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The influence of contact modelling on simulated wheel/rail interaction due to wheel flats

A. Pieringer [a,*], W. Kropp [a], J.C.O. Nielsen [b]

[a] *Division of Applied Acoustics/CHARMEC, Chalmers University of Technology, 412 96 Gothenburg, Sweden*
[b] *Department of Applied Mechanics/CHARMEC, Chalmers University of Technology, 412 96 Gothenburg, Sweden*

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ABSTRACT

Most available wheel/rail interaction models for the prediction of impact forces caused by wheel flats use a Hertzian spring as contact model and do not account for the changes in contact stiffness due to the real three-dimensional wheel flat geometry. In the literature, only little information is available on how this common simplification influences the calculation results. The aim of this paper is to study the influence of contact modelling on simulated impact forces due to wheel flats in order to determine the errors introduced by simplified approaches. For this purpose, the dynamic wheel/rail interaction is investigated with a time-domain model including a three-dimensional (3D) non-Hertzian contact model based on Kalker's variational method. The simulation results are compared with results obtained using a two-dimensional (2D) non-Hertzian contact model consisting of a Winkler bedding of independent springs or alternatively a single non-linear Hertzian contact spring. The relative displacement input to the Hertzian model is either the wheel profile deviation due to the wheel flat or the pre-calculated vertical wheel centre trajectory. Both the 2D model and the Hertzian spring with the wheel centre trajectory as input give rather similar results to the 3D model, the former having the tendency to slightly underestimate the maximum impact force and the latter to slightly overestimate. The Hertzian model with the wheel profile deviation as input can however lead to large errors in the result. Leaving aside this contact model, the correct modelling of the longitudinal geometry of the wheel flat is actually seen to have a larger influence on the maximum impact force than the choice of contact model.

1. Introduction

A wheel flat is a defect of the running surface of a railway wheel, giving rise to noise and safety problems. This type of wheel damage occurs when the wheel locks and slides along the rail because of malfunctioning brakes or because the braking force is too high in relation to the available wheel/rail friction. Leaves, grease, frost and snow on the rail surface may aggravate the problem. As a consequence, a part of the wheel tread is worn off and locally the wheel temperature is raised significantly. When the wheel starts rolling again, this is followed by a rapid cooling due to the conduction into the large steel volume surrounding the flat. This process may lead to material phase transformations (formation of martensite) and residual stresses beneath the wheel flat [1].

A wheel with a flat generates large impact forces. As a consequence, large vibration amplitudes of wheel and rail occur, resulting in high noise radiation. Furthermore, these impact forces may cause significant damage to the track, causing for example the initiation and propagation of fatigue cracks. Further damage to the wheel is also likely to occur. Cracking in the brittle martensite leads eventually to large pieces of metal breaking off from the wheel tread, a phenomenon known as spalling [1].

The prediction of the dynamic interaction of railway wheel and track in response to discrete irregularities of the running surface such as wheel flats requires the application of time-domain models. In contrast to frequency-domain models, time-domain models are able to include a non-linear contact model. Non-linearities in the wheel/rail contact cannot be neglected in the case of excitation by wheel flats because of the resulting large contact forces and the occurrence of loss of contact for train speeds above the critical speed [2,3].

Most available interaction models for the prediction of impact forces caused by wheel flats use a Hertzian spring as contact model and introduce the wheel flat as relative displacement excitation between wheel and rail, e.g. the models [4–9]. Wu and Thompson [8] improved the Hertzian contact model for wheel flats by accounting for the finite size of the wheel. They introduced a relative displacement excitation based on the vertical wheel centre trajectory which differs from the geometric shape of the wheel flat. This approach is similar to considering the contact filter effect [10] for wheel/rail interaction due to roughness excitation.

Nevertheless, all models using a Hertzian contact spring have in common that they rely on one effective contact point and a simplified geometry of the wheel flat. Further, they do not account for the changes in contact stiffness due to the real three-

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* Corresponding author. Tel.: +46 31 772 2209; fax: +46 31 772 2212.
E-mail address: astrid.pieringer@chalmers.se (A. Pieringer).

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dimensional (3D) wheel flat geometry. In the literature, only little information is available on how these common simplifications influence the calculation results. Baeza et al. [11] compared the dynamic response due to wheel flats obtained from the Hertzian model (accounting for the finite size of the wheel according to [8]) and a 3D non-Hertzian model. It was concluded that the Hertzian model tends to overestimate the peak impact force. Zhu et al. [12] concluded that the impact forces obtained with a two-dimensional (2D) continuous bedding model differ considerably from results obtained with the Hertzian model (not accounting for the finite size of the wheel according to [8]). An earlier study by Pieringer et al. [10] on wheel/rail dynamic interaction due to roughness excitation showed that the choice of contact model and the detailedness of the considered roughness data significantly influence the simulation results.

The aim of this paper is to study in detail the influence of contact modelling on simulated impact forces due to wheel flats. For this purpose, the dynamic wheel/rail interaction caused by a wheel flat is investigated with the time-domain interaction model from [10] which accounts for the 3D geometry of the wheel flat. The implemented contact model is based on an influence-function method for the elastic halfspace and considers the 3D running surfaces of the rail and the wheel featuring the flat. To allow for an investigation of the influence of the contact modelling on the calculation results, the interaction model is also used with two simpler contact models. The first such contact model is a 2D model consisting of a Winkler bedding of independent springs. This model uses a simplified wheel and rail geometry and a 2D description of the wheel flat. The second simplified contact model is a Hertzian contact spring.

In a first step, the wheel/rail interaction model together with the 3D contact model is applied to study the dynamic response due to different types of wheel flats. Parameters investigated include the shape and dimensions of the wheel flat, the train speed and the impact position on the rail in relation to the discrete supports.

In a second step, selected simulations are repeated with the 2D and Hertzian contact models, in order to assess the errors introduced by these simpler contact models in comparison to the 3D model. The study will thus address the question of which level of contact model complexity is needed to calculate the dynamic wheel/rail interaction due to wheel flats.

2. Description of wheel flats

In published prediction models, the shape of the wheel flats is almost exclusively described by simple analytic functions. Measured wheel profiles have been used in [7]. In the absence of measurement data, the current study also uses analytical functions. Two types of wheel flat geometries are considered: the newly formed wheel flat with sharp edges as occurring right after formation and the rounded wheel flat, which rapidly develops from the newly formed flat as a result of wheel tread wear and plastic deformation, see Fig. 1. Further wheel damage as spalling is not taken into account.

The two-dimensional shape of the idealised newly formed wheel flat can be modelled as a chord of the wheel circumference. The length l_0 of the newly formed wheel flat is related to its depth d according to

$$l_0 \approx \sqrt{8R_W d}, \tag{1}$$

where R_W is the wheel radius and it has been assumed that the depth of the flat is small in comparison to the wheel radius. The vertical wheel profile deviation (i.e. the difference between the surface of the undamaged wheel and the wheel featuring the flat) for a newly formed flat is approximately given by

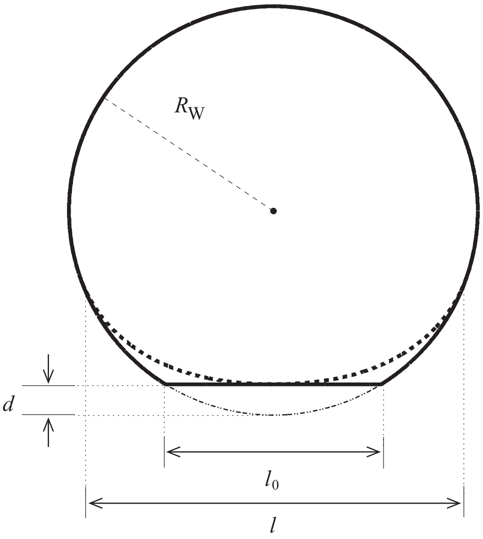

Fig. 1. Idealized 2D geometry of newly formed and rounded wheel flats (size of the wheel flats exaggerated).

$$z_{nf} \approx d - \frac{x^2}{2R_W}, \quad -\frac{l_0}{2} \le x \le \frac{l_0}{2}, \tag{2}$$

where x describes the horizontal distance from the centre of the wheel flat.

The rounded flat is assumed to have the same depth d as the newly formed flat, but a length $l > l_0$. Following the approach in [4], the vertical profile deviation of the rounded wheel flat is described by

$$z_{rf}(x) = \frac{d}{2}\left(1 + \cos\left(2\pi \frac{x}{l}\right)\right), \quad -\frac{l}{2} \le x \le \frac{l}{2}. \tag{3}$$

In order to guarantee that $z_{rf}(x) \ge z_{nf}(x)$ for all x (i.e. the rounded wheel flat is at least as deep as the new wheel flat), the length of the rounded flat has to satisfy $l \ge \pi/2\, l_0$.

It is not evident how to model the three-dimensional shape of wheel flats, which is required as input to the 3D contact model. In the current study, the approach by Baeza et al. [11] has been adopted, where it is assumed that the shape of the newly formed flat corresponds to the shape of the rail head on which it was formed. Cylindrical profiles have been used for both wheel and rail and Fig. 2(a) shows an example of the flat shape obtained by this means. For the newly formed flat, parameter lines of the vertical wheel profile deviation in the rolling direction are of the type given in Eq. (2), while parameter lines in the transverse direction are circular arcs with rail head radius R_R. Analogously, parameter lines of the vertical wheel profile deviation for the rounded flat in the rolling direction are assumed of the type given in Eq. (3), while parameter lines in the transverse direction are circular arcs with rail head radius R_R (Fig. 2(b)). In practice, the shape of wheel flats will differ from the idealized shapes considered in this study.

3. Wheel/rail interaction model

The wheel/rail interaction model, which is illustrated in Fig. 3, is described in detail in [13] and has been earlier presented in [10]. In order to facilitate the task for the reader, the description from [10] is partly repeated here. Adaptations have been made to excitation by wheel flats where necessary, see Section 3.3.

The wheel/rail interaction model is formulated in the time-domain and includes a linear wheel model and a linear track