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Reliability for systems of degrading components with distinct component shock sets

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ABSTRACT

This paper studies reliability for multi-component systems subject to dependent competing risks of degradation wear and random shocks, with distinct shock sets. In practice, many systems are exposed to distinct and different types of shocks that can be categorized according to their sizes, function, affected components, etc. Previous research primarily focuses on simple systems with independent failure processes, systems with independent component time-to-failure, or components that share the same shock set or type of shocks. In our new model, we classify random shocks into different sets based on their sizes or function. Shocks with specific sizes or function can selectively affect one or more components in the system but not necessarily all components. Additionally the shocks from the different shock sets can arrive at different rates and have different relative magnitudes. Preventive maintenance (PM) optimization is conducted for the system with different component shock sets. Decision variables for two different maintenance scheduling problems, the PM replacement time interval, and the PM inspection time interval, are determined by minimizing a defined system cost rate. Sensitivity analysis is performed to provide insight into the behavior of the proposed maintenance policies. These models can be applied directly or customized for many complex systems that experience dependent competing failure processes with different component shock sets. A MEMS (Micro-electro mechanical systems) oscillator is a typical system subject to dependent and competing failure processes, and it is used as a numerical example to illustrate our new reliability and maintenance models.

1. Introduction

Many systems or components are subject to the competing risks of a degradation process and random shocks. When considering competing degradation processes and random shocks, some researchers assumed that the failure processes are independent of each other [1–7] and whenever a shock comes, it affects all components in the system. However, the dependent characteristic between two failure processes is of great importance, and should not be neglected [8]. Furthermore, shocks with specific sizes or function may selectively affect one or more components in the system, but not necessarily all components. Therefore, it is practical and realistic for some applications to classify random shocks into different sets based on their sizes and function, and the affected components.

Consider a battery used in a laptop computer that supplies electric power by a chemical reaction. It gradually weakens through usage, and becomes ineffective once the chemicals in the battery are exhausted, which can be considered as a soft failure process. When shocks arrive to the system, they also cause incremental damage to this degradation. In addition, environmental shocks, overheating or over-voltage can cause abrupt battery failure, which can be considered as hard failure process. These two failure processes are competing, i.e., no matter which failure process happens first, the battery fails. Alternatively, striking the keyboard is a different type of shock which probably has no effect on battery life, but may impact other components of the laptop. There is significant interest in categorizing each component's own shock set for the reliability modeling of a system subject to dependent and competing failure processes.

1.1. Background

Studies on reliability of systems subject to degradation wear or random shocks have been conducted by many researchers. Previous research on degradation focused on establishing degradation models and estimating time-to-failure distributions [9–13], and using experimental design to improve reliability [14–16]. Lu and Meeker et al. [17] developed general statistical models to estimate the time-to-failure distribution from degradation measures. Mi [18] studied the limiting availability, or steady state availability of a repairable system, in which the lifetimes of components are

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independent but not necessarily identically distributed, and the times for repairing the failed systems are also independent. Proschan and Hameed [19] indicated that life distribution properties of a device subject to shocks governed by a nonhomogeneous Poisson process were related to corresponding properties of the probability of failing after experiencing a given number of shocks. Kuniewski and Weide [20] proposed a sampling inspection strategy for the evaluation of time dependent reliability of deteriorating structures, where the deterioration is assumed to initiate at random times and at random locations.

This current model involving shock sets builds upon the foundations and fundamental results in [21–24]. Jiang et al. [25] presented reliability analyses for dependent failure processes and dependent failure threshold. Rafiee et al. [26] developed reliability model of dependent competing risks with mixed shock model. Reliability analysis for parallel systems with different component shock sets was also developed by Song et al. [21].

Jayabalan and Chaudhuri [27] developed the optimal maintenance and replacement policy for a deteriorating system with increased mean downtime. Usher et al. [28] presented a method for predicting a cost-optimal PM policy for a repairable system with an increasing rate of occurrence of failure. Zhou [29] proposed reliability-centered predictive maintenance scheduling for a continuously monitored system subject to degradation. The maintenance planning horizon is segmented into discrete and equally-sized periods. For each period, they predicted which of three possible actions (maintain the system, replace the system, or do nothing) should be taken, such that the total net present worth of all future costs is minimized. A maintenance cost model for determining optimal inspection schedule and replacement threshold for a single-unit degrading system has been developed by Grall et al. [30].

Chaudhuri and Sahu [31] calculated the optimum PM intervals for systems with imperfect PM, where the system may not be restored to its original state. Liao et al. [32] developed a condition-based maintenance model for a continuous degradation process by considering imperfect maintenance, and a short-run availability constraint to reduce uncertainty in cost estimates. Jiang and Jardine [33] showed the effectiveness of a jointly applied burn-in and preventive replacement policy for situations where the failure time follows a mixture distribution.

Zhu et al. [34] examined the maintenance model for a competing risk of degradation and sudden failure in which the unit is renewed when it reaches a predetermined degradation level, or comes to a sudden failure within the limit of a certain degradation threshold. Peng et al. [22] developed reliability and maintenance modeling for systems subject to multiple dependent competing failure processes. Song et al. [23] developed series system reliability models with age replacement for complex multi-component systems subject to multiple dependent competing failure processes (MDCFP). The model was extended to consider any system configuration with dependent competing failure processes and dependent failure times, in which shocks are assumed to affect all components in the system [24].

Little research has been done on system reliability with specific and distinct component shock sets. However, for some applications, it is necessary and practical that shocks are categorized according to their sizes, function, affected components, etc. The idea of component shock sets originates from many engineering applications. Considering a complex system of an automobile, shocks affecting a car can be categorized according to their attributes: mechanical shocks, thermal shocks, voltage shocks and other types of shocks. Within the category of mechanical shocks, different types of failures can be caused due to the sizes, function, affected components, e.g., fracture of steering and brake system, disconnection of fuel system, rupture of engine cooling fan blade, or tire puncture. A preliminary shock set model specific for parallel systems was presented in [21].

For deteriorating systems with components subject to categorized shock processes, this paper proposes a dependent competing risk model and a preventive maintenance model. We derive mathematical models for system reliability and the expected cost rate for the preventive maintenance model. A non-linear optimization model is formulated and solved based on an iterative numerical search, i.e., golden section search method. The assumptions for the reliability and maintenance modeling in this paper are listed as follows:

1. When the total degradation of component l is beyond its threshold value H_l, soft failure occurs. The overall degradation of each component is accumulated by both continuous degradation over time and abrupt damage shift due to random shocks.
2. When a shock load exceeds the hard failure threshold level D_l, that component fails.
3. The two failure processes are dependent due to the shared shocks, and also competing, i.e., component fails no matter which failure process occurs first.
4. Shocks with specific size or function affect one or more components, but not necessarily all components. Therefore, each component has a distinct shock set. There is no damage to component failure processes if shocks do not belong to the shock set of that component. If a shock type is not included in a component shock set, then the corresponding shock magnitude and damage size are not defined and do not exist.
5. Random shocks arrive according to its respective Poisson process for a specified type.
6. The maintenance model is for systems that are packaged and sealed together, making it impossible or impractical to repair or replace individual components within the system, e.g., MEMS oscillator.
7. Age replacement policy is considered as the first PM policy. The system is preventively replaced at a fixed age. However, if the system fails before the age, it is replaced immediately. Replacements are assumed to be instantaneous and perfect.
8. Scheduled inspection at periodic intervals is considered as the second PM policy. If the system fails before the inspection, it is not detected or replaced until the next inspection. A penalty cost is imposed due to the system downtime.

In this paper, we consider a realistic case that shocks can be classified according to their sizes, function and affected components. Each component has its distinct shock set, meaning a set of shocks that impact that particular component. If two or more components share a common shock type in their shock sets, the times-to-failure of these components are dependent. For example, consider two components within a system that are affected by the same type of shocks. If one component fails relatively frequently, it is more likely that the number of shocks from this shared shock type is relatively large, and they impact these two components at the same time. This potentially causes components sharing the same type of shocks to probabilistically fail more often as well.

This paper is organized as follows. Section 2 analyzes the reliability of the complex system with different component shock sets. Section 3 describes maintenance modeling and optimization based on the replacement time interval and inspection time interval. A MEMS oscillator example is given in Section 4 to illustrate the developed reliability and maintenance models.

1.2. Notation

The notation used in formulating the reliability and maintenance models in Sections 2 and 3 is listed as follows: