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An integrated framework for health measures prediction and optimal maintenance policy for mechanical systems using a proportional hazards model

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ABSTRACT

This paper considers an integrated framework for health measures prediction and optimal maintenance policy for mechanical systems subject to condition monitoring (CM) and random failure. We propose the proportional hazards model (PHM) to consider CM information as well as the age of the mechanical systems. Although the form of health prediction for the mechanical systems under periodic monitoring in the PHM with Markov chain was developed previously, the case of the continuous-state degradation process allowing possible degradation between the inspections still has not appeared. To this aim, the paper allows the use of Gamma process with non-constant degradation, which broadens the application area of PHM. A matrix-based approximation method is employed to compute health measures of the machine, such as condition reliability, mean residual life, residual life distribution. Based on the health measures, the optimal maintenance policy, which considers both hazard rate control limit and age control limit, is proposed and the optimization problem is formulated and solved in a semi-Markov decision process (SMDP) framework. The objective is to minimize the long-run expected average cost. The method is illustrated using two real data sets obtained from feed subsystem of a boring machine and GaAs lasers collected at regular time epochs, respectively. A comparison with other methods is given, which illustrates the effectiveness of our approach.

1. Introduction

With the development of sensor technologies and CM techniques, advanced studies in reliability and maintenance framework have been proposed based on the actual information regarding the degradation process for efficient health monitoring of aging mechanical systems [1,2]. Comprehensive literature reviews on the reliability modeling and maintenance policy of mechanical systems have been provided in [3–6]. Among these approaches, degradation process can be modeled as discrete-state stochastic process, continuous-state stochastic process, or PHM. Discrete-state degradation process includes Markov and semi-Markov models. Kim et al. [7] provided an effective hidden Markov model in Bayesian control chart for the oil transmission unit fault detection. Peng and Dong [8] presented a four-state age dependent hidden semi-Markov model

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for prediction of remaining useful life of the hydraulic pumps. Subsequently, Liu et al. [9] proposed an adaptive four-state hidden semi-Markov model for the integrated diagnosis and prognosis of multi-sensor equipment. In contrast with discrete-state degradation process, continuous-state degradation process has also been widely used, such as regression-based method, Gamma process and Wiener process. Gebraeel et al. [10] developed a regression-based degradation model for computing residual life distributions of rotating machinery operating under time-varying environmental conditions. Nicolaia at al. [11] considered non-stationary Gamma process to measure the deterioration of organic coating layer of steel structures. Huang et al. [12] proposed an adaptive skew-Wiener process for assessment of residual life of ball bearings in rotating electrical machines. Other approaches about continuous-state degradation process modeling can be found in [13,6].

As the failure of a mechanical system is a developing process involving the load action and damage accumulation [14], a good health assessment method should take advantage of mutual information from multiple features for system degradation modeling [15]. PHM combines the system age and CM information as covariate, in which can be modeled by discrete-state or continuous-state process. [16–18]. Makis and Jardine [16] were the first to present PHM with continuous time Markov chain covariate for system degradation modeling, and provided an optimal replacement policy. Banjevic et al. [17] extended the Makis-Jardine model by relaxing the monotonicity assumption of the hazard function. Makis and Jiang [19], Ghasemi et al. [20] used PHM to model degrading systems under partial observations and derived an optimal replacement. These models assumed degradation process is constant between inspections and state transitions only can be observable at inspection epochs, which is not actual case for most real world systems. Even although PHM with discrete-state degradation process has been utilized in practice for many years, few papers have considered continuous-state degradation process covarate in PHM. Tang et al. [21] presented an autoregressive model as a covariate in PHM to model the GaAs laser degradation path. In their paper, the degradation process is assumed to be constant between inspections for convenient computation. Another continuous-state stochastic process covariate presented by Liu et al. [22] has considered system degradation level following a time-varying Gaussian distribution, which means the degradation level was determined before condition monitoring and new CM information was not taken into account for both health prediction and maintenance decision making. This also leads to limited applications.

So far, from most existing research works, to derive health measures based on PHM is still a great challenge. An exception to this is the papers by Wu and Ryan [23,24], who considered non-constant Markov model and semi-Markov model in PHM to model a deteriorating system under various monitoring schemes. Nevertheless, the proposed approach only works for the discrete-state degradation process with very limited states, i.e. Markov or semi-Markov, and cannot deal with continuous-state degradation process or large numbers of discrete degradation states due to the dramatically increasing of the computational complexity.

To overcome the challenge above, a continuous-state deterioration process with non-constant degradation mechanism is considered in this paper. Since the most mechanical systems present continuous and gradual degradation process where damages accumulate monotonically over time in a sequence of tiny increments, we consider Gamma process to model the accumulative damages and use PHM to describe the hazard rate. A matrix-based approach is employed to derive the health measures and a control policy is proposed to make maintenance decision for mechanical systems. It should be noted, to mutually and sufficiently exploit the CM information, our approach has combined the health prediction and maintenance policy to make a maintenance decision whenever monitoring information is collected. The predicted health measures serve as indicators for maintenance decision making, the maintenance policy can therefore prolong the lifetime of mechanical system dependent on the system health condition. Unlike previous approaches which prediction computation is usually time-consuming and maintenance optimization is unpractical or complicated, our approach uses matrix operations to obtain health measures and solves maintenance optimization problem in SMDP framework with matrix form. The closed form expressions of health measures and corresponding optimal maintenance action can be obtained through the simple multiplication of matrices, which is particularly attractive for practical applications.

Once the health measures are predicted, an optimal maintenance policy for monotonically degrading systems is presented. Similarly, Tang et al. [21], Jafari and Makis [25] proposed hazard rate-based maintenance policy using PHM for systems subject to condition monitoring. As we consider the system deterioration is influenced by age and degradation process simultaneously, it is natural to make an extension by considering both preventive age threshold and hazard rate threshold in our policy. The health condition of mechanical system is determined by the age and covariate values, and the hazard rate is calculated right after obtaining the new information through CM. Whenever the hazard rate of system exceeds certain level or the system reaches the preventive age level, the preventive maintenance will be set up. The control limits as hazard rate threshold and age threshold are decision variables in our maintenance policy, which will be determined by formulating and analyzing the decision problem in a SMDP framework.

To our knowledge, this is the first paper applying an integrated framework for matrix-based estimation and two-level maintenance control policy to degrading systems based on PHM with practical degradation mechanisms. The main contributions of this paper can be summarized as follows:

(I) Incorporation of the influence of both aging and degradation state in modeling the hazard rate. The continuous, non-constant degradation process is considered.
(II) Development of matrix-based approximation method which provides closed form expressions for health measures prediction.