



Stochastic degradation process modeling and remaining useful life estimation with flexible random-effects[☆]

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Received 13 December 2015; received in revised form 18 April 2016; accepted 30 June 2016

Abstract

Models with random-effects are generally used in the field of degradation modeling and remaining useful life (RUL) estimation for describing unit-to-unit variability. The wide employment of parameters, which is assumed to be subjected to normal distribution to capture this variability, may disaccord with actual industrial conditions, and will introduce misspecifications. Such misspecification can affect the accuracy of RUL estimation and the subsequent inference results. In this paper, we propose a degradation model with flexible random-effects, which makes it flexible to choose distributions to portray the unit-to-unit variability according to the available information. To do so, the mixture of normal distributions, as a distribution describing random-effects, is incorporated into a class of diffusion process based degradation models whose drift coefficient is a linear combination of some time-dependent functions with known forms. The combination coefficients of each function are treated as random variables drawn from the mixture of normal distributions. An analytical approximated probability density function (PDF) of the RUL is derived under the concept of first passage time (FPT). To identify the model parameters, a framework for parameter estimation is presented based on stochastic expectation maximization (SEM) algorithm. Finally, simulation studies are provided to demonstrate the superiority of the normal mixture over the individual normal distribution for describing random effects in RUL estimation.

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[☆]This work is partially supported by National Nature Science Foundation under Grant 61174030, 61374126, 61374120, 61473094, 61104223, 61573365, 61573076, 61573366, and the NSF of Shaanxi Province of China under grant 2015JQ6235.

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1. Introduction

To guarantee a reliable, safe and economical operating of a system, condition monitoring (CM) [45–47], prognostics and health management (PHM) technique have been adopted more and more frequently by both industrial and military systems [24,44,28]. As the foundation of PHM, remaining useful life (RUL) estimation is the kernel evidence for decision-making on the sequential managerial activities including inspections, maintenance, spare parts ordering and replacement. Degradation modeling based method, making full use of the reliability information in the CM data, can be an effective way to estimate RULs for expensive field systems with long life, thus becomes a hot issue as well as the mainstream in the field of reliability [34,31]. Among the numerous existing degradation models, stochastic process based ones, with specific physical interpretation and the ability to handle various kinds of uncertainties caused by the interaction of a system's inner state and the external environment conditions, have drawn much more favor. Compared to the Gamma process based models [23,20] and the inverse Gaussian process based models [36,42,27,25] which only suit for monotonous degradation process modeling, diffusion process based models [26,30] exhibit much more application prospect. Therefore, the research work in the paper is based on diffusion process based degradation models.

A common phenomenon encountered when we consider the degradation of systems from the same kind is the unit-to-unit variability. Even units from one patch show much difference in their degradation paths. Such kind of unit-to-unit variability, which is generally captured through random effects [19], has to be thoroughly incorporated into degradation modeling and RUL estimation for specific systems. The kernel of modeling random effects is to set some important parameters of a model, such as drift and diffusion coefficients in the diffusion process, intercepts and slopes of the mixed linear model, as random variables subjected to a special probabilistic distribution. During the specification of the random effects, the incentive to select parameters and its corresponding distributions is much centered on the mathematical convenience. For instance, [35] pointed out that it is only for computing convenience rather than physical meanings when random effects were introduced into diffusion process. Specifically, it is assumed that the diffusion coefficient σ_B was Gamma distributed and the conditional distribution of drift coefficient ν given σ_B is normal, i.e. $\sigma_B^2 \sim \text{Gam}(r^{-1}, \kappa)$ and $\nu | \sigma_B^2 \sim N(1, \theta \sigma_B^2)$ consecutively. Another example is that normal distributions have been widely adopted to describe the unit-to-unit variability in degradation paths, primarily for computing convenience [43,33,14].

It has been analytically studied and practically applied to give priority to mathematics, from which parameter estimation and hypothesis test can benefit a lot. However, such a priority to mathematical computation is really not all having no problem. There will be large bias in the estimated results if the normal-distribution assumption is discrepant with the fact. Indeed, here have appeared some researches addressing on issues including misspecification analysis, diagnosis and estimation [16,9,4,2]. Nevertheless, most existing researches are carried out based on the mixed linear model and the generalized mixed linear model, which belong to stochastic coefficient regression based method that cannot model time-varying dynamics of the system. Many developments have been made to improve the normal distribution assumption in the random effects methods, involving multilevel prior model (MPM), nonparametric model (NPM) and mixtures of distributions model (MDM). Similar to the Bayesian framework, MPMs set parameters in the distribution describing the random effects as random variables subject to some specific distributions [15]. Nonparametric methods have been used in NPMs to depict distributions to which the random effects are subjected and thus enhance the practical usability of random effects [12,11]. Both MPMs and NPMs face difficulties in computation, inference, and

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