Computers & Industrial Engineering 105 (2017) 210–222

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

# A condition-based maintenance model for a three-state system subject to degradation and environmental shocks

Li Yang, Xiaobing Ma *, Yu Zhao

School of Reliability and Systems Engineering, Beihang University, Beijing 100191, China

ARTICLE INFO

Article history:
Received 20 July 2016
Received in revised form 17 November 2016
Accepted 9 January 2017
Available online 11 January 2017

Keywords:
Condition-based maintenance
Degradation
Shock
Competing failure
Expected cost per unit time

ABSTRACT

Condition-based maintenance (CBM) is a key measure in preventing unexpected failures caused by internal-based deterioration and external environmental shocks. This study proposes a condition-based maintenance policy for a single-unit system with two competing failure modes, i.e., degradation-based failure and shock-based failure. The failure process of the system is divided into three states, namely, normal, defective and failed, and a defective state incurs a greater degradation rate than a normal state. Random shocks arrive according to a non-homogenous Poisson process (NHPP), leading to the failure of the system immediately. The occurrence of external shocks will be affected to the degradation level of the system. Periodic inspections are performed to measure the state and the degradation level of the system, and two preventive degradation thresholds are scheduled depending on the system state. The expected cost per unit time is derived through the joint optimization of the two preventive thresholds as well as the periodic inspection interval. A numerical example is proposed to illustrate the maintenance model.



## 1. Introduction

In actual industrial practice, preventive maintenance (PM) is a critical measure to prevent unexpected failures triggered by complex internal-based deterioration and environmental conditions such as random shocks. An effective PM programme could reduce the probability of costly corrective replacement as well as avoid excessive-maintenance, and thus significantly cut down servicing costs. Preventive maintenance could be substantially divided into two categories, i.e., time-based maintenance (TBM) and condition-based maintenance (CBM). CBM is a maintenance program that recommends maintenance actions (decisions) based on the information collected through condition monitoring process (Ahmad & Kamaruddin, 2012). It has drawn extensive attentions in maintenance of degradation systems and muti-state systems.

For a majority of engineering systems, such as aircraft, medical equipment, oil (gas) pipeline networks, power generation systems, electronic devices, their quality characteristics usually undergo continuous internal-based degradation over time due to different factors, e.g., erosion, corrosion, wear and fatigue (Shafiee & Finkelstein, 2015). Failures of such devices are generated when the degradation levels reach or exceed a critical threshold, which is usually pre-determined by the industrial standard. Many studies have established stochastic models to describe the degradation behaviors of industrial systems. Among them, Gamma process (Caballé, Castro, Pérez, & Lanza-Gutiérrez, 2015; Castro, Caballé, & Pérez, 2015; Huynh, Barros, Bérenguer, & Castro, 2011), Wiener process (Ye, Chen, & Shen, 2015; Ye, Yan, & Xie, 2012; Zhai, Ye, Yang, Zhao, 2016) and Inverse Gaussian process (Chen, Ye, Xiang, & Zhang, 2014; Ye & Chen, 2014) are addressed the most. It is worth noting that the Wiener process has achieved satisfactory results in modeling the gradually evolving degradation with many actual applications. This is due to its nice mathematical property, especially when dealing with competing failures (Zhang et al., 2016).

In addition to internal-based degradation, many practical systems suffer from environmental shocks that may cause their failures (Nakagawa, 2007; Sheu, Chang, Zhang, & Chien, 2012; Sheu, Liu, Zhang, & Chien, 2015; Zhao, Qian, & Nakagawa, 2013). Models combing both competing causes of failures are generally called Degradation-Threshold-Shock (DTS) models. There are many research efforts concentrating on DTS models. For instance, Shafiee, Finkelstein, and Bérenguer (2015) investigated an opportunistic condition-based maintenance policy for offshore wind turbine blades subjected to degradation and external shocks. Rafiee et al. (2015) and Rafiee et al. (2014) presented condition-based maintenance models for dependent competing failure processes

* Corresponding author.
E-mail address: maxiaobing@buaa.edu.cn (X. Ma).

http://dx.doi.org/10.1016/j.cie.2017.01.012
0360-8352/

subject to generalized mixed shock. In recent years, the single internal-based degradation process in DTS models was extended to the multiple internal-based degradation processes by some authors (Li & Pham, 2005; Peng, Feng, & Coit, 2010; Wang & Pham, 2012). These degradation processes are initiated at different time according to Poisson processes, and internal failures could be trigged by any of them. A common assumption is that these processes are independent of each other and also with the external shock process. Caballé et al. (2015) addressed a representative example on components subject to multiple crack growth processes and environmental shocks. In this example, a component could have a random number of growing cracks at each instant of time, and a failure occurs when the size of at least one of the cracks reaches a critical level or a fatal shock occurs.

Most DTS models assumed a binary system state, i.e., normal or failed and a stationary degradation rate, whereas multi-state systems are rarely addressed. However, in numerous practical situations maintainers could defect one or more defective (potential failure) state of industrial systems before ultimate failures (Yang, Ma, Peng, Zhai, & Zhao, 2017). For such systems, their degradation rates are not stationary but related to the system states. A typical example is the crack propagation process of mental components, where the crack propagation rate increases sharply when the crack length reaches a certain level (and the component becomes defective) (Zhang et al., 2016). Recently, some researchers modeled such three-state degradation process adopting the delay time concept. The delay time concept was first proposed by Christer and Waller (1984), which defines three possible system states, i.e., normal, defective and failed. The random time from the initialization of a defect to a failure is called delay time. Wang and Wang (2015) and Wang, Zhao, and Peng (2014) proposed a condition-based maintenance policy based on the delay time concept, where two different Gamma and Wiener processes are utilized to describe system degradation laws. Additionally, Zhang et al. (2016) established an inspection-based maintenance model for a three-state mechanical system, where a wear-out state is involved with a higher degradation rate.

This paper focuses on a single-unit system subject to two competing causes of failures, i.e., degradation-based failures and shock-based failures. Three internal system states are involved, i.e., normal, defective and failed, and two different Wiener processes are utilized to model the degradation processes at both the normal and defective states. Moreover, the system suffers from fatal shocks arriving according to a non-homogenous Poisson process (NHPP). Note that, our internal failure is threshold-based, which is triggered when the degradation level reaches a pre-determined threshold. Such failures are broadly reviewed in literature and commonly observed in practice, since most degradations of quality characteristics could be measured through diagnostic techniques (e.g., crack length) (Ye et al., 2012). Our degradation process is also different from that in Zhang et al. (2016) in that a defective system could still perform its desired function and no production or economic loss is incurred. For instance, several types of defects (e.g., dents, holes and cracks) could occur at oil pipeline walls due to corrosion. However, the influence of these defects on oil transportation is negligible unless they grow continually and penetrate the pipe walls (resulting in leakage failures).

It is noted that most DTS models assumed the independence between shock-based failure (fatal shock) and degradation-based failure. The influence of degradation condition on the occurrence of fatal shocks has received limited attention. In the existing literatures, Huynh et al. (2011) formulated a DTS model, in which the intensity function of shock process increases when the degradation level exceeds a critical level. Castro et al. (2015) and Caballé et al. (2015) extended this idea by further providing a wear-out degradation level for multiple degradation processes. However, as far as we know, no study investigated how the occurrence of fatal shocks is influenced by the system state. In this paper, we present a novel assumption that the intensity function of shock process (following NHPP) increases when the system enters the defective state. This actually reflects the fact that a deviant or weak device is more susceptible to external shocks. For instance, leakages (caused by corrosion crack propagation processes) and burst (caused by environmental shocks, e.g., wind, icing, waves and thunder) are two main failure modes of oil pipelines (Guo, Song, & Garlambor. A., 2013). When crack defects arise due to corrosions, pipelines become much more fragile to shock damages and the occurrence possibility of burst is sharply increased (Parvizsedghy, Senouci, Zayed, Mirahadi, & El-Abbasy, 2015).

To effectively prevent failures caused by internal-based degradation and external shocks, we propose a condition-based inspection and replacement policy. Inspections are executed at a sequence of equally spaced time points, which corresponds to the periodic inspection strategy. This is the most popular measure in CBM due to its implementation convenience (Flage, 2014; Sheu, Tsai, Wang, & Zhang, 2015; Wang, Hu, Wang, Wu, & He, 2011; Yang, Ma, Zhai, & Zhao, 2016). For this paper, the purpose of periodic inspections is triple: (1) revealing shock-based failures; (2) checking the state of the system; and (3) measuring the degradation level of the system. If a failure (either degradation-based or shock-based) is revealed at an inspection, a corrective replacement is immediate to renew the system. On the other hand, if the cumulative degradation level of the system exceeds a preventive threshold, the system is preventively replaced.

Most condition-based maintenance policy assumed a constant preventive replacement threshold to deal with degradation-based failure. This is an appropriate setting when the degradation rate of the system stays constant. However, it is not suitable for the three-state system defined in this paper. This is because the degradation rate of the system increases significantly when it becomes defective, and thus preventive actions must be schemed earlier in this state. For this reason, we provide two different preventive thresholds depending on the system state. The preventive threshold at a normal state is called a ‘‘normal threshold”, and the preventive threshold at a defective state is called a ‘‘defective threshold”. Compared with the constant threshold setting, a considerable cost-saving may be achieved due to a more effective prevention of internal failures.

The main contribution of this paper to the current literature lies in the following four aspects.

- A new maintenance model is established based on three-state degradation and external environmental shocks. This is an extension to the current degradation-threshold-shock model.
- The impact of system state on the internal-based degradation as well as external shocks is considered and qualified in this paper.
- An optimal condition-based maintenance policy is introduced to deal with the competing failures, where two preventive thresholds are arranged based on the system state.
- The average cost of the proposed maintenance policy is formulated and compared to the constant threshold-based policy, which validates the benefit of our policy.

The rest of the paper is structured as follows. Section 2 provides the basic notations used for reliability and maintenance modeling. Section 3 describes the failure behavior of the system and constructs reliability models based on the stochastic process theory. Section 4 introduces the condition-based maintenance policy with two preventive thresholds. Section 5 presents a numerical example to validate the reliability and maintenance model.