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Reliability of complex systems under dynamic conditions: A Bayesian multivariate degradation perspective

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ABSTRACT

Degradation analysis is critical to reliability assessment and operational management of complex systems. Two types of assumptions are often adopted for degradation analysis: (1) single degradation indicator and (2) constant external factors. However, modern complex systems are generally characterized as multiple functional and suffered from multiple failure modes due to dynamic operating conditions. In this paper, Bayesian degradation analysis of complex systems with multiple degradation indicators under dynamic conditions is investigated. Three practical engineering-driven issues are addressed: (1) to model various combinations of degradation indicators, a generalized multivariate hybrid degradation process model is proposed, which subsumes both monotonic and non-monotonic degradation processes models as special cases, (2) to study effects of external factors, two types of dynamic covariates are incorporated jointly, which include both environmental conditions and operating profiles, and (3) to facilitate degradation based reliability analysis, a serial of Bayesian strategy is constructed, which covers parameter estimation, factor-related degradation prediction, and unit-specific remaining useful life assessment. Finally, degradation analysis of a type of heavy machine tools is presented to demonstrate the application and performance of the proposed method. A comparison of the proposed model with a traditional model is studied as well in the example.

1. Introduction

1.1. Motivation

Reliability prediction of complex systems has long been a critical issue within the field of reliability engineering [1,2]. Recently, reliability data of complex systems is evolving toward a big data situation [3]. By monitoring failure related performance indicators, reliability of complex systems can then be assessed and predicted through degradation analysis of these performance indicators [4]. Degradation based methods are increasingly introduced to lifetime analysis of complex system for facilitating reliability assessment [5–7], spare parts and preventive maintenance decision [8–10], and system health management [11,12]. Within these degradation-based methods, two general assumptions are adopted, which include the assumptions of (1) single degradation indicator and (2) constant external factors. However, modern complex systems are generally composed by multiple and mutually interactive subsystems and components [13,14], and are well characterized as multiple functional under dynamic environmental/operating conditions [15,16]. It is not uncommon for a modern complex system to possess multiple dependent performance indicators. In addition, these indicators can be significantly affected by external environmental conditions as well as operating profiles. A practical example that motivates this research on multivariate dependent degradation analysis of complex system under dynamic conditions is the reliability analysis of one type of CNC heavy machine tools.

The DL150 CNC heavy duty lathes (DL 150s) are serving as indispensable equipment in the industries of energy, transportation, aerospace, aviation and military. By summarizing operating and maintenance records, manufacturers of DL 150s have found that two types of gradually-evolving failures are critical to the reliability of these lathes: losing of machining accuracy, and accumulation of lubrication debris. Meanwhile, they also found that these types of failures vary from factories to factories due to differences of environmental conditions and loading profiles that the DL 150s endured. To achieve high availability and productivity, unit-specific condition monitoring and degradation analysis are carried out on the DL 150s by making machining accuracy and lubrication debris as performance indicators [17]. Methods for degradation analysis with multiple performance indicators under

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dynamic conditions are naturally become primary research initiatives. Moreover, degradation of machining accuracy and lubrication debris are founded to be correlated with each other. Their degradation processes are presented separately in a non-monotonic form and a monotonic form. To fully address these challenges, three engineering-driven problems are then tackled in this paper: (1) joint modeling of various types of dependent degradation indicators, (2) explicit study of environmental conditions' effects and operating profiles' influences, and (3) continual update of unit-specific reliability evaluation and factor-related degradation prediction.

1.2. Related works

Investigation on degradation-based reliability methods has received much attention. Both theoretical methods and practical approaches have been proposed. Up-to-date investigations on degradation models include the works by Guida et al. [18], Bae et al. [19], and Wang et al. [20] for stochastic process degradation models, the work by Bae et al. [21] for general path degradation models, and the researches by Kharoufeh and Cox [22] and Kharoufeh et al. [23] on Markov process degradation model and so on. Recently, Ye and Xie [24] present a review of degradation models, and they emphasize that more efforts should be focused on new types of degradation models such as inverse Gaussian process degradation models [25–27]. They also put forward that most published literatures on degradation modeling are one-dimensional, and the research on multivariate degradation modeling is far from adequate.

A few attempts have made to extend one-dimensional degradation models to the multi-dimensional domain. Wang and Coit [28] introduced the problem of degradation modeling for complex system with more than one degradation indicator and proposed a multivariate degradation model based on a multivariate normal distribution. Pan and Balakrishnan [29] introduced a bivariate degradation process model based on a bivariate Birnbaum–Saunders distribution and gamma processes. Motivated by reliability analysis of light-emitting diode, Sari et al. [30] introduced a bivariate degradation model by combining generalized linear degradation path models with copula function. Furthermore, by utilizing the flexibility of copula function to construct dependency among stochastic degradation models, Pan et al. [31] and Wang et al. [32] introduced bivariate degradation models based on Wiener process, gamma process and copula functions. Nevertheless, all these models are built on the assumption of "constant external factors", and the influences of environmental conditions and operating profiles are not considered in these models. These models can hardly be applied to fulfill the needs introduced by reliability analysis of complex systems under dynamic conditions, such as the challenges of DL 150s introduced above. Moreover, these degradation models are either based on Wiener process or gamma process, where degradation processes are characterized either in a monotonic or a non-monotonic way. In reality the degradation processes of complex systems may evolve in a hybrid way. Such as the DL 150s presented above, a combination of monotonic and non-monotonic degradation processes is desirable. Accordingly, an in-depth analysis on multivariate degradation is necessary to address the influences of dynamic environmental and operating conditions, and to characterize the time-varying nature of multiple hybrid degradations.

1.3. Overview

Based on the motivation and literature review presented above, we are motivated to explore the research topic by making three contributions as following.

1. A generalized multivariate hybrid degradation model is developed to address the modeling of complex systems exhibiting monotonic and non-monotonic degradation processes.
2. Both dynamic covariates and random effects are incorporated in the multivariate hybrid degradation model to characterize degradation processes under dynamic conditions.
3. A Bayesian inference framework is presented to perform parameter estimation, reliability assessment, and degradation prediction. Unit-specific reliability assessment and factor-related degradation prediction are investigated within the Bayesian framework.

An illustrative example is drawn from the engineering practice of DL 150s introduced in the motivation session. It is used to demonstrate Bayesian reliability analysis of complex system with the proposed multivariate hybrid degradation model. A comparison between the proposed model and existing models in literature is implemented as well. The proposed model is demonstrated a hybrid modeling technique, and being capable of incorporating different types of stochastic processes. In addition, the Bayesian framework presented in this paper can overcome the difficulty in parameter estimation, which is challenged by combing different types of marginal stochastic processes. It can also facilitate degradation inference of complex system, where unit-to-unit variability and effects of external factors are incorporated. The degradation inference is then carried out in a unit-specific and factor-related way. This is of critical importance to degradation-based optimal decision-making when systems possess multiple failure modes and their failure mechanisms are sensitive to environmental conditions and operating profiles.

The remainder of this paper is organized as follows. Section 2 introduces a generalized model for multivariate hybrid degradation processes with random effects and dynamic covariates. Section 3 presents methods for Bayesian estimation of model parameters and Bayesian inference of unit-specific remaining useful life and factor-related degradations. A numerical example is then presented in Section 4 to demonstrate the performance of the proposed method. Section 5 concludes this paper with brief discussion of future research.

2. Multivariate degradation models for complex systems

The model developed in this paper aims to characterize various combinations of dependent degradation indicators, and to study the influences of external factors on these degradation indicators for reliability analysis. This requires: (1) modeling degradation processes with different characteristics, (2) incorporating variables (covariates) of external factors into degradation models, and (3) characterizing dependence among degradation indicators for multivariate hybrid degradation model construction. In this section, these three aspects are handled progressively and ended up with a generalized multivariate hybrid degradation models.

2.1. Baseline degradation model with dynamic covariates and random effects

Suppose there is a complex system with n degradation processes, and let $\{Y_i(t), t \geq 0\}, i = 1, ..., n$ with $Y_i(0) = 0$ denote the ith degradation process of this complex system. We first introduce the baseline degradation model for each degradation process, and the modeling of dependence among these degradation processes is presented in the next section based on these baseline degradation model and copula function. To characterize different types of marginal degradation processes, we use a basic Wiener process