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Wheel-rail creep force model for predicting water induced low adhesion phenomena

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ABSTRACT

A computationally efficient engineering model to predict adhesion in rolling contact in the presence of water is presented which may be implemented in multibody dynamics software or in braking models to study train performance and braking strategies. This model has been developed in a project funded by the Rail Safety and Standards Board (RSSB) and Network Rail. It is referred to as the water-induced low adhesion creep force (WILAC) model. The model covers a wide range of conditions from dry over damp to wet. Special emphasis is put on little amounts of water which can cause low adhesion without any oil or grease. Such conditions may be encountered in humid weather or at the onset of rain. The model is parameterised based on experimental results from a tram wheel test rig. Adhesion values as low as 0.06 are observed at high creep with only wear debris and little water present in the contact. The model results also agree with experimental data from locomotive tests in dry and wet conditions.

1. Introduction

For braking of railway vehicles a minimum adhesion of approximately 0.15 is usually required between wheels and rails for safe operation [1]. Adhesion values $T/Q < 0.15$ may be referred to as "low adhesion" [2].

In Great Britain during the autumn period (from October to November) numerous incidents, such as "station overruns" and signals passed at danger (SPADs) occur every year which are related to low adhesion conditions [3]. For about half of the incidents an autumn leaf contamination has been reported [3] which is known to cause low adhesion [4–8]. A proportion of the other half were related to small amounts of water on the rail head caused by prevailing environmental conditions. Detailed analysis shows a peak in incidents, for example, around dew point conditions in the morning and evening [9]. There is also experimental evidence that low amounts of water in combination with iron oxides on the surface reduce adhesion in rolling contacts without the presence of other contaminants [10].

The objective of this work was to develop a computationally efficient creep force model which is able to predict adhesion depending on the "wetness" of the surface. The focus is on low amounts of water causing low adhesion conditions in the absence of oil or grease. Model development is accompanied by experiments on a tram wheel test rig which provided data for the model parameterisation. The model may be used in multibody dynamics (MBD) simulations to study the effect of low adhesion on train performance, or it may be implemented in braking models to study possible braking strategies.

2. Influence of water on adhesion

Two mechanisms govern the adhesion in rolling contact in the presence of interfacial fluids: Boundary lubrication and hydrodynamic lubrication. The transition region where both mechanisms govern adhesion is referred to as mixed lubrication. Which mechanism dominates depends on the relative velocity between the surfaces, the fluid viscosity and the normal force [11]. In addition the size and the shape of the contact patch and the surface roughness play a role [12].

Creep curves (adhesion as a function of creep) in dry conditions differ from creep curves in wet conditions with respect to the adhesion level, the shape of the curve and the initial slope [13]. Wetting the surface with water reduces the adhesion level, shifts the adhesion maximum to higher creep values and reduces the decrease of adhesion with increasing creep [13].

Measurements with various locomotives show that the maximum adhesion value is around 0.35 in dry conditions at low speeds [13]. In test rig experiments maximum adhesion values between 0.5 and 0.6

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Nomenclature

A	Ratio of friction coefficient at infinite slip velocity to μ_O in the Polach model
a	Semi-major axis length of Hertzian contact ellipse
B	Decay constant in the friction law of the Polach model
b	Semi-minor axis length of Hertzian contact ellipse
c_x	Longitudinal creep
c_y	Lateral creep
c_z	Spin creep
e	Transition functions in the WILAC model
f	Weights for blending of conditions in the WILAC model
k_A	Stiffness reduction factor in the area of adhesion in the Polach model
k_S	Stiffness reduction factor in the area of slip in the Polach model
m	Reference water flow rate of transition between conditions in the WILAC model
μ_O	Maximum friction coefficient in the Polach model
Q	Normal force
s	Width of transition between conditions in the WILAC model
T	Creep force
T_x	Longitudinal creep force
T_y	Lateral creep force
T/Q	Adhesion value
v	Rolling speed
w	Water flow rate

have been observed for axle loads of 44 kN and 67 kN [14]. Locomotive tests with an axle load of 220 kN showed maximum adhesion values between 0.3 and 0.4 for rolling speeds from 5 m/s to 20 m/s [15].

In the presence of water maximum adhesion values drop with respect to dry conditions. A typical value of 0.25 has been found in locomotive tests in wet conditions at low speeds [13]. Test rig results showed maximum adhesion values ranging from 0.10 to 0.16 at a speed of 100 km/h for axle loads of 44 kN and 67 kN [14]. In locomotive tests maximum adhesion values of 0.25 have been observed at axle loads of 220 kN at a speed of 10 m/s with artificially watered rails [15]. Small-scale laboratory experiments on a ball-on-disc machine showed a typical maximum adhesion value of 0.15–0.20 for a roughness of R =0.15 µm at rolling speeds of 1.5 m/s when submerged in water [16].

Chen et al. investigated the influence of rolling speed, surface roughness, maximum contact pressure, and water temperature on the maximum adhesion in Twin Disc experiments in wet conditions. The results show that high rolling speeds, smooth surfaces and low water temperatures can lower the adhesion to values of 0.02 [17].

Beagley and Pritchard [10] investigated the change of adhesion over time in an Amsler experiment, where two steel discs roll on each other with a fixed (longitudinal) creep of 0.033 at a circumferential velocity of about 0.3 m/s (see Fig. 1). When water is applied to the contact the adhesion drops from around 0.6 to around 0.3. When the wet surfaces are allowed to dry a viscous paste of wear debris and water forms on the surface which reduces the adhesion to a minimum value of 0.2 before the dry adhesion value is observed again. If the generated wear debris in the rolling contact is continuously removed from the surface by a wire brush, no adhesion minimum is observed [10].

These experiments demonstrate that wear debris in combination with little amounts of water reduce adhesion to values well below the adhesion value when large amounts of water are present on the surface [10]. However, the observed minimum adhesion values cannot be considered “low adhesion”.

3. Existing creep force models taking the effect of water into account

Several creep force models already exist which take the influence of water on adhesion into account in various ways.

Kalker's half-space model CONTACT [18] considers boundary lubrication only. The influence of water on adhesion is usually included by adjusting the constant values of the static and dynamic coefficient of friction. Recent extensions of CONTACT [19] include the implementation of a falling friction law and the implementation of an elastic interfacial layer.

Likewise, in the simplified theory of rolling contact, which is implemented in the algorithm FASTSIM [20], the influence of water can be considered by adjusting the constant coefficient of friction in terms of boundary lubrication. Spiryagin [21] extended the FASTSIM algorithm by a variable contact flexibility and a slip dependent friction law (variable friction coefficient) to allow a better reproduction of measured creep curves.

The Polach model [13,22] is a computationally fast alternative to the FASTSIM algorithm, built on the theory of boundary lubrication as well. The model can be tuned to experimental results under wet conditions by adjusting the initial slope of the adhesion curve and the decrease of adhesion with increasing slip velocity (variable friction coefficient). The amount of water is not explicitly taken into account.

Beagley [23] estimated adhesion in the wheel/rail contact based on hydrodynamic lubrication theory assuming full sliding. Key input parameters are the viscosity of the iron oxide/water mixture and the film thickness on the rail. This model is not a full creep force model, so that adhesion at low creep cannot be calculated.

The Chen model [24,25] uses both boundary lubrication theory and hydrodynamic lubrication theory. Adhesion under wet conditions for rough surfaces is predicted by distributing the load between contact asperities experiencing boundary lubrication (with constant friction coefficient) and the hydrodynamic water film based on statistical methods. Key input parameters are the surface roughness and the fluid viscosity.

The Popovici model [26] uses boundary lubrication theory (with a constant friction coefficient) for the contact between surface asperities and hydrodynamic lubrication theory to describe the behaviour of the fluid layer. The model takes rough surfaces, frictional heating in the elastohydrodynamic component and starved contact conditions (limited supply of liquid to the contact) into account.

The Tomberger model [12] combines the FASTSIM algorithm with an interfacial fluid model, a temperature model and a micro-contact model. Fluid related input parameters are the viscosity and the amount of liquid on the rail surface. The (variable) friction coefficient in the

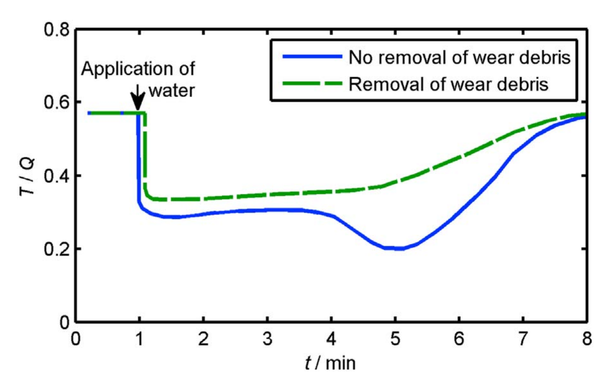

Fig. 1. Schematic change of adhesion T/Q in an Amsler experiment when the surface dries up after an initial application of water; Solid line: Adhesion minimum without continuous removal of wear debris; Dashed line: Continuous removal of wear debris by wire-brushing the surface; data reproduced from [10].