Journal of Manufacturing Systems 36 (2015) 109–114

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

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

Technical Paper

Maintenance interval decision models for a system with failure interaction

Qi Gao, Yang Ge*

Department of Equipment Management Engineering, Mechanical Engineering College, Shijiazhuang, Hebei, China

ARTICLE INFO

Article history:
Received 19 December 2013
Received in revised form 22 April 2015
Accepted 28 April 2015
Available online 19 May 2015

Keywords:
Maintenance
Complex system
Failure interaction
Maintenance interval
Cost model

ABSTRACT

Based on the three types of failure interactions, two periodical maintenance cost models were presented for a two-state series system and a three-state series system respectively, which all subjected to failure interactions between units. Consider any unit fails would cause damages to other units. The failure interaction influences included instantaneous damages and continuous damages between units. The result indicated that failure interactions will shorten system preventive maintenance interval, if the preventive maintenance strategy is based on the cost.

1. Introduction

For many multi-unit systems, one unit fails often affects the failure characteristics of the other units, we call this failure interaction. Failure interactions occur commonly in engineering assets. For example, nuclear power plants are often made up of redundant units, probability of system failure which caused by one unit fails is quite low, but the failed unit may increase load of other units, then affects the failure characteristics of the other units. For another example, when a car get a flat tire, other tires will be subjected to strong impact, and the failure characteristics of tires may be different from the state before burst.

Nakagawa and Murthy [1] divided failure interactions into three categories:

(1) Type I failure interaction: When a unit fails, it can induce simultaneous failure of the other units or there is no failure interaction, and the occurrence of any one event is according to a fixed probability.
(2) Type II failure interaction: The failure of one unit in multi-unit system will act an interior shock to affect or modify the failure rates of the other units.
(3) Shock damage interaction: When unit 1 in a two-unit system fails, it causes a random amount of damage to unit 2. The damages on unit 2 are accumulated and unit 2 fails when the accumulated damage exceeds a specified level. And the failure of unit 2 make unit 1 into failure simultaneously.

Satow and Osaki [2] considered a two component system where component 1 failures occurred according to a Poisson process, each component 1 failure caused a random amount of damage to component 2 leading to its failure when the total damage exceeded a specified level, they studied a two-parameter maintenance policy which minimized the expected cost per unit of time for infinite time operation. Lai and Chen [3–6] presented an economic periodic replacement model for a two-unit system with failure rate interaction between units, developed an optimal periodical replacement policy for a multi-unit system subject to failure rate interaction between units by incorporating costs of replacement and minimal repair, optimized replacement period of a two-unit system with failure rate interaction and external shocks, and studied a repairable two-unit parallel system with failure rate interaction between units. Yu et al. [7] studied the design of a redundant system with the consideration of a specific kind of failure dependency (i.e. the redundant dependency). Sun et al. [8] developed an extended split system approach which consolidated both split system approach and analytic model for interactive failure, and used it to predict the reliability of repairable systems with interactive failures. Golmakani and Moakedi [9] proposed a model

* Corresponding author. Tel.: +86 031187994624.
E-mail address: gy090@163.com.cn (Y. Ge).

http://dx.doi.org/10.1016/j.jmsy.2015.04.012

Nomenclature

Notations

Δt_{ij}	mean degradation-time of unit j due to the failure damage of unit i
T	preventive maintenance interval of system
$\lambda_i(t)$	failure rate of unit i without failure interaction
$N_i(t)$	failure times of unit i within $[0, t]$
$E[N_i(t)]$	mean-value of $N_i(t)$
C	expected maintenance cost per unit time of the system
C_p	mean cost of system per replacement
C_{ci}	mean cost of unit i per minimal repair
T_p	mean time of system per replacement
T_{ci}	mean time of unit i per minimal repair
Δt	mean degradation-time of unit 2 due to the failure damage of unit 1
α	mean degradation rate of unit 1 due to the degradation of unit 2
$F_1(t)$	life distribution function of unit 1
$G_2(u)$	life distribution of unit 2 before its degradation
$g_2(u)$	density function of $G_2(u)$
$F_2(h)$	life distribution of unit 2 from degradation to functional failure
$f_2(h)$	density function of $F_2(h)$
$E[N_1(0, u)]$	unit 1 expected functional failure number of during $[0, u]$
$P_m((k-1)T,\ kT)$	probability of the fact that unit 2 has degraded, but no functional failure, and system is replaced at time kT
$P_b((k-1)T,\ kT)$	probability of the fact that unit 2 has degraded, and failed functionally at time $u+h$ before kT, system is replaced at $u+h$
$T_w(kT)$	the expected life of system
$T_{sm}(kT)$	the expected maintenance time of system

to find the optimal periodic inspection interval on a finite time horizon for a two-component repairable system with failure interaction. The proposed modeling approach can be used in electrical distribution systems, where capacitor bank and high power transformer are coupled in a distribution substation. Zhang et al. [10] and Hou et al. [11] also carried through relative researches.

The above studies about maintenance policies for the system with failure interaction supposed either only one unit's failure would cause a damage to other units [1–6,9–11], or the units interacted with each other continuously whether they were faulted or not [7,8]. In this paper, we propose two different cases about failure interactions. The first one is failure of any units will cause an instantaneous damage to other units for a multi-unit series system that all units have only two state (normal and failure). The second one is about a two-unit series system composed with a two-state unit (normal and functional failure) and a three-state unit (normal, degradation and functional failure), if the two-state unit fails functionally, it will cause an instantaneous damage to the three-state unit, if the three-state unit fails potentially, it will cause a continuous damage to the two-state unit, and if the three-state unit fails functionally, it will make the two-state unit into instantaneous functional failure. In this paper, the maintenance actions include minimal repair, failure inspection, and preventive replacement.

Failure of a unit during actual operation is sometimes costly or dangerous. To avoid this, we inspect and maintain an operating unit as a preventive measure against failure in many situations. A technique called delay time analysis has been developed for modeling the consequences of an inspection policy for a production plant. Christer [12] and Christer and Waller [13,14] utilized the notion of delay time, which the span of time from when it is considered to have failed. If a defect is found at an inspection, then the component is replaced or repaired to a new condition and thus avoiding a failure. Then Christer and Wang [15], Christer and Lee [16], L. Wang et al. [17], and W. Wang [18] did further study on the delay time models.

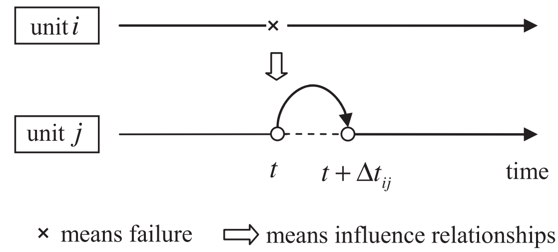

Fig. 1. A multi-unit system with failure interactions.

2. Two-state model

2.1. Assumptions

(1) A system is composed of n units connected in series ($n = 1, 2, 3, \ldots$).
(2) Each unit only has two states: normal and failure. As Fig. 1 shows: if any unit fails (denoted as unit i, $i = 1, 2, 3, \ldots, n$), it will cause a certain amount of damage to other units (denoted as unit j, $j = 1, 2, 3, \ldots, n$, $j \neq i$) by aging time Δt_{ij} on average, the state age of unit j becomes $t + \Delta t_{ij}$, when its working age is t.
(3) Without failure interaction, the failure rates of units are also increasing as their ages increasing.
(4) The system will be replaced by a new one when its working age achieves time T. Before replacement of system, all failures of units are assumed to be corrected by minimal repair (after repair, the failure rates of units remain unchanged).
(5) Unit i has a failure rate $\lambda_i(t)$ without failure interaction, and $\lambda_i(t)$ is an increasing function of t.

2.2. Cost model

According to the assumptions, without failure interaction, before replacement of system, it is well known that the failures of unit i occur randomly according to a non-homogeneous Poisson process $\{N_i(t), 0 \le t \le T\}$ with a mean-value function $E[N_i(t)] = \int_0^t \lambda_i(u)du$.

Consider the damage from failures of other units, at working age t, the state age of unit i is

$$t_i = t + \sum_{j\in\{1,\ldots,n\}\backslash i} E[N_j(t)]\Delta t_{ji} \tag{1}$$

And the actual failure rate function of unit i is

$$\lambda_i(t_i) = \lambda_i\left(t + \sum_{j\in\{1,\ldots,n\}\backslash i} E[N_j(t)]\Delta t_{ji}\right) \tag{2}$$

Since each replacement of the system is a renewal point, the mean failure times of unit i during a replacement cycle can be obtained as follow.

$$E[N_i(T)] = \int_0^T \lambda_i\left(t + \sum_{j\in\{1,\ldots,n\}\backslash i} E[N_j(t)]\Delta t_{ji}\right) dt \tag{3}$$