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Prognostics of slurry pumps based on a moving-average wear degradation index and a general sequential Monte Carlo method

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ABSTRACT

Slurry pumps are commonly used in oil-sand mining for pumping mixtures of abrasive liquids and solids. These operations cause constant wear of slurry pump impellers, which results in the breakdown of the slurry pumps. This paper develops a prognostic method for estimating remaining useful life of slurry pump impellers. First, a moving-average wear degradation index is proposed to assess the performance degradation of the slurry pump impeller. Secondly, the state space model of the proposed health index is constructed. A general sequential Monte Carlo method is employed to derive the parameters of the state space model. The remaining useful life of the slurry pump impeller is estimated by extrapolating the established state space model to a specified alert threshold. Data collected from an industrial oil sand pump were used to validate the developed method. The results show that the accuracy of the developed method improves as more data become available.

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1. Introduction

Slurry pumps play a vital role in pumping mixtures of abrasive and erosive liquids and solids in oil sand mining operations. Such activity causes constant wear of slurry pump impellers. The failure of the slurry pump impellers is the main reason for the breakdown of slurry pumps, which results in significant economic losses. The current and future health conditions of the slurry pump impellers must be assessed immediately to prevent unexpected downtime.

Walker and Bodkin [1] investigated the empirical wear relationship of a slurry pump impeller and revealed that solid particle sizes, slurry concentration and pump speeds greatly influence wear rate. Li et al. [2] conducted a failure analysis of a slurry pump impeller and demonstrated that duplex stainless steel with an equal austenite/ferrite ratio can resist corrosive wear. Bross and Addiei [3] proposed a model to predict the influence of different impeller design parameters on wear behavior. Xing et al. [4] used a finite element analysis tool, namely, ANSYS, to simulate the wear process of flow components and found that pits on the surface of flow components are caused by particle impact. A systematic study on the failure

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analysis of slurry pump impellers revealed that weight loss of corrosive wear is influenced by impact velocity, and that impeller failure is mainly caused by wear [5]. These results aid in improving the design of slurry pumps and in predicting wear degrees under steady working conditions. However, the wear relationships established by using the aforementioned methods may not be useful in evaluating the current and future health conditions of slurry pump impellers in practice because of uncontrollable working conditions. Therefore, developing online methods for evaluating impeller health condition is necessary.

The University of Alberta recently collaborated with Canadian oil sand mining industry on a series of research that assesses impeller health condition. An experimental system designed by Wang et al. [6] was used at the early stage to provide controllable working variables in studying the wear process of slurry pump impellers. Different damage modes with different wear degrees were produced artificially on the slurry pump impellers. Intelligent impeller fault diagnosis and prognosis methods were developed by using data collected from the experimental system. A support vector machine, a novel data cleaning algorithm and a classical sequential backward feature selection were combined to classify four different impeller damages: hole-through damage, vane trailing edge damage, vane leading edge damage, and expeller vane damage [7]. Their results illustrated that the data cleaning algorithm is effective in improving identification accuracy. Qu and Zuo [8] then developed a least squares support vector regression-based fault diagnosis method to evaluate impeller wear degrees and to provide a quantitative description for wear degrees. Zhao et al. [9] developed a modified neighborhood rough set model to select useful features for impeller fault identification. The results found that the selected features can be used to achieve a higher classification rate than the features generated by the original neighborhood rough set model. The combination of half and full spectra, fuzzy preference-based rough sets and principle component analysis was then developed to generate a monotonic health indicator to describe impeller health condition. However, these developed online impeller health condition evaluation methods were validated by data collected from the experimental system with some artificial damages. The data do not fully reflect the natural wear propagation of slurry pump impellers. Our literature review reveals that a health evaluation of slurry pump impellers that uses natural wear data remains lacking [10]. In this paper, we developed a prognostic method to analyze industrial slurry pump data, which facilitates an assessment of the natural wear of the slurry pump impellers.

The developed method consists of two steps. The first step aims to assess the performance degradation of a slurry pump impeller. Such an assessment monitors the current condition of a component or system. This step aims to assess the deviation of the current condition of the component or system from its normal condition. Our literature review shows that numerous methods were recently developed to evaluate the health condition of bearings and gears. Qiu et al. [11] used an optimal wavelet filter to enhance weak bearing fault signatures and employed a self-organizing map to track bearing defect development. Wang et al. [12] developed a rapid performance degradation assessment method based on discrete wavelet transform to evaluate gears. Wang et al. [13] employed a complex Morlet wavelet transform to analyze gear motion residual signal to assess gear health condition under various load conditions. Lin et al. [14] developed a weighted fault growth parameter based on gear residual error signal to track gear condition. Ocak et al. [15] used wavelet packet node energies to train a normal hidden Markov model. The probabilities of the trained hidden Markov model were used to track bearing health condition. A similar idea was used by Miao et al. [16] to describe gear health evolution, but, with the application of an adaptive signal processing method, namely, empirical mode decomposition [17], to extract gear fault features. Liao and Lee [18] proposed a novel degradation assessment method based on data collected from transient periods of different working loads. Pan et al. [19] combined wavelet packet transform and a fuzzy c-means to assess bearing health condition and then developed a hybrid method [20], that consists of a support vector data description and a fuzzy c-means, to evaluate bearing health condition. Wang et al. [21] used a series of wavelet filters to extract gear fault features and employed a support vector data description to track the current health condition of a gear. In the work, two health indicators were developed to identify an early gear fault and to assess gear degradation. The use of these two health indicators is reasonable because gear performance degradation assessment is insignificant until an early gear fault is detected. Zhu et al. [22] developed an incremental rough support vector data description method for assessing the performance degradation of a bearing. Yu [23] developed locality preserving projections-based Gaussian mixture models to track bearing health condition. Miao et al. [24] constructed a wavelet filter bank to extract bearing fault features in describing fault propagation in fan bearings. To explore the performance degradation assessment of the slurry pump impeller, a health indicator called moving-average wear degradation index (MAWDI) is proposed in this paper to describe the current health condition of the slurry pump impeller.

Based on the proposed MAWDI, the second step aims to estimate the remaining useful life (RUL) of the slurry pump impeller. RUL estimation is the prediction of the period from the current time until the component or system no longer satisfies its functionality [25–27]. RUL estimation aids in conducting maintenance activities, providing spare parts on time, and preventing accidents. A general sequential Monte Carlo method, particularly a general particle filter, has recently been applied to derive the posterior probability functions of state parameters of a state space model given known measurements. The established state space model is then used for component or system prognosis [28]. For example, Sun et al. [29] employed a particle filter to estimate the RUL of a gas turbine. He et al. [30] used the Dempster–Shafer theory to initialize the sum of two exponential functions and employed a particle filter to estimate the RUL of lithium-ion batteries. Following the work of He et al., Miao et al. [31] used an unscented particle filter for RUL estimation of lithium-ion batteries. Xing et al. [32] developed an ensemble lithium-ion battery state space model and used a particle filter to estimate the parameters of the state space model and the RUL of the lithium-ion batteries. Zio et al. [33,34] applied a

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