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Predicting railway wheel wear under uncertainty of wear coefficient, using universal kriging

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ABSTRACT

Railway wheel wear prediction is essential for reliability and optimal maintenance strategies of railway systems. Indeed, an accurate wear prediction can have both economic and safety implications. In this paper we propose a novel methodology, based on Archard's equation and a local contact model, to forecast the volume of material worn and the corresponding wheel remaining useful life (RUL). A universal kriging estimate of the wear coefficient is embedded in our method. Exploiting the dependence of wear coefficient measurements with similar contact pressure and sliding speed, we construct a continuous wear coefficient map that proves to be more informative than the ones currently available in the literature. Moreover, this approach leads to an uncertainty analysis on the wear coefficient. As a consequence, we are able to construct wear prediction intervals that provide reasonable guidelines in practice.

1. Introduction

In the maintenance of railway wheel suspending operations, reductions in transportation and safety accidents caused by unforeseen failures are very costly, both in terms of repairs and unrealized profits. These huge losses arouse great interest in the development of efficient methods and procedures that could reduce unforeseen failures and improve equipments safety and availability [1]. Prognostics enables safer and more reliable operations, allowing the equipment to run as long as it is healthy. Moreover, it is useful for optimally scheduling the maintenance interventions. In other words, prognostics substantially helps in achieving the goals of maximum safety and availability, minimum unscheduled shutdowns of transportation and economic maintenance [2], which are issues of utmost relevance for railway systems. In this paper, we propose a novel methodology to predict the future degradation of railway wheel, by means of wear, and to calculate the remaining useful life (RUL), namely the residual distance that the wheel can run according to its design specifications.

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According to [3], the wheel wear of rail vehicles is typically predicted evaluating either the sliding contact by using Archard's equation, or rolling/sliding contact by using the energy dissipation effect (developed for the first time in [4]). Archard's equation is more commonly used in railway industry for wear prediction [3,5–7]; indeed, it has been successfully applied in [8] to predict wear of roller bearings, which is quite similar to wheel-rail rolling contact wear. For this reason, we choose to employ Archard's equation in our methodology. Briefly, Archard's equation states that the volume of material worn V_w is proportional to the sliding distance s and the normal load N, and inversely proportional to the hardness of material H, namely

$$V_w = K\frac{sN}{H}, \tag{1}$$

where the wear coefficient K is a dimensionless constant that indicates the severity of wear.

Wear is a complicated process that involves a large variety of contributions from different phenomena, combining the short-term dynamics that produces the wear debris and the long-term dynamics of the material transportation that goes on. For these reasons, exact wear prediction is usually unattainable. As for engineering applications, the sliding contact model seems sufficiently accurate and adequate to approximate the wheel failure due to wear.

The wear coefficient K plays an important role in wheel wear

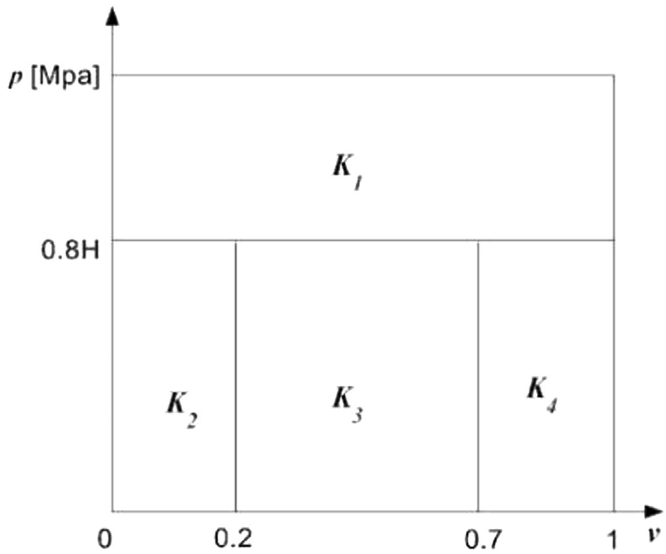

Fig. 1. Wear coefficient K chart, with data from [5].

prediction through Eq. (1). Currently, it can be derived from laboratory tests or, alternatively, from extensive calibrations based on geometrical comparisons between simulated and measured wheel profiles. Nowadays there exist in literature a few wear charts and maps for the wear coefficient K as a function of contact pressure p and sliding speed v, concerning different rail–wheel materials and environments (see for example Fig. 1, with data from [5], or the charts presented in [9]). Conversely, there are really limited data on cases where third body materials (grease, water, friction modifiers, etc.) are present [10]. The available wear maps are mostly for dry conditions. Furthermore, they are not very accurate due to the limited number of experiments available in each condition. Hence such charts are of restricted usefulness and it would be desirable to have more accurate maps.

Given this background, it is advisable to provide a measure of the uncertainty concerning wear prediction. Actually, no uncertainty analysis is usually supplied by available wear prediction tools. In sensitivity analysis, metamodels are built to approximate the behavior of large computational models and study how the inputs can influence the predicted output values. Several global sensitivity analysis techniques have been investigated in literature (see e.g. [11]). Regression-based methods employ linear regression models to measure the effect of the inputs on the model response. For example, polynomial chaos expansion [12,13] and sparse polynomial chaos expansion [14] of the response have been shown to provide an efficient and accurate computation of global sensitive indices. Another class of techniques is based on an ANOVA decomposition (variance-based methods) of the output variance as a sum of contribution of the different inputs. In this framework, a complex model can be approximated via smoothing spline ANOVA [15] or using state dependent parameter modeling [16–18]. Gaussian process models [19] and kriging [20] have also been successfully applied to build metamodels. All these different approaches are very useful when there is uncertainty about the input values in a particular setting and evaluating the actual model response on all possible input configurations requires too much time. An underlying hypothesis is the smoothness of the function of response given inputs. Here we want to employ a methodology similar to these global sensitivity analysis techniques, to compute the wear coefficient K given the contact pressure p and sliding speed v as inputs. In this setting we do not have any uncertainty about the values of pressure and speed (since they are derived by the local contact model as explained in Section 2). However, an approximate model of the wear coefficient K is needed because, as noted above, only a limited number of experiments, for particular choices of p and v, are available.

In this paper we propose a novel wear prediction methodology that provides an assessment for the wear of a rail vehicle wheel with uncertainty. The wear coefficient is estimated in a continuous way by using spatial statistic techniques (in particular, universal kriging). In this way, we are able to take advantage of the spatial dependence of measures (in the v and p plane) to overcome the issue of having few available data. In addition, these techniques provide a measure of the uncertainty concerning the value of the coefficient K. Hence, we can compute a prediction interval for K associated to each choice of v and p instead of a single point prediction. As a consequence, our model predicts a range for the amount of wheel material removal and a prediction interval for the RUL.

In the following, Section 2 contains the wheel wear model proposed; Section 3 shows the mathematical model used to estimate K with uncertainty, and Section 4 describes the prediction of RUL. Finally, applications of the proposed methodology are presented in Section 5.

2. Wheel wear model

The degradation model for wheel wear prediction adopted in this paper is shown in Fig. 2. We consider the wear coefficient K involved in Archard's equation as a function of contact pressure p and sliding speed v, both varying over the specific contact patch of interest. A local contact model is implemented by employing the non-Hertzian contact method developed in [21]. Using this method, we estimate the shape of the contact patch and the pressure distribution given the normal force, the local geometry and the material properties. Here the contact stress distribution is assumed to be ellipsoidal and it is discretized in the direction of rolling. The density of discretization can be tuned to ensure that the size of each cell is small enough to consider the pressure p as a constant on the cell. Next, the corresponding sliding speed for each cell in the slip area of the contact patch is obtained using the method suggested in [5], as depicted in Fig. 3. In detail, the sliding velocity is given by

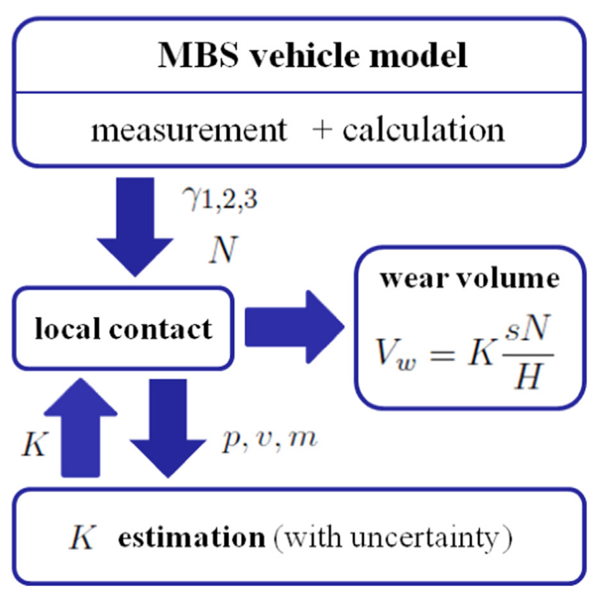

Fig. 2. The proposed methodology for wheel wear prediction.