Journal of Sound and Vibration 409 (2017) 274–286

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Contact stiffness considerations when simulating tyre/road noise

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A R T I C L E I N F O

Article history:
Received 1 March 2017
Received in revised form
21 July 2017
Accepted 24 July 2017

Keywords:
Tyre/road noise
Tyre/road noise modelling
Contact stiffness

A B S T R A C T

Tyre/road simulation tools that can capture tyre vibrations, rolling resistance and noise generation are useful for understanding the complex processes that are involved and thereby promoting further development and optimisation. The most detailed tyre/road contact models use a spatial discretisation of the contact and assume an interfacial stiffness to account for the small-scale roughness within the elements. This interfacial stiffness has been found to have a significant impact on the simulated noise emissions but no thorough investigations of this sensitivity have been conducted. Three mechanisms are thought to be involved: The horn effect, the modal composition of the vibrational field of the tyre and the contact forces exciting the tyre vibrations. This study used a numerical tyre/road noise simulation tool based on physical relations to investigate these aspects. The model includes a detailed time-domain contact model with linear or non-linear contact springs that accounts for the effect of local tread deformation on smaller length scales. Results confirm that an increase in contact spring stiffness causes a significant increase of the simulated tyre/road noise. This is primarily caused by a corresponding increase in the contact forces, resulting in larger vibrational amplitudes. The horn effect and the modal composition are relatively unaffected and have minor effects on the radiated noise. A more detailed non-linear contact spring formulation with lower stiffness at small indentations results in a reduced high-frequency content in the contact forces and the simulated noise.

1. Introduction

Traffic noise is a major environmental problem [1]. The noise created when a tyre rolls on a road, *tyre/road noise*, is the main contributor to overall road traffic noise for driving speeds above 30 km/h [2,3]. In addition, the significance of tyre/road noise is expected to increase as the powertrain noise of modern vehicles decreases or, for electrical vehicles, even approaches a negligible level.

In this context an accurate prediction model for tyre/road noise is of substantial value as it allows identification and quantification of solutions for the reduction of tyre/road noise generation. Simulation tools for tyre/road noise commonly include a tyre model, a contact model, and a radiation model. While tyre models and radiation models are well established in the literature (e.g. [4–6] and [7,8]), there is still a need for a better understanding of the contact physics and a higher

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http://dx.doi.org/10.1016/j.jsv.2017.07.044

degree of control in the formulation of contact models.

A variety of tyre/road contact models (and interaction models) can be found in the literature ranging form brush models (see e.g. [9]) to more advanced formulations, e.g [10]. The contact model typically introduces a third medium between tyre and road that allows the incusion of local deformation when individual road asperities intrude into the tyre tread. This third medium would be unnecessary with a *perfect* tyre model that precisely integrates the local deformation. Unfortunately, such perfect tyre models seem very difficult to achieve. Larsson [11] suggested an analytical two-layer model based on the elastic field equations. Although this model was able to predict local deformation correctly [12], it suffers from a simplification of the geometry, as it considers the tyre to be a flat plate. One alternative could be models based on numerical approaches such as Finite Elements (FE) (e.g. [13]). Such tyre models will, however, always suffer from a limited spatial discretisation, which might limit their potential to predict the local deformation with sufficient accuracy.

Therefore, the approach using a third medium has often been employed in combination with simplified tyre models. Typically winkler bedding models (e.g. [14]) or elastic half-space approaches are used (e.g. [15–17,8,18,19]). The elastic half-space includes local deformation and coupling between tread elements. However, it has some limitations and without the introduction of inertia and/or viscoelasticity, it assumes infinite wave speed, meaning that a single, frequency-independent, stiffness value must be approximated.

There is another challenge to overcome when modelling tyre/road contact, and this problem is due to the area of real contact. While roughness wavelengths down to millimetres represent the shape of individual road asperities that deform the tyre tread locally, the effects of even smaller wavelengths contribute to the stiffness in the contact between tyre tread and road asperities. This is due to the fact that the area of real contact is substantially smaller than the apparent contact area; what looks like complete contact within an element with one specific spatial discretisation will, with a finer resolution, consist of less total contact area. Consequently, the contact will be softer than what can be expected from the apparent area of contact.

This means that it is important to include the roughness over a wide range of length scales down to very small scales that cannot be captured by the spatial resolution of the contact model. The solution is to modify the stiffness of the third medium or the tread stiffness of the tyre model in order to include the influence of the area of real contact. Following such an approach, at least two major questions can be identified:

- What level of detail is needed in the contact model and what are the consequences of reducing the complexity with respect to the accuracy of modelled contact forces and simulated noise?
- How can the stiffness parameter in the contact model be determined (ideally without direct comparison with measurements)?

Wullens and Kropp [15] used an elastic half-space to model the tread and noted that the shortcomings of the approach (e.g. the disregard for the finite thickness and width of a real tread) were compensated for by updating the Young's modulus parameter of the half-space. They did so by evaluating the average contact area.

Zhang [19] found good agreement between measured and modelled maximum contact force when a pneumatic tyre rolls over a single asperity when using a “carefully calibrated Young's modulus” of the elastic half-space. He also noted that viscoelasticity is needed in the model in order to simulate the asymmetry in the time development of the contact force found in measurements.

Hoever reported a good match between simulated and measured truck tyre/road noise in [20]. The stiffness of the contact springs were updated to match the modelled static footprint with measurements. This procedure is very often used but was noted in [21] that the contact spring stiffness was at least partly, tuned to compensate for a less accurate side-wall stiffness.

Gäbel [22] found the non-linear stiffness function of a tread rubber block indenting a road surface by adding contributions from very many springs with constant stiffness, distributed according to a cumulative height distribution function (specific to each road surface). The stiffness of the springs was found through comparison with measurements. Andersson and Kropp [23] also used non-linear stiffness functions in their very detailed tread block/road contact model. For the smallest length scales, they applied a model of a circular punch indenting an elastic layer, taking into account the increase in contact area with increasing load. Winroth et al. [24] later extended the model to include damping and inertia in the tread model that couples the non-linear springs, suggesting that at least the stiffening effect of damping should be accounted for in a tread/road contact model.

Persson has been involved in analytical efforts to find the right stiffness function of a tread block indenting a road surface, see e.g. [25,26]. The strain dependency of the rubber's Young's modulus must be considered as well as assumptions of the fractal dimensionality of the road surface. Good agreement with measurements was found for many different road surfaces in [26].

The contact stiffness formulation affects the size of the contact patch, as reported in several studies in the literature. However, there is a lack of investigations showing the effect on the contact forces and radiated noise.

Wullens and Kropp found in [27] (results also briefly reproduced in [2]) that the choice of local contact stiffness of the rubber in the model proposed by Kropp [28] had a great effect on the spectrum of the modelled total contact force and averaged noise generation of simulated belt vibrations. The tyre model used was an orthotropic plate on an elastic foundation, discretised into lateral slices along the circumference, and the local stiffness of the tread rubber was represented by