translations $(u(\theta), w(\theta))$. Point P turns by an angle α to point P'. So a Timoshenko beam model is used. The displacement vector of a material point is:

$$\boldsymbol{u} = \boldsymbol{OP'} - \boldsymbol{OP} = (u + z(\cos\alpha - 1))\boldsymbol{u}_R + (w + z\sin\alpha)\boldsymbol{u}_\theta \tag{2}$$