Journal of Sound and Vibration 333 (2014) 3981–3995

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Time-domain prediction of impact noise from wheel flats based on measured profiles

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ARTICLE INFO

Article history:
Received 1 October 2013
Received in revised form
7 April 2014
Accepted 9 April 2014
Handling Editor: G. Degrande
Available online 1 May 2014

ABSTRACT

Railway impact noise is caused by discrete rail or wheel irregularities, such as wheel flats, rail joints, switches and crossings. In order to investigate impact noise generation, a time-domain wheel/rail interaction model is needed to take account of nonlinearities in the contact zone. A nonlinear Hertzian contact spring is commonly used for wheel/rail interaction modelling but this is not sufficient to take account of actual surface defects which may include large geometry variations. A time-domain wheel/rail interaction model with a more detailed numerical non-Hertzian contact is developed here and used with surface roughness profiles from field measurements of a test wheel with a flat. The impact vibration response and noise due to the wheel flat are predicted using the numerical model and found to be in good agreement with the measurements. Moreover, compared with the Hertzian theory, a large improvement is found at high frequencies when using the detailed contact model.

1. Introduction

Railway impact noise is caused by discrete rail and wheel discontinuities such as rail joints and wheel flats. Since the excitation is predominantly vertical this has a similar excitation mechanism to rolling noise, in which surface roughness induces a relative vertical displacement between wheel and rail [1]. However, the frequency-domain approach normally used for modelling rolling noise is not suitable for impact noise prediction due to the importance of nonlinearities of the contact zone in the presence of large deflections and potential loss of contact [2].

Wheel flats are caused by sliding of the wheels during braking in poor adhesion conditions, particularly in the autumn when leaves may contaminate the rail head. Nielsen and Johansson [3] reviewed the effects of wheel out-of-roundness including flats and it was pointed out that a better removal criteria of defective wheels based on impact loads was needed. Newton and Clark [4] used time-domain models of wheel/track interaction to predict the impact forces due to wheel flats, although the impact noise was not considered. A similar modelling approach was used by Nielsen and Igeland [5]. Newton and Clark [4] also performed experiments with a defect ground into the rail head to represent the inverse of a wheel flat for a given wheel diameter. However, it should be noted that the wheel centre trajectory will be different from the irregularity shape due to the finite size of the wheel, as pointed out in [2]. Dong et al. [6] compared these measured results with their finite element model of the wheel/rail system and relatively good agreement was found for speeds up to 120 km/h. Steenbergen [7,8] analysed the effects of wheel flat geometry on the impact force. He argued that the minimum curvature

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http://dx.doi.org/10.1016/j.jsv.2014.04.026
0022-460X/

of the wheel tread is a more appropriate parameter for wheel flat classification than the length and depth of the flat because the effective depth is a function of velocity. In [8] different stages of the wheel flat growth are presented, including the corresponding wheel centre trajectories and their frequency transform. As the flat grows longer (more wear at the edges), the frequency distribution of the trajectory tends to be focused more at low frequency. This indicates the increasing importance of track stiffness on the response. Cordier et al.[9]provided an analysis of measured noise from different wheel defects that are generated during real operation. Compared with regular surface roughness, these wheels showed increases in noise of up to 8 or 9 dB for defects such as a wheel flat and local crushing. More recently Pieringer [10] has developed an efficient time-domain prediction model of wheel/track interaction based on moving Green's functions for the track.

Although for most of the studies above, the wheel is often simplified to a rigid body, improved wheelset models has been considered to calculate wheel flat impact force [11]. The wheelset was modelled as a flexible rotating body and the train–track interaction forces have been computed for roughness, corrugation and wheel flat excitations. Although the contact force was found overestimated if the wheelset flexibility is neglected for a single harmonic corrugation, this difference from random roughness and wheel flat was relatively small. The effect of a flexible wheelset was found mainly on the transient forces after the impact due to wheel flat. The effect of the wheelset flexibility was also found to affect the vehicle running behaviour in [12].

In order to study noise generation from a wheel flat it is important to model the system reliably up to higher frequencies than is necessary for impact force determination. A hybrid method was developed by Wu and Thompson [2] in which the contact force was determined in the time domain using a simple rail/wheel model. This was transformed to determine an 'effective' roughness spectrum, which was then used as input to a frequency-domain model, the Track–Wheel Interaction Noise Software (TWINS) [13], to predict the impact noise from wheel flats. The results confirmed the relation of approximately $20\log_{10}V$ between sound power level and train speed found in [14] before contact loss, but unlike [14] the level was found not to tend to a constant value above a critical speed.

The wheel and rail are in contact over an area due to local deflection under the normal load. For contacting surfaces that can be defined in terms of a parabolic shape, Hertz theory can be applied to normal contact problems with a nonlinear Hertz stiffness that depends on the radii of curvature of the two surfaces [1,15]. For Hertz theory to be valid the surfaces of the two bodies should be continuous, non-conforming and frictionless, the elastic strains should be small and each of the bodies should be large enough that they can be represented by an elastic half-space [15]. However, if the two bodies can be considered quasi-identical, as here, the normal and tangential contact problems are decoupled and therefore friction has no effect on the normal Hertz contact problem [16]. In the vicinity of a discontinuity such as a wheel flat, however, the Hertzian contact model requirements are not fulfilled due to the large variations in the geometry, although in most previous models of wheel/rail impact, e.g. [2,5], a nonlinear Hertzian contact spring has been employed for time-domain simulation.

Real solids have rough surfaces and in general the contact only occurs at asperities when the two rough surfaces come together [17]. In [17], the elastic contact of rough spheres was studied using a statistical roughness model. It was found that the Hertz solution forms the high load limit of the result for the rough surface but for low loads differences occur. Alonso and Giménez [18] studied the influence of such roughness for wheel and rail applications, with measured wheel roughness, and concluded that roughness has an insignificant effect on the apparent contact pressure distribution for railway vehicles at typical loads.

However, for wheel flats the surface defects are similar in scale to the geometry of the solid bodies and this makes the contact non-Hertzian. For most general profiles, closed form solutions are not possible. Numerical methods for contact mechanics, such as the matrix inversion and variational methods, can be applied to non-Hertzian problems [15]. These methods have been well developed and were used for example in [19] and [20] for applications to real wheel/rail situations. However, they are all based on the assumption that the elastic behaviour of the contacting bodies can be approximated by an elastic half-space [15]. In [21], the wheel/rail contact at a railway switch frog was studied using both the finite element method (FEM) and Hertz theory. The contact distribution from Hertz theory agreed very well with the FEM results. The contact problem at railway switches was also investigated in [22]. It was found that although the minimum radius of curvature of the two contacting bodies was very close to the largest semi-axis of the contact patch, the contact model based on a half-space agreed well with the FE model. In [23], the transient rolling contact problem between wheel and rail was studied using a 3D FE model. This model was validated against Hertz and CONTACT [16] models for quasi-static cases. From that comparison, it was pointed out in [23] that half-space is a good approximation for contact on the rail head. As the essence of the half-space assumption is that the distant approach of the two contacting bodies is not affected by the local deformation [24], in railway applications, the half-space assumption might only be invalid for flange contact where the thickness of the wheel flange is comparable to the contact size. Moreover, flange contact is often associated with multiple contact regions. It is shown in [25] that in a tight curve with triple contact positions, there are large differences between FEM and the contact methods based on the half-space approximation. For tread contact, however, the half-space assumption can be used without difficulty.

Longer wavelength roughness, or unevenness, with wavelengths between around 5 mm and 500 mm, has been recognised as the primary source of railway rolling noise [1]. Theoretical rolling noise models such as TWINS use measured surface roughness as the excitation, assuming that the roughness essentially acts at single point and the contact parameters will be independent of the roughness present [26]. However, the finite contact area between wheel and rail is known to introduce a 'contact filter' effect for railway noise generation [1]. Wavelength components of roughness that are comparable to or shorter than the length of the contact area in the rolling direction tend to be less effective in exciting the wheel/rail