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The effect of non-uniform train speed distribution on rail corrugation growth in curves/corners

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ABSTRACT

Rail corrugation is a significant problem in railway engineering, manifesting as an oscillatory wear pattern on the rail head. These profile variations induce unwanted vibrations, excessive noise and other associated problems. Constant train speed for consecutive train passes has been shown to accelerate corrugation growth while widening the probabilistic speed distribution can be shown to mitigate the phenomena. This paper extends this research by investigating the effect of non-uniformity (or asymmetry) in speed distribution on corrugation growth on curved track/corners. To this end, an efficient corrugation growth prediction model is further developed to include quasistatic bogie cornering dynamics and investigated under non-uniform speed distribution conditions. The results indicate that under typical cornering conditions, the rate of corrugation growth is increased (or decreased) when the mean or skewness of the distributed set of passing speeds is biased to higher (or lower) speeds. In particular, for the conditions investigated, controlling (or not controlling) skewness could achieve a further 12% (or −20%) in corrugation growth rate reduction from a nominal 41% reduction due to symmetric speed variation. Hence, non-uniform speed distribution could cause up to a 50% reduction in predicted effectiveness of widened speed distribution control to reduce corrugation growth rate.

1. Introduction

Wear-type rail corrugation is a dynamic wheel-rail contact phenomena that manifests as a periodic wear pattern on rail heads. It is a significant problem in railways worldwide [1] that grows over many train passages, causing unwanted vibrations, excessive noise and other associated problems. Fig. 1 shows a corrugation profile after approximately 9 months of passenger rail traffic. Recent studies have shown that uniformity in train passing speed accelerates corrugation growth on straight track and conversely, widening the probabilistic train passing speed distribution can be used as a mitigation tool. The dominant mitigating mechanism is that different vehicle speeds lead to different wavelengths and positions of periodic wear along the track and therefore cancellation of corrugation growth.

Wear-type rail corrugation is caused by vehicle vibrations interacting with oscillatory contact conditions between the wheel and rail, resulting in a periodic variance in frictional power between the two running surfaces. This in turn differentially wears the surface of the rail, resulting in a ripple pattern on the rail head. This corrugated profile re-excites the wheel-rail contact and vehicle on subsequent wheel passages, at a similar vibration frequency if the speed is similar, which accelerates the growth process [2]. The primary cure for corrugations at present is expensive reprofiling of the rail by grinding. To better understand this problem, a number of models to simulate the rail corrugation growth process have been developed. Simplified analytical corrugation prediction models have shown the capacity to predict dominant frequencies and amplitudes in dynamic normal force oscillation and subsequently, associated corrugation growth rates [2–6]. More complex three dimensional numerical models can provide more fidelity but are computationally expensive, making effective analysis of speed distribution effects over many vehicle passes difficult. However, simplifications in modelling based on identifying the dominant interactions may be used to provide efficient analysis such as that developed in [7]. A variety of control techniques have also been proposed and developed to mitigate rail corrugation growth. Most have proven unreliable under varying conditions (see reviews of [1,8]). However the application of friction modifiers [22,23] for reducing the occurrence of rail corrugations has been relatively successful by changing the friction coefficient and stick-slip behaviour in the contact. Alternatively, recent studies have shown that widening the probabilistic passing speed distribution over a section of rail can be an effective corrugation mitigation tool [7,9,10], although environmental effects may swamp performance in the field [24]. Often though, the variance of

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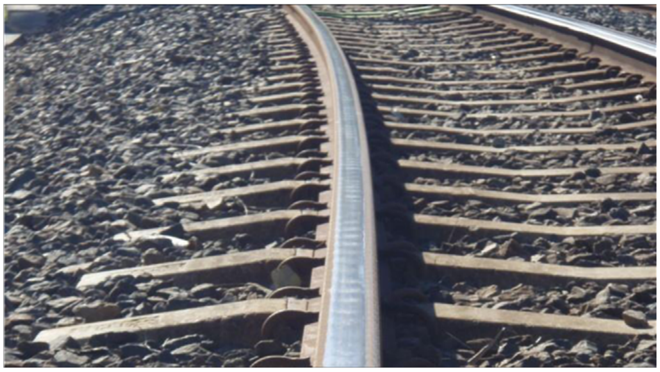

Fig. 1. 9-month-old corrugated rail profile.

train speed approved by rail operators will be limited in order to meet existing timetables. For this reason, the amount of increase of train passing speed standard deviation may be limited, so alternative methods of controlling the train passing speed distribution for mitigating corrugation growth is of interest.

This paper aims to predict and quantify the effects of using a non-uniform speed distribution on the corrugation growth rate under curving/cornering conditions. In particular, asymmetric speed distribution parameters are defined and the additional benefits of asymmetry in corrugation control under a range of bogie cornering speeds are investigated. This was achieved by integrating triangular speed distributions of varying skewness to quantify its effects on the growth rate of the dominant wavelength of corrugation formation. The main contributions of this paper are an enhancement and validation of an efficient corrugation growth model to include bogie-wagon cornering dynamics and quantification of the effect of non-uniform speed distribution on rail corrugation growth in cornering/curved track conditions.

To this end, a modified frequency domain corrugation model is first presented as a sequence of transfer functions and combined with a variable speed input to create a new, efficient corrugation growth model for cornering/curving conditions. It is noted that the modelling is made as simple as possible to enable efficient calculation of a distribution of train pass velocities while encapsulating the dominant dynamic behaviour. Subsequently, a method of integrating the corrugation growth function with a series of asymmetric triangular speed distributions is provided. The direct effects of nominal speed on corrugation growth on both rails in cornering is then determined and discussed. Cornering/curving results of traction and bogie yaw angle were benchmarked against a linearised cornering model presented in Wickens [16] and corrugation growth rate was benchmarked against modelling from Daniel et al. [19]. Finally, the effect of non-uniform speed distribution on corrugation growth in cornering is quantified under a case study.

2. Theoretical modelling

Corrugation modelling consists of four basic components shown in Fig. 2: (I) vibrational dynamics of the train and track causing oscillating contact forces, (II) contact variations in the interface between the rail head and wheel, (III) material removal from the rail head due to variation in frictional power at the contact interface, and (IV) transient dynamic effects between successive wheel passes due to a finite pass delay. Component IV is not considered in the present paper but its effects are detailed in [11].

The following subsections outline details of the components in Fig. 2 used to derive a corrugation growth expression for a bogie in cornering under varying speed conditions. In this case, the corrugation mechanism is based on the field and modelled behaviour identified in [7] whereby cornering corrugations were shown to be associated with dynamic normal forcing of the wheel/rail contact inducing high amplitudes of varying lateral slip. This behaviour was validated using a more complex 3D model and field measurements where vertical dynamics was shown to dominate because the high effective lateral contact damping is found to minimise the effect of the lateral dynamics (see Appendix in [7]). Hence rail corrugation growth caused by wheelset torsional oscillation modes is not considered in this paper. In addition, in order to develop an efficient corrugation growth model, the vehicle-track dynamics is modelled using a rigid wheelset and a finite number of modes in the frequency range of curving corrugations of interest (ie typically 50–500 Hz). This approach was validated with field measurements in [17]. However this assumption could be relaxed by the use of measured receptances if desired. Also transient and nonlinear geometric contact mechanics associated with short pitch corrugations, that typically do not occur in curves, are also ignored.

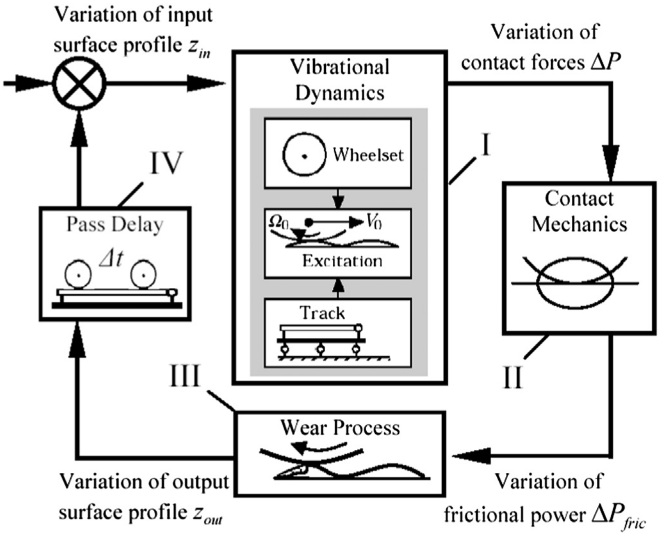

Fig. 2. Corrugation modelling block diagram.

2.1. Vibrational dynamics (I)

In the presence of high lateral contact damping experienced at creep conditions below critical, vibrational dynamics in cornering are dominated by vertical rail and wheel responses to existing profile height variations [7]. In particular, in this case the mechanism of corrugation growth is dominated by lateral traction variations, predominantly excited by vertical vibrations due to high lateral contact damping. Further details, validated by field measurements are provided in [7]. Hence, lateral dynamics are neglected in predicting corrugation growth in this paper. Under these conditions, referring to Fig. 2(I), the normal contact force variation, ΔP, resulting from an input surface profile height variance Z_n, may be adequately expressed using the following receptance based equation [13],

$$\Delta P/Z_n(\omega)=k_c/\left[1+k_c(R_{rv}(\omega)+R_{wv}(\omega))\right], \tag{1}$$

where R_{rv} and R_{wv} are the vertical rail and wheel receptance functions of frequency, ω, and k_c is the contact stiffness, predetermined by the steady state normal force [13]. A five mode track model was utilised to model a typical vertical track receptance (see Appendix A) and the wheel receptance was assumed to be that of the unsprung mass.

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