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DYNAMIC VEHICLE-TRACK INTERACTION WITH MULTIPLE SHORT RAIL DEFECTS OVER LONG WAVELENGTH TRACK SETTLEMENT

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Daily, hundreds of millions of train journeys are operated around the world. Trains are running on tracks at a wide range of speeds, causing dynamic effects onto track systems. The dynamic interactions between vehicle and track impose vibrations and acoustic radiations and become moving vibro-acoustic sources along the railway corridor. Especially when there is imperfection of either wheel or rail, the dynamic amplification of loading conditions and reflected vibration effects on infrastructure and rolling stocks is significantly higher. Therefore, dynamic resistance of every component (derived from dynamic testing of materials and structure) is vital in improving dynamic performance of track system. In real life, imperfection of rail tracks is inevitable and can be classified into short wave length and long wave length defects. The short wavelength defects include high-frequency related rail surface defects such as dipped joint rails, rail squats, rolling contact fatigues (RCFs), rail gabs and crossing nose. The long wavelength defects are those associated with low frequency vibrations such as differential track settlement, mud pumping, bridge ends, stiffness transition zone, etc. Most previous studies into vehicle-track interactions are concerned only to a single discreet defect individually. This study is the world first to evaluate the coupling dynamic vehicle-track interactions over coupled multiple short and long wavelength rail defects. The vehicle model has adopted multi degrees of freedom coupling with a discrete supported track model using Herzian contact theory. The validated multi-body simulations have been used to investigate the effects of the multiple short defects (e.g. multiple squats or continuous RCFs). This paper highlights the dynamic impact load factors experienced by railway track components due to wheel/rail contacts. The insight into the dynamic amplification will enable predictive track maintenance and risk-based track inspection planning to enhance public safety and reduce unplanned maintenance costs.

Keywords: Dynamic interaction, Coupling vehicle-track modelling, short wavelength defect, long wavelength defect, multiple rail surface defects

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1. Introduction

For nearly a hundred years, modern ballasted railway tracks have become the most efficient and effective infrastructure catering operations below 250 km/h of train speed. Over time, ballasted tracks have been tailored and optimised to suit its purposes, such as light rail tracks, metro networks, suburban rail network and intercity rail lines. Ballasted tracks are relatively inexpensive and quite superior in terms of maintainability and constructability [1-4]. In contrast, ballastless tracks or concrete slab tracks are often utilised for highspeed rail lines (with train speed over 250 km/h) to reduce maintenance costs due to faster degradation of ballast due to high-frequency dynamic problems (e.g. accelerated densification and dilation of ballast, poor ride comfort due to differential track settlement/stiffness, ground-borne noise and vibration problems, etc.) [1, 5-9]. In practice, railway maintainers and operators are suffering from many of rail surface defects that lead to increased maintenance (either planed or unplanned), operational downtime and delay, more frequent monitoring and track patrol, and possibly the broken rails leading to train derailments [10-12]. These are clear evidences of actual dynamic problems in railway infrastructures, which have been neglected totally overtime.

In recent years, the majority of people have been moving to and dwelling in cities and urban space. Social problems of ground-borne, structure-borne noise and vibration induced by short and long wavelength rail defects have become noticeable by the publics, reinforcing the political influences to resolve the issues. For instance, extra level of noise excited by rail squats (short wavelength type) was observed by residents near Woolloomooloo viaduct in Sydney, Australia [13-14]. Reportedly, the cost of rail replacement due to rail squats and studs has become a major part of the whole track maintenance cost in European countries [15]. It is important to note that the rail squats and studs are typically classified as the growth of any cracks that has grown longitudinally through the subsurface. The subsurface lamination crack later results in a depression of rail surface sometimes called 'dark spot' [16]. There are two initiation types of the rail surface defects. Such rail defects are commonly referred to as '*squats*' when they were initiated from rolling contact fatigue (RCF) cracks, and as '*studs*' when they were associated with white etching layer due to wheel slips or excessive tractive effort [16]. In addition, with heavier and faster trains, the realistic dynamic load conditions transferring on to track and its components such rails, sleepers, ballast and formations are higher and amplified by the traffic speeds and rail surface defects. These dynamic impact loading conditions will excite and resonate each component; frequently deteriorate the track support; and, cause initial differential settlement and plastic deformation. The track maintenance issue does not stop here. Such the plastic deformation and initial differential settlement further form and couple with short wavelength defects (if any) to exponentially aggravate the dynamic loading conditions [17-19]. Therefore, *it is highly important to know the dynamic properties of components and its materials (which constitute the components)*, in order to understand the coupled dynamic effect of rail defects on the rail infrastructure so that rail operators and maintainers can develop suitable cost-effective strategies for operations and maintenance. An example of strategies is to carry out preventative track maintenance (such as re-tamping, re-grinding and ballast cleaning when early sign of damage is inspected). In many regional railways (such as freight services), speed restrictions have been adopted to delay the maintenance regime when the rail defects exist. Note that these strategies are often called 'Base Operating Conditions (BOCs)' in railway industry practices. The BOCs have been developed from internal R&D activities and extensive empirical experience in the rail industry over the centuries.

Rail track dynamic and wheel-rail interaction was studied thoroughly in 1992 using a detailed programming, D-track program, for dynamic simulations considering appropriate track components [20]. Afterward, Iwnick has done a benchmark, which was called Manchester Benchmarks in 1998 [21]. In 2005; Steffens [22] has adopted the parameter of Manchester Benchmarks to compare performance of vary dynamic simulation programs and also developed the user-interface of D-track. On the other hand, D-track had still an issue of lower result than others and then the owner has revised the program after this benchmark. Subsequently, Leong has done the Benchmark II with the revised version of D-Track in 2007 [23]. In this study, the dynamic simulation concept by Cai [20] has been adopted as seen in Fig.1 since the track model has included Timoshenko beam theory for rail and sleepers, which enable a more accurate behaviours of tracks. Note that rail cross section and sleeper pre-stressing are among the key influences on shear and rotational rigidities of Timoshenko beam behaviors in numerical modelling of railway tracks [24-27]. The irregularity of wheel and rail will cause higher dynamic impact force that the design condition level or serviceability limit state. The exceeing magnitude of the force generated by wheel and rail irregularities will damage track components and impair ride quality [28-37]. This study thus is the first to present the wheel-rail dynamic forces over multiple short-pitch defects (see Fig. 2) coupled with a long-wavelength defect (track settlement). The dynamic amplification factor will be highlighted to identify the effect of train speeds. The scope of this study will be focused on ballasted railway tracks. The commonly used passenger wagons (14t axle load) will be modeled and coupled with the discrete supported track model. The track model will be based on a standard rail gauge (1.435m). The outcome of this study will help rail engineers improve the predictive maintenance and inspection regimes of railway track systems.

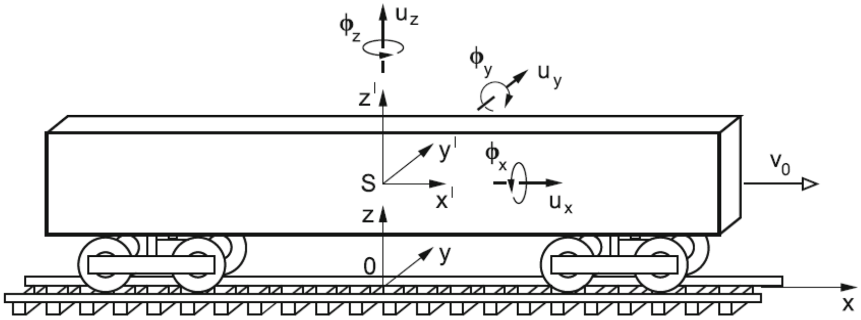


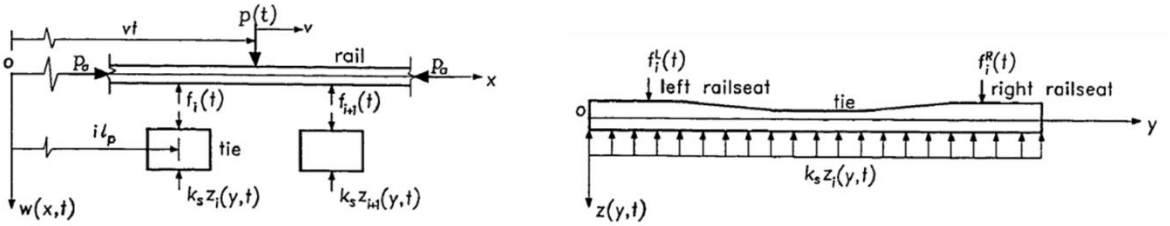
Figure 1: Vehicle-track modelling.

Figure 2: Multiple short-pitch rail surface defects.

2. Train-track modelling

A railway track is commonly idealised as beams on Winkler foundation in which the cross-section and dynamic responses of track can be considered symmetrical. Both rails and sleepers can be represented by elastic Timoshenko beams, taking into account both bending and shear rigidity. The sleepers support the rails as discrete cross-beam elements. A free-body diagram of the track model is shown in

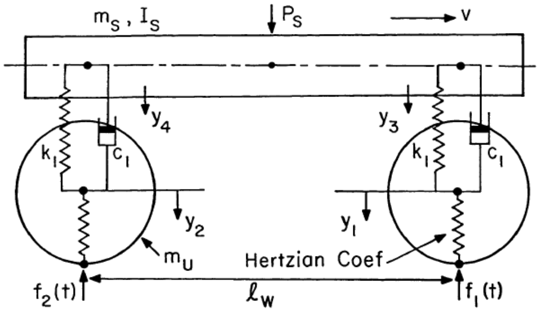
Fig. 3(a) where *P(t)* is a moving wheel force at a constant speed (v). Fig. 3 (b) represents the force (*f*) from rail to sleeper through the rail seat (i^{th}) and the support reaction force $k_s z_i(y,t)$ per unit length.



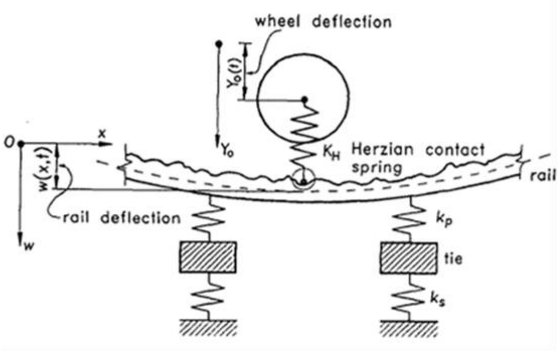
a) forces on the rail

b) force on the sleeper

Figure 3: Track model.



a) wheelset model



b) Herzian wheel-rail contact

Figure 4: Vehicle model.

The wheelset in this modelling consists of a four-degree of freedom system which includes one bogie with two axles over a rail track. The wheelset model uses the unsprung masses (m_u) and the sideframe mass (m_s, I_s) to calculate forces acting on a rail through the primary suspension (k_1, c_1) as shown in Fig. 4(a). The vehicle components are idealised by using Hertzian contact spring model. In addition, the equations of motion in this model adopt the principles of Newton's law and beam vibration. Integration between wheelset and track equations can be formulated by the nonlinear Hertzian wheel-rail interaction model as illustrated in Fig. 4 (b). The train-track model, called 'D-Track' is adopted for this study. D-Track has been benchmarked by [28] in order to assess the accuracy and precision of numerical results. The track structure used for analyses is based on UIC 60kg/m rail, HDPE rail pads (stiff), prestressed concrete sleepers with 600mm spacing, ballast with 300mm depth, and medium stiffness soil (compacted soil) [38]. The profile irregularity of each rail squat can be esimated as inverse half-sinusoidal curve. The dimension of moderate rail squats is around 50mm in length and 0.1mm indentation [5, 39-41]. This rail squat dimension will be used for the track loading simulations.

3. Results and discussion

The numerical simulations have been carried out using 14.5t axle-load Manchester passenger train with wheel radius of 0.46m and Hertzian spring constant of 0.734 x 10^{11} N/$m^{3/2}$. The dynamic wheel/rail contact forces can be seen in Fig. 5. It can be seen that long-wavelength track settlement can cause dynamic factor from 1.8 to 2.2 (static wheel load is 70 kN), while the multiple rail squats (wavelength of 100 mm and amplitude of 5mm) can induce dynamic impact loading up from 6 to 8 times of the static wheel load. This implies that more dynamic load will be transferred to fastening systems, sleepers, and ballast support, especially when the multiple impacts are generated by multiple short-pitch surface defects.

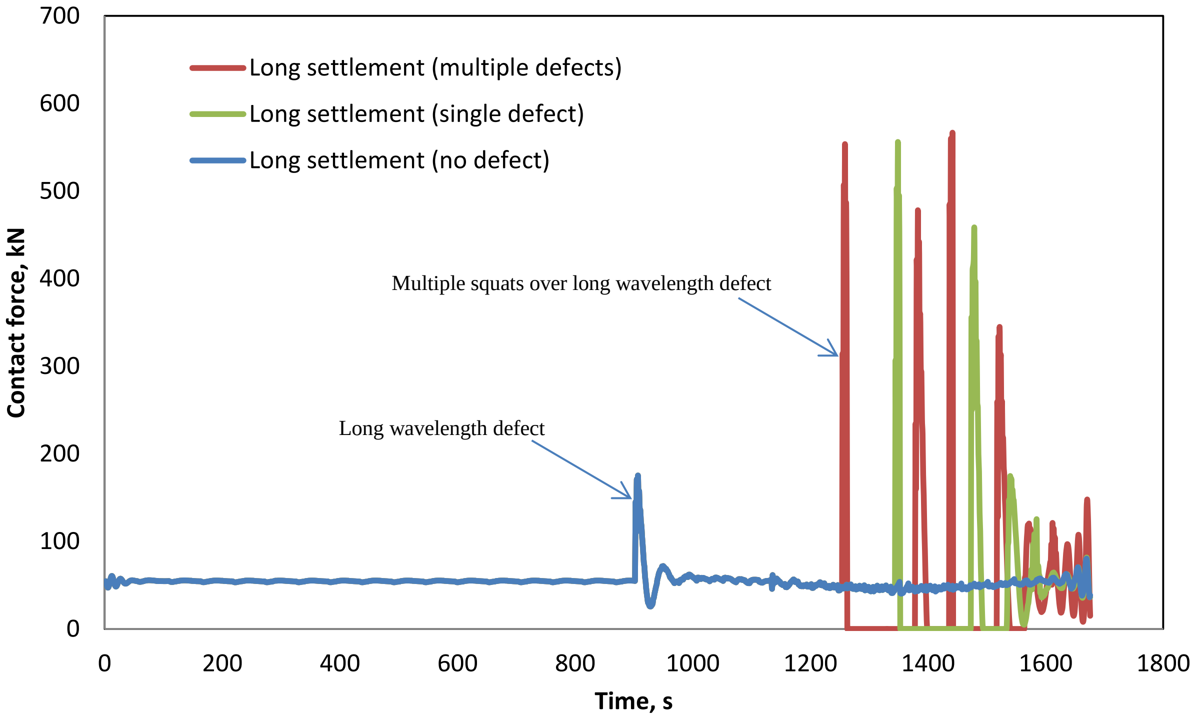


Figure 5: Wheel/rail contact forces (time staging to pronounce the force level differences).

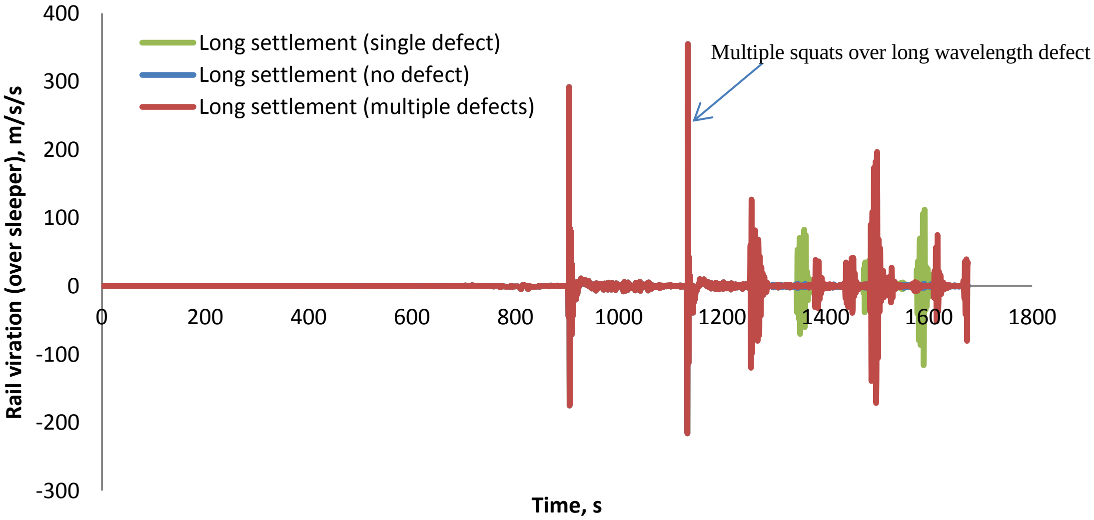


Figure 6: Rail vibrations (the multiple defect data overlays on top of the data of settlement without defect).

The vibrations of rail and sleeper can be observed in Figs. 6 and 7. It is clear that multiple short defects tend to play a more influential role on vibrations of both sleepers and rail. The multiplication of short-pitch defects tends to amplify the vibration levels of both rail and sleeper, causing higher dynamic amplitude and longer duration of the vibrations. Noticeably, the sleepers will vibrate over a longer duration due to the short-pitch defects. These vibrations could cause densification and dilation of ballast, which are the root cause of differential track settlements. This also implies that sleepers no longer behave in a static or fatigue loading condition (based merely on axle counting) as initially designed for.

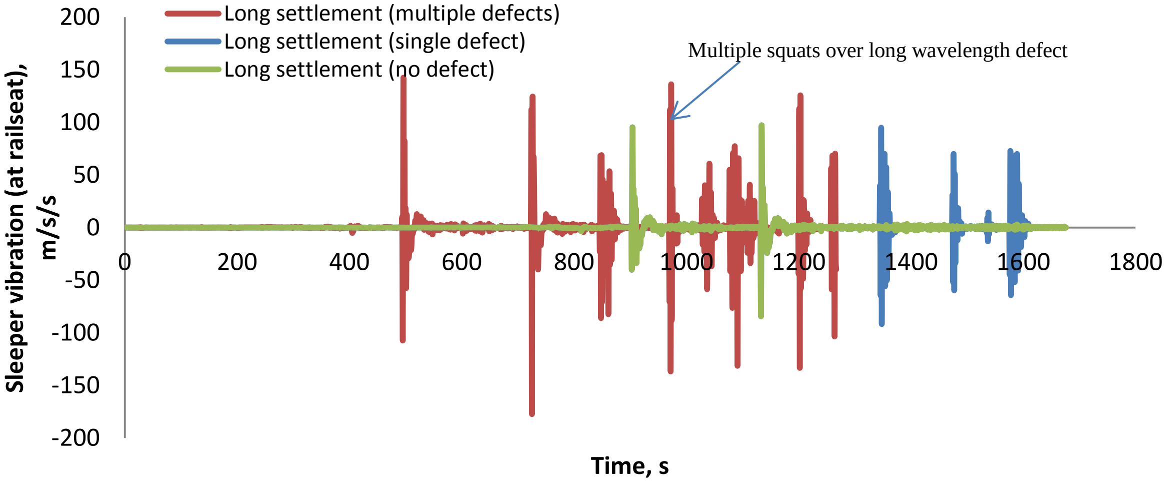


Figure 7: Sleeper vibrations (short-pitch defects generate longer duration and larger amplitude vibrations).

4. Conclusion

This paper highlights the dynamic effects of short-pitch rail surface defects coupled with track settlement on the contact forces between train and track, which can cause large-amplitude vibrations and acoustic radiations to railway neighbourhood. The effects of multiple short-pitch rail defects on track loading conditions and load distribution have been clearly demonstrated. It is the first to evaluate the coupling dynamic vehicle-track interactions over multiple rail defects coupled with long-wavelength track settlement. The results show that short-pitch rail defects are more dominant than track settlement; and the multiplication of short-pitch rail defects can magnify the rail/sleeper contact forces (railseat loads) up to 8 times as well as can amplify the vibrations of both rail and sleeper. The insight implies that sleepers will experience excessive dynamic behaviours in real life, which can deteriorate and weaken ballast-sleeper friction and lateral track stiffness. It is thus important to consider dynamic resistance and properties of track components in order to mitigate vibro-acoustic problems in railway industry. The insight is imperative to improve long term track maintenance strategy by appropriate design of rail infrastructure and its components.

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