Wear 352-353 (2016) 196–208

Contents lists available at ScienceDirect

Wear

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

A versatile method in the space domain to study short-wave rail undulatory wear caused by rail surface defects

N. Correa, E.G. Vadillo*, J. Santamaria, J. Herreros

Department of Mechanical Engineering, University of the Basque Country UPV/EHU, Escuela Técnica Superior de Ingeniería, Alda Urquijo s/n, 48013 Bilbao, Spain

A R T I C L E I N F O

Article history:
Received 16 November 2015
Received in revised form
18 February 2016
Accepted 19 February 2016
Available online 27 February 2016

Keywords:
Rail–wheel tribology
Wear
Corrugation
Rail defects
Train speed dispersion

A B S T R A C T

This paper examines the development of short-wave undulatory wear caused by vehicles running over defects on rail surfaces. The track model used was obtained using a Rational Fraction Polynomial (RFP) method modified using genetic algorithms. This produces an extremely accurate and simple wheel-track model requiring minimum computational times. As corrugation formation simulations in the time domain require such a large number of thousands of wheelset passovers, it was essential to develop such a simple but precise model. A non-linear Hertzian spring was used to study the interaction between wheel and rail. Wear is considered to be proportional to the friction work, as some other authors assume for this type of problems, emerging upon contact. This model has been validated by comparing its results with experimental results of undulatory wear measured on a track. The developed tool enables the evolution of rail wear to be studied for different ride conditions that are not affordable to study experimentally. Some of the factors studied in the paper are: the influence of the frequency at which the partially worn rail surface profile is updated during the wear evolution simulation; the influence of the train speed dispersion that usually exists around the nominal speed; the influence of the position of the rail defect within a span between two sleepers; and the influence of the train's nominal speed.

1. Introduction

In recent years, important research activity has been carried out related to vehicle-track interaction and its influence on track degradation, including TrioTRAIN and DynoTRAIN projects [1], and INNOTRACK project [2]. Research has also been conducted recently on various aspects of wheel-rail interaction [3] and on predictions of damage formation on curved track [4].

One aspect of track deterioration related to the vehicle-track interaction is rail undulatory wear. This wear, sometimes called corrugation wear, is a wear process that frequently arises on railway lines, commonly in double-track commuter trains, running at the same speed and with identical dynamic properties. Corrugation wear is manifested by dull areas in which the rail remains unworn and periodic shiny areas in which wear is produced.

It has been observed that corrugation wear increases rapidly if the rail surface has an irregularity (welding defect, squat, wheel burn, etc.) that may act as a trigger exacerbating the undulatory wear along the subsequent metres of track. As an example, Fig. 1 shows a short-wave corrugation span on an Iberian gauge railway line in the Bilbao area, brought on by the presence of a rail weld on the preceding centimetres of rail. Specifically, the photo shows the low rail on a curved section of track.

The corrugation wear phenomenon has been studied by many authors over the years. This has led to the development of a large number of models to conduct a specific study of trends in corrugation. Other models have also been developed to study general purpose wheel-rail interaction problems, and can in some cases be applied for the purposes of studying rail corrugation problems. These models are classified as frequency-domain models and time-domain or spatial-domain models. The major difference between them is that frequency-domain models are linear, whereas time-domain models may be either linear or non-linear.

Models studying corrugation wear in the frequency domain are generally based on the mobile irregularity hypothesis, whereby the relative movement between wheel and rail is not produced by the movement of the wheel along the track, but by the movement of the irregularity beneath the wheel. Thus, the wheel remains fixed at a certain position on the track, and it is the irregularity that moves.

On the other hand, time-domain models, although they can use any moving reference system, are generally based on the mobile wheel hypothesis. In this case, the wheel rolls above the irregular rail, making it possible to take into account the parametric excitation due

* Corresponding author. Tel.: +34 94 601 4223; fax: +34 94 601 4215.
E-mail address: ernesto.garciavadillo@ehu.es (E.G. Vadillo).

http://dx.doi.org/10.1016/j.wear.2016.02.012
0043-1648/

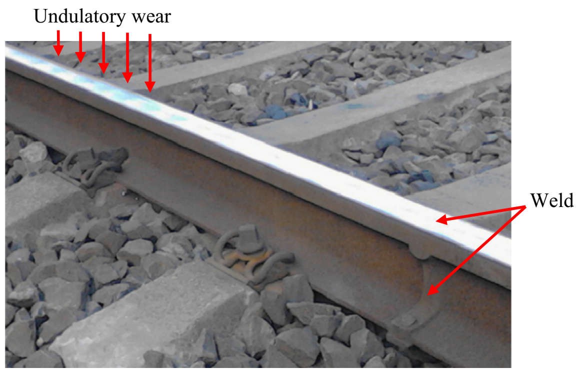

Fig. 1. Corrugated worn rail in Bilbao.

to the track stiffness variations along each position within a span between two sleepers. It is for this reason that, although a model in the frequency domain with mobile irregularity can predict the tendency of undulatory wear to emerge on the rail at different positions along the rail span, it is nevertheless not possible to take account of the track's changing stiffness during movement over the various positions on a span. On the other hand, unlike models based on the frequency domain, models based on the time domain do study the rail undulatory wear evolution after successive wheelset passovers, as this paper intends.

Models in the frequency domain to study railway undulatory wear have been used for decades, such as the Hempelmann [5] and Müller [6] models. Working in the frequency domain permits a study of the vehicle-track interaction and also enables the steady-state response to be obtained in an accurate manner and with low computing time expenses, both for tracks with discrete sleepers [7] and for continuously supported tracks [8]. Likewise, some extremely comprehensive models working in the frequency domain predict undulatory wear formation, portraying track dynamics to a high degree of accuracy, including all track components and also the deformation of the rail section and the propagation of bending, elongation and torsional waves along an infinite track [9–11]. As a result, they are able to predict whether or not corrugation wear will develop on the rail sections above a sleeper, at midspan or at any other section, although they can barely quantify the wear to be generated in sections that follow a defect. Recently, an article was published on the prediction of corrugation and noise on tangent rail [12], and another one which studies and validates a model to examine corrugation with consideration of environmental effects [13].

These models in the frequency domain are not suited to the examination this paper wishes to conduct, as they would be unable to study developments in the corrugation caused by a rail defect or the influence of the discrete supports on the track. Therefore the option pursued is a model in the time domain or a combination of the time domain and the frequency domain. Moreover, the model to study the development of corrugation that is required for this paper must necessarily entail rapid calculation and enable thousands of wheelset passovers to be simulated on the track over a reasonable period of time. This necessarily means discarding certain characteristics which could produce more comprehensive models, but would slow down the integration of the model and thereby prevent the study from being carried out due to an excessively high computational cost.

For instance, some authors study corrugation on the basis of the assumption that it may arise due to the emergence of instabilities associated with self-excited vibrations during the contact between the wheel and the rail [14,15]. Others, however, the vast majority [16–22], suggest models to develop corrugation in the time domain or a combination of both domains, in which corrugation emerges as the result of differential wear phenomena between wheel and rail as a consequence of the dynamic interaction between them, taking no account of the instabilities associated with self-excited vibrations. These are borne out by recent studies in which the wavelength-fixing mechanism proves to be some type of resonance in the interaction between wheel and rail or in the track, such as in one paper [23] that studies and addresses corrugation in the Beijing metro on an experimental basis. The present model may be categorised within the latter set of models.

The time-domain models of a number of authors, such as [24], emphasise the possible effect of non-steady non-Hertzian contact on the development of corrugation. Others have also used this type of contact [20,22,25]. In [18], a non-Hertzian contact model is used on a 3D model. [19] features a model for normal tangential contact that uses a surface-to-surface contact algorithm. These types of models would require an inconceivable computation time to simulate thousands of wheelset passovers.

Other time-domain models feature a flexible wheelset [20–22], and even a rotating wheelset model [20,21,25]. For example, [20] employs a flexible rotating wheelset and a track model based on substructuring techniques that consider an infinite track over which an infinite number of vehicles pass with a certain constant distance between them. Considering the flexible wheelset allows to detect a type of corrugation in which the wavelength-fixing mechanism is associated with the wheelset structural modes [25], and which would not be detected by other models [21] concludes that it is advisable to use this type of wheelset model when the contact forces are extremely powerful at high frequencies. However, it must be reiterated that considering a flexible rotating wheelset would slow down calculations.

Others have proposed models that require shorter computation times, albeit at the cost of not including some of the characteristics previously mentioned. These models include [16], which uses a vertical Hertzian contact and FASTSIM [26] to study tangential contact. The vertical model uses a wavenumber-based approach to predict the emergence and growth of corrugation [27] also models the contact on a non-linear Hertzian spring in a model based on Green's functions. Likewise, [28,29] also availed themselves of this contact model [17] experimentally validates two numeric models in the time domain, one in 2D and a more complex (and therefore slower) 3D model.

This paper places the emphasis on the speed of calculation and the ability to carry out many thousands of simulations with a minimum loss of accuracy in the wheel-track model to study the development of corrugation against many thousands of wheelset passovers. In any case, if the situations examined in this paper were simulated (influence of the frequency at which the worn rail profile is updated during the wear evolution simulation; influence of train speed dispersion and influence of the position of the rail defect), even the most complete models would produce very similar results.

This paper sets out a spatial-domain model based on an RFP method [30] obtained from dynamic track results in the frequency domain, which was modified with respect to the Wu/Thompson [28,29] model by means of optimisation with multiobjective genetic algorithms in order to improve the model fits at low frequency. The RFP method obtains transfer functions calculated in such a way that their associated receptances match the track receptances. These transfer functions may be used to produce a system of differential equations to represent the track that are integrated along with those associated with the wheelset dynamics. This track model is validated and described in detail in [31], and a more elaborate description is provided in Section 2.

Studying rail corrugation wear development and evolution in the spatial or time domain requires hundreds of thousands of wheelset