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A nonlinear state-dependent model for vibrations excited by roughness in rolling contacts

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ABSTRACT

A state-dependent method to model contact nonlinearities in rolling contacts is proposed. By pre-calculation of contact stiffness and contact filters as functions of vertical relative displacement, a computationally efficient modelling approach based on a moving point force description is developed. Simulations using the state-dependent model have been analysed by comparison with measurements. Results from the investigated case – consisting of a steel ball rolling over a steel beam having two different degrees of roughness – show good agreement between nonlinear simulations and measured beam vibrations. The promising results obtained with the proposed method are potentially applicable to wheel–rail interaction and rolling element bearings.

1. Introduction

The roughness-induced forces in rolling contacts found in for instance bearings, tyres and railway wheels lead to excitation of vibrations, which in turn lead to noise, wear and rolling resistance. Accurate prediction of these effects thus relies on detailed modelling of the surface roughness in simulations. However, even for a simplified normal contact model considering only linear elastic forces, computational effort grows critically due to the resolution of the small-scale roughness and – for many cases – becomes forbiddingly large. As a consequence, rolling contact predictions are often based on a reduction of the full contact geometry to a point interaction model with a nonlinear spring, which models the local flexibility between contacting bodies associated with small scale deformations. As an example of this, an early work by Nayak presents a time-domain dynamic model for vertical vibrations, in which the interacting bodies are related through a moving point contact force [1]. The force has a Hertzian pressure-representation as in [2, p. 93], thus including the influence of relative displacement due to the shape of the contacting bodies. In Nayak's model, surface roughness has no effect on the nonlinear stiffness but it may be included as a possible excitation mechanism.

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For roughness-induced high frequency rolling excitation as in the wheel–rail contact and the rolling contacts in ball bearings, a dynamic contact filter effect is present owing to the contact force resultant *not seeing* the wavelengths which are shorter than the contact dimensions. In rolling, this spatial filtering reduces the excitation from short wavelengths and forms a low-pass filter, where low frequencies correspond to wavelengths which are long compared to contact dimensions. For the contact filtering effect to be implicitly included in rolling contact predictions, full three-dimensional geometry is required as input. The filtering effect is not included in a point contact model unless the input line texture is low-pass filtered, which in that case requires a determination of filter characteristics on beforehand. Since the filtering effect depends on the contact dimensions – which in turn depend on the vertical relative displacement – it is also a nonlinear effect, as will be further discussed in the present work.

In a seminal work by Remington and Webb, an elastic foundation model as well as a Boussinesq contact model is used to calculate blocked force time-series for wheel–rail rolling contact [3]. The calculated force-series are transformed into frequency-domain and included in linear frequency-domain rolling noise simulations. Later, Nordborg presents both a time-domain model and a frequency-domain model for prediction of wheel–rail rolling excitation [4]. Results from performed numerical simulations show that high corrugation on rail leads to loss of contact between wheel and rail even for relatively high train weights. More recently, Wu and Thompson also perform both frequency-domain and time-domain simulations of the wheel–rail interaction followed by an analysis of the influence of varying relative displacement between wheel and rail [5]. It is concluded that higher roughness amplitudes and lower static preloads lead to increased dependence on the wheel–rail relative displacement. In recent works, advanced contact modelling using two- and three-dimensional surface data are integrated in time-domain modelling of the wheel–rail interaction, such as Pieringer's et al. [6], where an extensive study of the contact filtering effect is presented.

In contrast to the rather well investigated influence from roughness on the wheel–rail interaction, a limited amount of research is dedicated to this aspect in case of rolling machine elements like rolling element bearings and gears. A natural explanation for this could be the lower importance of roughness-induced excitation compared to the more distinguishable harmonic excitation from roller/ball passing frequency in rolling element bearings, and the tooth meshing frequency in spur gears. For rolling machine elements, contact nonlinearities are most often twofold: the force dependence on vertical relative displacement caused by surface roughness and shape of bodies is accompanied by that due to elastohydrodynamic conditions in lubrication [7]. For spur gears, an investigation of the influence of surface roughness on the friction coefficient is found in [8] in which the load sharing concept introduced by Johnson et al. is used [9]. The concept is applicable to partly lubricated contacts with rough surfaces, where the total load is shared between elastohydrodynamic pressures and roughness asperities. In [10], roller bearing vibrations are investigated considering both Hertzian and elastohydrodynamic contributions to the total load. In [11], and more recently, in [12–14], dry contact is assumed and the influence of surface waviness on the resulting vibrations of bearings is studied using a Hertzian pressure-representation. Contact nonlinearities due to short wavelength roughness are to the knowledge of the authors not yet included in dynamic modelling of rolling element bearings.

As the above literature review indicates, a great variety in methodology and complexity is used to include surface roughness in rolling contact simulations. The most advanced models combine a full geometrical description of the contact with detailed material modelling, thus aiming at increasing simulation accuracy and consequently narrowing the gap between prediction models and the real physics of contact. Two drawbacks, however, come with the inclusion of detailed contact models in time-domain: first, computational cost increases and second, surface roughness data with very high spatial resolution is needed for the complete surface, but such data is not easy to gather.

This paper proposes an intermediate approach between time-domain models with full geometrical description and time-domain models using a Hertzian point force representation. Instead of performing the computationally costly contact computations in each time step, nonlinear parameters are pre-calculated by a three-dimensional static contact model (see e.g. [15,16]) and included in the time-domain model as state-dependent functions of the vertical relative displacement. The requirement of a complete set of roughness data is omitted by using samples of surface roughness. Contact stiffness and – for the first time – contact filtering are implemented as state-dependent functions in a rolling contact model with point force interaction. To illustrate the proposed methodology and investigate its accuracy, simulations are performed and compared to measurements for a well-defined steel–steel rolling contact experiment.

Section 2 is dedicated to the methodology of the proposed state-dependent nonlinear approach. Then, the presented method is brought into practice for a rolling contact application in Section 3. Therein, the dynamics of a ball rolling over a beam is studied. The nonlinear simulations are analysed by comparison with measurements presented in [17]. Finally, conclusions and recommendations for future work are presented in Section 4.

2. State-dependent nonlinear contact model

In the proposed model, which is schematically represented by Fig. 1, state-dependent means that the contact conditions depend on the vertical relative displacement. State-dependent contact stiffness and dynamic contact filter – in the form of filtered surface textures – are pre-calculated and subsequently included in the nonlinear point force expression, which in turn forms part of the rolling contact time-domain model. Therein, the dynamic interaction is governed by the linear dynamic models of the contacting bodies coupled by the nonlinear point force expression.