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Modelling and mitigation of wheel squeal noise amplitude

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ABSTRACT

The prediction of vibration amplitude and sound pressure level of wheel squeal noise is investigated using a concise mathematical model that is verified with measurements from both a rolling contact two disk test rig and a field case study. The model is used to perform an energy-based analysis to determine a closed form solution to the steady state limit cycle amplitude of creep and vibration oscillations during squealing. The analytical solution compares well with a numerical solution using an experimentally tuned creep curve with full nonlinear shape. The predicted squeal sound level trend also compares well with that recorded at various crabbing velocities (proportional to angle of attack) for the test rig at different rolling speeds. In addition, further verification is performed against many field recordings of wheel squeal on a sharp curve of 300 m. A comparison with a simplified modified result from Rudd [1] is also provided and highlights the accuracy and advantages of the present efficient model. The analytical solution provides insight into why the sound pressure level of squeal noise increases with crabbing velocity (or angle of attack) as well as how the amplitude is affected by the critical squeal parameters including a detailed investigation of modal damping. Finally, the efficient model is used to perform a parametric investigation into means of achieving a 6 dB decrease in squeal noise. The results highlight the primary importance of crabbing velocity (and angle of attack) as well as the creep curve parameters that may be controlled using third body control (ie friction modifiers). The results concur with experimental and field observations and provide important theoretical insight into the useful mechanisms of mitigating wheel squeal and quantifying their relative merits.

1. Introduction

Wheel squeal is a high-pitched tonal noise that can occur as a train negotiates a curve (corner) of a railway line. It often occurs in the frequency range where our ears are the most sensitive, and is therefore very annoying for receivers near the track. This phenomenon has plagued the railway industry for many years and continues to rise in importance as railway usage increases and subjective human noise tolerance decreases. For instance, wheel squeal is a major impact from freight rail operations on tight curves in Australia, particularly in the metropolitan areas. Although much research insight has been obtained into the mechanisms of squeal over the past decade the occurrences and amplitude of wheel squeal still appear unpredictable in the field as it appears to be dependent on a wide range of vehicle and track parameters. Also the squeal

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amplitude is determined by nonlinear limit cycle oscillations that have remained difficult to model except via complex simulation. Much modelling of wheel squeal has been performed particularly following the renowned works of Rudd [1] and review by Remington [2] and Thompson et al. [3] in which the fundamental mechanism due to lateral creepage was consolidated. Curve squeal is believed to originate from the unstable vibratory response of a railway wheel when subject to large creep forces whilst negotiating corners. The conventional mechanism from the literature is that the unstable excitation of the squealing wheel originates from a lateral 'stick-slip' mechanism in the contact region analogous to the bowing of a violin string. In particular, when a bogie negotiates a curve of a track, there is a misalignment between the rolling velocity and the wheel velocity, namely angle of attack, leading to a crabbing velocity, i.e., lateral sliding velocity, of the wheel across the top of rail as shown in Fig. 1.

Referring to Fig. 1, the squeal mechanism is analogous to playing a violin and depends on the behaviour of lateral creep force/traction and lateral creepage ($\approx$angle of attack) conditions during the excitation of a railway wheel [4,5]. The friction coefficient and shape and slope of the traction/creepage curve is affected by the so-called third body of the contact; an interfacial layer consisting of any lubricants, contaminants and material generated as a result of the contact interaction [6]. If the crabbing velocity (or angle of attack) is large enough its oscillations will occur in the full sliding region c). The negative slope in this region can be shown to be associated with negative damping of creep oscillations and hence squeal instability. This leads to self-excited "stick-slip" oscillations, which in turn excite wheel (or violin string) vibrations and radiated sound. It is noted that, conversely, some recent research contends that a modal coupling phenomena between the normal and tangential dynamics may cause the instability eg. Ref. [7]. Pure tone components of squeal, are generally related to wheel natural frequencies that correspond to the out-of-plane wheel bending (or axial) modes.

Much research on the modelling of squeal has been performed in the past with differences in modelling details of wheel/rail mechanical impedances (analytical [8–12], FEM [4,13,14]), vertical dynamics [4,14], contact forces and wheel sound radiation [4,13,14]. Some have also included wheel/rail roughness or wheel rotation effects [11,12]. Recently, a transient analysis of the lateral creepage of the wheel was performed to account for nonlinearities of friction forces and resultant excited wheel modes appeared to match field observations better [15]. Notably, a time domain model was presented by Heckl and Abrahams [11], which focused on the squeal noise generated by a flat round disc excited at one point along the edge by a dry-friction force dependent on the disc velocity. This paper concluded that curve squeal is an unstable wheel oscillation that grows to a limit cycle oscillation, whose velocity amplitude is equal or very close to the crabbing velocity. Furthermore, the simulation results of Chiello et al. [16] also showed that the vibration velocity stabilises below the lateral sliding velocity. Rudd [1] developed an approximation for squeal noise amplitude assuming particular simplified (exponential) creep and cornering mechanics that was limited to lower lateral sliding velocities (or angles of attack). For higher angles of attack, Rudd also stated the vibration velocity approaches the lateral sliding velocity (ie. crabbing velocity). The present authors investigated this further in Refs. [17,23] using a numerical power balance analysis, however, an analytical prediction and explanation was not achieved.

Much recent research has also been focused upon experimental verification of model predicted conditions under which squeal occurs and the effect of friction modifiers [18] on the phenomena. Recent predictive modelling includes that of [4,19] which include detailed representation of the dynamic behaviour of the wheel and rail and creepage in the saturated region. Twin disk and bogie testrigs have been utilised for verification under controlled environments [20]. Experimental results reported on the rolling contact force conditions during squeal include those by de Beer et al. [4], Monk-Steel et al. [19] and Koch et al. [21]. In Monk-Steel et al. [19] the inclusion of longitudinal creep was shown to reduce the lateral creep force and thereby change the slope of the friction curve. This leads to a lower incidence of squeal in the presence of longitudinal creep, and an increase in the threshold of lateral creepage necessary for squeal. In Koch et al. [21], measurements were carried out on a 1/4 scale test rig including a mono-block wheelset, and tests of anti-squealing solutions. A relation between noise level, rolling speed and angle of attack was confirmed experimentally and the average friction coefficient as a function of lateral creep was measured/inferred in dry conditions and with water. In Ref. [20] novel instrumentation directly on twin disc wheels close to the contact patch was used to obtain more direct measurements of lateral force to provide some verification of

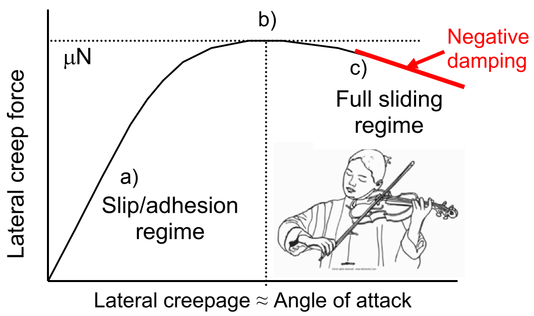

Fig. 1. Lateral creepage characteristic of railway wheel-rail contact. a) region of slip/adhesion, b) critical point at which full sliding first occurs and c) negative slope region of increased sliding causing negative damping of creep oscillations.