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A preventive maintenance policy based on dependent two-stage deterioration and external shocks

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ABSTRACT

This paper proposes a preventive maintenance policy for a single-unit system whose failure has two competing and dependent causes, i.e., internal deterioration and sudden shocks. The internal failure process is divided into two stages, i.e. normal and defective. Shocks arrive according to a non-homogeneous Poisson process (NHPP), leading to the failure of the system immediately. The occurrence rate of a shock is affected by the state of the system. Both an age-based replacement and finite number of periodic inspections are schemed simultaneously to deal with the competing failures. The objective of this study is to determine the optimal preventive replacement interval, inspection interval and number of inspections such that the expected cost per unit time is minimized. A case study on oil pipeline maintenance is presented to illustrate the maintenance policy.

1. Introduction

Many industrial systems (e.g., transportation devices, manufacturing systems, energy generation systems and oil pipeline networks) suffer from inevitable failures due to complex degradation processes and environmental conditions such as random shocks. These unexpected failures may result in severe consequences, including massive production losses, high corrective replacement (repair) costs and safety hazards to environment and personnel [1]. For this reason, preventive maintenance (PM) is extremely important as it could effectively avoid occurrence of unexpected failures, and thereby save servicing costs. An effective and efficient preventive maintenance plan should be formulated based on the failure characteristics of the system considered. In the current study, a new inspection and replacement policy is proposed to deal with both internal deterioration and external shock damages.

Most devices will deteriorate over time due to wear, fatigue, aging, corrosion and so on. In many realistic situations, several defects could be detected by maintainers during deterioration processes, which would ultimately lead to failures. The signals of such defects include cracks, dents, excessive vibrations, overheating, unusual noise etc. [2]. Such two-stage failure processes are commonly modeled adopting the delay time concept, which is proposed by Crister [3]. A variety of research efforts have contributed to delay time-based maintenance models within broad application areas, e.g., manufacturing industry, energy industry, transportation industry and electronics industry. For

instance, the delay time concept was adopted for crack initialization and propagation process within welded joints of steel structures, aircraft critical structure and railway tracks [4–6]. Cavalcante and Scarf [7] and Flage [8] investigated inspection strategies of defective valves installed in gas and oil supply network. Wang and Pecht [9] reported a study on electronic systems equipped with canaries to monitor pending failures.

In addition to internal deterioration, industrial systems/equipment may also fail due to external shocks, such as voltages, stress, temperature and various environmental phenomena. Poisson processes are most extensively utilized stochastic processes in describing shock occurrence laws [10–13]. Among various reliability and maintenance models incorporating internal deterioration and external shocks, Degradation-Threshold-Shock (DTS) model is addressed the most with abundant real-world applications. Shafiee et al. [14] proposed an opportunistic condition-based maintenance policy for offshore wind turbine blades subject to stress corrosion cracking and environmental shocks. Peng et al. [15], Song et al. [16] and Rafiee et al. [17] applied DTS models to micro-electro-mechanical systems (MEMS) whose failures are triggered by gradually wear and debris from shock loads. Ye et al. [18,19] established reliability models under extreme shocks and natural graduation for automobile tires, laser devices and hard disks. Zhou [20] proposed a periodic preventive maintenance method for leased equipment subject to competing failures.

It is noted that most DTS models assumed a stationary deteriora-

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Nomenclature

T	Preventive replacement interval
s	Periodic inspection interval
m	Number of inspections
X_1	Defect arrival time
X_2	Delay time
$\overline{F}_{X_1}(x_1)$	Survival function of X_1
$\overline{F}_{X_2}(x_2)$	Survival function of X_2
Y	Random time to a sudden (fatal) shock
$B(t)$	State set of the system at time t

$\{N(t), t \geq 0\}$	Counting process of random shocks
$v_1(t)$	Intensity function of $\{N(t), t \geq 0\}$ when the system is normal
$v_2(t)$	Intensity function of $\{N(t), t \geq 0\}$ when the system is defective
c_f	Average cost of an internal failure replacement
c_c	Average cost of a failure replacement due to sudden shocks
c_{ir}	Average cost of a replacement at the time of an inspection
c_{pr}	Average cost of a preventive replacement at T
c_{in}	Average cost of a periodic inspection

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tion process utilizing Gamma, Wiener and IG processes [21–23]. On the contrary, two-stage deterioration processes (which defined a higher system deterioration level when defects arise) received limited attention in DTS models. However, such failure forms are commonly observed in practice, such as the crack propagation process of metal components [24]. This motivates our study, where a single-component system subject to two-stage internal deterioration and external fatal shocks is considered. Furthermore, the impact of system state on shock occurrence is studied in this paper, which is also rarely addressed in literatures. This consideration mainly relies on the intuitive fact that a device would be more sensitive to shock damages when it becomes defective or wear-out [25,26,40]. For instance, when corrosion defects (e.g., cracks, dents) arise on oil pipelines, shock-based failures such as burst and fractures are more likely to occur.

To deal with the competing failures in a cost-effective way, we propose a new preventive maintenance policy by incorporating two broadly reviewed maintenance actions, i.e., age-based replacements [30,31] and periodic inspections [32–35]. A preventive replacement is conducted at a certain age to prevent shock-based failures, and regular inspections are performed to detect the defective state. In this policy, postponed replacement of a defective system is also provided, which is motivated by the fact that a delayed replacement ensures sufficient preparation of maintenance resources and reduction of operation downtime. Note that, our postponement setting is different from that in reference [36–39] in that the realization of postponement is through the manipulation of inspection number instead of providing an additional postponement period. This is more applicable to some situations where the execution of inspections incurs relative high costs and their number should be strictly controlled.

The rest of the paper is structured as follows. Section 2 introduces the necessary notations and problem descriptions of the system. Section 3 develops probabilistic models for competing failures. Section 4 formulates the cost model based on the probabilistic models. In Section 5, the proposed maintenance policy is applied to an oil pipeline for illustration. Section 6 makes some final remarks.

2. Problem statement

2.1. Failure behaviors

We consider a single-unit system. There are two competing causes of failures for the system, i.e., internal deterioration and fatal shocks. When a failure occurs due to either a cause, the system is stopped immediately.

(a)Two-stage deterioration

The system is subject to a two-stage deterioration process, i.e., from new to the initial point of a defect and from that point to failure, which is defined using the *delay time concept* (see, e.g., Crister [3]). In that way, three possible stages are involved for the system, namely, normal, defective and failed.

The durations of both the normal and defective stages are independent. This is a common assumption shared by most delay time

models [33–37], which could explicitly distinguish the different characteristics of the two stages and simplify the formulation of corresponding maintenance models. The dependence between the two stages could be an interesting topic in the future study, but is not the major concern of this paper. We also assume that the average defect initialization time is greater than the average defect growth time, which could also be validated by industrial practice [4–6]. The defective stage itself will not lead to the stoppage or production losses of the system, but could be revealed by maintenance personnel and remind them of carrying out necessary preventive repair or replacement actions.

(b)External shocks

The system also suffers from external shocks arriving at random times according to a non-homogeneous Poison process $\{N(t), t \geq 0\}$. These shocks are fatal, i.e., each shock will result in the breakdown of the system immediately.

It is assumed that state of the system will affect the occurrence of fatal shocks. This setting is motivated by the practical observation that a defective or wear-out system is more susceptible to external shocks compared with a normal working system (see, e.g., Zhang et al. [25] and Caballé et al. [26]). More precisely, the occurrence rate of a fatal shock depends on the current system state. Let $v_1(t)$ denote the occurrence rate of a shock when the system is normal, and $v_2(t)$ denote the occurrence rate of a shock when the system is defective, where $v_1(t) \leq v_2(t)$ for all $t \geq 0$. This type of shock process is called the doubly stochastic Poisson process or Cox process [46]. We also assume that both $v_1(t)$ and $v_2(t)$ are monotone increasing function of time t.

Three possible failure scenarios due to both internal deterioration and external shocks are depicted in Fig. 1 for illustration.

2.2. Maintenance policy

Both corrective and preventive maintenance actions are executed to deal with the above mentioned failures. Corrective replacement is immediate once a sudden shock or an internal failure occurs (Both failures are assumed to be self-announced). In order to avoid fatal shocks with increasing occurrence rates, a preventive replacement is also performed when the age of the system attains T. The system needs to be shut down during the execution of replacement. After a replacement, the system becomes new, i.e., the age of the system is reset to 0.

The system also undergoes periodic inspections to reveal the defective state. We assume that the inspection interval s is not larger than the preventive replacement interval T. In other words, $m_T = \lfloor T/s \rfloor \geq 1$, where m_T denotes the maximum number of inspections that could be performed before T. Inspections are assumed to be instantaneous and perfect, but lead to the stoppage of the system.

We assume that only m $(1 \leq m \leq m_T)$ periodic inspections are schemed. Under this setting, a defect arriving within (ms, T) is unable to be detected, and thus the system has to be replaced at T. On the other hand, when the system is defective at the i th inspection for $1 \leq i \leq m$, replacement is immediate. Two possible scenarios for replacement of a defective system are depicted in Fig. 2.