Mechanical Systems and Signal Processing 96 (2017) 226–238

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Particle filter-based prognostic approach for railway track geometry

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ARTICLE INFO

Article history:
Received 6 March 2017
Received in revised form 7 April 2017
Accepted 9 April 2017

Keywords:
Prognostics
Railway track geometry
RUL
Particle filter

ABSTRACT

Track degradation of ballasted railway track systems has to be measured on a regular basis, and these tracks must be maintained by tamping. Tamping aims to restore the geometry to its original shape to ensure an efficient, comfortable and safe transportation system. To minimize the disturbance introduced by tamping, this action has to be planned in advance. Track degradation forecasts derived from regression methods are used to predict when the standard deviation of a specific track section will exceed a predefined maintenance or safety limit. This paper proposes a particle filter-based prognostic approach for railway track degradation; this approach is demonstrated by examining different railway switches. The standard deviation of the longitudinal track degradation is studied, and forecasts of the maintenance limit intersection are derived. The particle filter-based prognostic results are compared with the standard regression method results for four railway switches, and the particle filter method shows similar or better result for the four cases. For longer prediction times, the error of the proposed method is equal to or smaller than that of the regression method. The main advantage of the particle filter-based prognostic approach is its ability to generate a probabilistic result based on input parameters with uncertainties. The distributions of the input parameters propagate through the filter, and the remaining useful life is presented using a particle distribution.

1. Introduction

Tracks are an essential part of railway infrastructure, and track degradation due to varying loads, different environments and different actions on the track plays a critical role in track performance. A track is designed using tangent track sections, curved track sections and railway switches and crossings, which are all normally mounted on concrete slabs or ballast [1]. Other assets such as bridges and level crossings are normally not mounted on ballast. Ballasted tracks are less expensive but can experience greater dynamic changes compared to the more stable and expensive slab tracks.

A well-known challenge for railway infrastructure managers (IMs) is ensuring the required railway service capacity and quality by maintaining and restoring the track functions. This service is performed by planning and executing a variety of maintenance actions. For ballasted tracks, which currently represent the majority of railway networks, tamping is an important action that aims to restore the design geometrical shape of the track. Tamping has to be conducted along the network on

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http://dx.doi.org/10.1016/j.ymssp.2017.04.010
0888-3270/

a regular basis to counteract the track degradation induced by failing ballast and substructure support. Tamping moves ballast material under the sleepers to elevate degraded sections; this action aims to keep the track geometry within specified limits. Failing to ensure this geometry could result in safety and comfort issues and thus speed restrictions or closed line sections. The degradation of the track geometry is quantified by five factors: longitudinal level, alignment, cant (cross-level), twist and gauge [2].

Measurement trains are normally used to monitor track geometry over large distances. Most measurement trains measure the acceleration of the wheels and transform this value into displacement along the track and perpendicular to the track. The displacements are measured for both rails and can be presented for different wavelength intervals. Then, the averages of the track geometry parameters are calculated using standard deviation. In Sweden, this calculation is performed over a sliding track segment window of 200 m, and this procedure is regulated by the IM. The indicator of track degradation used for tamping is the standard deviation of the longitudinal level, filtered in the wavelength range of 3–25 m. Tamping is usually performed using train-based tamping machines, which normally travel at a speed of approximately 2 km/h. The tamping intervention thus occupies the track and reduces the effective network capacity. To limit this effect, tamping campaigns are typically planned up to 18 months in advance; therefore, effective maintenance planning requires a prognostic capability. Another important aspect of railway track tamping is the tamping of railway switches and crossings (S&Cs). Due to their more complicated mechanical structure compared to tangent and curved tracks, railway switches have to be tamped in a special way. Typically, the S&Cs are not tamped when the adjacent line sections are tamped because two different tamping machines are used, which makes them particularly interesting in terms of monitoring and prediction.

Many general methods exist for predicting the remaining useful life (RUL) of systems and components. The most common prognosis methods are physics-based approaches, which use mathematical formulations based on physical phenomena or principals, and data-driven approaches.

Many physics-based degradation models have been developed for railway track settlement that can also be used for prognostics, e.g., the British model [3], German model [4], Japanese model [5], South African model [6], and US model [7]. As a result of a European project, a track degradation model has also been suggested by ORE (Office de Recherches et d'Essais de l'Union Internationale des Chemins de Fèr, 1988) [8]. Other studies have further described how settlement is affected by different vehicles [9] and high speed trains [10,11]. An overall model for both track deterioration and track settlement that includes component fatigue, wear and rolling contact fatigue was presented by [12]. The stochastic approach defines the track degradation model based on the uncertainties of the track behaviour, whereas mechanistic models are based on the mechanical properties of the track structure [13,14]. Some of the statistical models and mechanistic models are presented in the literature [1,8,15].

Data-driven approaches rely on monitored data that are used to learn a system's behaviour. These approaches can be further categorized into statistical models (e.g., regression and autoregressive models), stochastic models (e.g., reliability and covariate-based hazard models and Markov models), and machine learning (e.g. neural network and support vector machine). Although stochastic approaches and machine learning have shown advances in prognostics in various areas [16], the statistical methods are commonly used for predicting railway track irregularities and planning track maintenance, such as tamping [17,18]. The statistical methods include linear [19], polynomial [20], and exponential regression models [21] as well as grey box models [22]. Stochastic models for track geometry degradation are based on the Markov chain model [23] and Gamma process [24]. The regression-based prognostic techniques are simple and fast and work well when the covariance function is well defined, such as for low noise in the data and simple behaviour of the degradation model. If there is significant noise in the data, this method makes it more difficult to determine relationships, especially when one-to-many relationships exist between the inputs and the output [25]. A disadvantage of the data-driven approaches is the limited ability to run scenarios for future increases in traffic and axle load, especially where the increase contains uncertainty.

Today, the Swedish IM uses a linear regression model to predict when the track geometry will reach a maintenance or a safety limit. For general risk-based maintenance planning, the output of a prognostic model should include a distribution related to the estimated RUL [16]. Preferably, the distribution should describe the inherent uncertainty of the degradation process and future operation as well as the errors associated with the prediction techniques used. Then the prognostics decisions can be based on a probabilistic forecast rather than on a specific deterministic value without any associated probability. Today, many railway IMs are aiming for risk-based maintenance planning, which is the main motivation for this study. This study aims to accommodate this need by proposing an alternative method for track geometry prognostics that offers a probabilistic prediction.

Particle filter-based prognostics allow the use of a Bayesian problem formulation. Both physical models and data can be incorporated into the method, and the state vector formulation links the state of the system to numerous inputs. Among these techniques, particle filters were recently developed for prognostics in Prognostic and Health Management (PHM). The particle filter methods can be used to model multivariate deterioration processes and are not limited to standard state distributions. Therefore, these methods are suitable for conducting risk-based maintenance planning. Particle filter-based prognostics has grown in popularity and has been implemented for many applications; numerous publications address this topic in applications for crack growth [26–31], Li-ion batteries [27,32–44], pneumatic valves [45], wind turbines [46], and Aircraft actuator systems [47].

This paper proposes a particle filter-based prognostic approach for railway track degradation. The approach is demonstrated by examining four different railway S&Cs. The standard deviation of the longitudinal track degradation is studied,