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Reliability-based residual life prediction of large-size low-speed slewing bearings

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ABSTRACT

Critical failure of a slewing bearing used in large machines would bring disastrous loss to an enterprise. Accurate residual life prediction of a slewing bearing can reduce unexpected accidents and unnecessary maintenances. In this paper, a residual life reliability prediction approach for slewing bearings was firstly presented based on the Weibull distribution. Afterwards, a novel approach for parameter estimation was proposed based on a small-sample test, which built the relationship between the characteristic life of a slewing bearing and the maximal load over the raceway. To verify the proposed approach, a full-load accelerated life test was implemented on a QNA-730-22 slewing bearing. It was observed that the damage of the outer (fixed) ring caused the failure of the slewing bearing, while the inner (rotatable) ring was still in good condition. After which, the residual life prediction model was then established by the proposed approach. Compared to ISO 281 and NREL design guide 03, the proposed approach is closer to engineering practice, and thus has the potential for slewing bearing prognostics.

1. Introduction

As a large-size rolling rotational connection used in cranes, wind turbines, construction machines and so forth, a slewing bearing is basically a bearing with a gear wheel integrated in the inner or outer ring, which is subjected to a complex set of heavy loads. Residual life prediction of slewing bearings can help operators to repair or replace the slewing bearings in time, which can not only avoid the occurrence of major accidents, but also reduce unnecessary regular maintenances. Therefore, many researchers have laid their emphasis on residual life prediction in recent years. There are generally two kinds of methods to conduct life prediction: one is the data-driven based method, which uses well processed vibration signal to generate a life prediction model; the other one is the reliability-based method, which uses history and event data to generate a life prediction model with a proper statistical method.

A data-driven based life prediction model firstly extracts features from vibration signals, and then establishes a degradation model of the equipment according to the trend of the extracted features. Eventually, the residual life of the equipment can be obtained by the degradation model and online vibration signals. Hack-Eun Kim et al. [1] used the Support Vector Machine (SVM) classifier to estimate health state probability of machine degradation process and provided long term prediction by the health state probability. Similarly, Benkedjouh et al. [2] proposed an isometric feature mapping (ISOMAP) reduction technique for feature extraction and a life prediction method based on support vector regression (SVR). Kamal et al. [3] utilized a mixture of Gaussian hidden Markov models (MoG-HMMs) to represent the evolution of the component's health condition. Xu Dong et al. [4] built a relationship between simulated vibration signals and crack sizes, and used two improved Paris laws to predict a bearing life. Tian et al. [5] developed an Artifical Neural

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Network (ANN) model to predict a bearing life, in which the age and the condition monitoring data were regarded as inputs while the life percentage was regarded as output.

However, given the working condition of a slewing bearing, the rotational speed is usually low to 0.1–10 r/min, commonly used feature extraction methods mentioned above can hardly obtain useful information from such low signal-to-noise ratio signals [6]. Therefore, Zvokelj et al. [7] proposed an EEMD-MSPCA-based method for feature extraction of vibration signals. However, considering its complexity, the application of the method is difficult in practical engineering. Widodo et al. [8] researched on fault diagnosis of low speed bearings using multi-class relevance vector machine (RVM) and support vector machine (SVM), but their work focused on small bearings and didn't involve life prediction. As a consequence, data-driven based methods may not be suitable for life prediction of large-size low-speed slewing bearings at present.

Hence, many researchers studied the life prediction of slewing bearings using other methods, which can be found in many researches. Potočnik et al. [9–11] calculated the maximal contact force by means of analytical expressions of the Hertzian contact theory, and then used a strain–life model to calculate the fatigue life on the basis of the subsurface stresses. After which, Srečko Glodez et al. [12] compared the three methods for calculating the fatigue life of a slewing bearing: ISO 281 [13], strain-life approach and stress-life approach. Results show that the stress-life approach is the most precise method for calculating bearing fatigue lifetime. What's more is that, Gao Xuehai et al. [14] developed a method for evaluating RCF reliability of slewing bearings, which replaced the reliability factor a_1 from ISO281 by the Lundberg–Palmgren theory. Literature [15] proposed a universal statistical model based on a bivariate Weibull distribution to forecast the reliability of bearing rolling contact fatigue (RCF) life under various applied load levels, and pointed out that the Weibull distribution parameters could be constantly modified despite more history data were required.

Nevertheless, the diameter of a slewing bearing varies between 800 and 5000 mm, and the load distribution over the raceway in a slewing bearing is non-linear, thus making the finite element method [9–11] time-consuming and not entirely reliable. Meanwhile, a physically based life prediction model [14] requires Weibull distribution parameters, which are difficult to be obtained in engineering. Besides, a large amount of history and event data is demanded in commonly used Weibull distribution modeling [14,15], which requires a batch of fatigue life tests for slewing bearings. However, taking the size and the working conditions of a slewing bearing into consideration, it is unacceptable both in terms of cost and time to implement a batch of fatigue life tests for slewing bearings.

From the above summary, it can be seen that a reliability-based life prediction model is suitable for slewing bearing life prediction, and that the Weibull distribution modeling process needs to be improved in that case. To address the above challenges, this paper presents a novel approach to predict the residual life of a slewing bearing under different load cases, which includes a residual life reliability prediction model and a novel method for estimating the parameters of the model. To begin with, a residual life reliability prediction model is established based on Weibull distribution, and then the load distribution over the raceways in a slewing bearing is calculated by Hertz's theory [16]. Afterwards, an accelerated life test based on small-sample is proposed according to the Archard theory [17] and the characteristics of the load distributions over the raceways. Then, the Weibull distribution parameters can be estimated by the test results. Finally, the proposed approach is verified by an experimental slewing bearing life test, and some interesting concluding remarks are drawn.

2. Residual life reliability prediction model

2.1. Weibull distribution model

Given the stochastic process of bearing fatigue failures, Waloddi Weibull proposed the Weibull distribution in 1951 while he was studying the fatigue lives of ball bearings. Over the past few decades, many researchers have studied and improved the Weibull distribution. It is widely accepted that the fatigue life of a ball bearing conforms to a two-parameter Weibull distribution [17]. Therefore, in this study, Weibull distribution is used to establish the residual life reliability prediction model. The failure function of Weibull distribution is presented as Eq. (1):

$$F(t) = 1 - \exp\left[-(t/\eta)^{\beta}\right] \tag{1}$$

where t is the turning lap of a slewing bearing, β is the Weibull slope ($\beta > 0$) and η is the characteristic life of a slewing bearing ($\eta > 0$). Then, the probability density function (PDF) can be calculated by Eq. (2):

$$f(t) = F'(t) = (\beta/\eta)(t/\eta)^{\beta-1}\exp\left[-(t/\eta)^{\beta}\right]. \tag{2}$$

So the reliability of a slewing bearing can be obtained by Eq. (3):

$$R(t) = \exp\left[-(t/\eta)^{\beta}\right]. \tag{3}$$

2.2. Weibull distribution adjustment for residual life reliability prediction

The fatigue cracks and spalls caused by alternating stress cycles occurred in the raceway are the main reasons of a slewing bearing failure, which increase proportionally with the turning laps of a slewing bearing. If a slewing bearing has been turned to t ($t \geq 0$) laps