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Multi-level predictive maintenance for multi-component systems

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ABSTRACT

In this paper, a novel predictive maintenance policy with multi-level decision-making is proposed for multi-component system with complex structure. The main idea is to propose a decision-making process considered on two levels: system level and component one. The goal of the decision rules at the system level is to address if preventive maintenance actions are needed regarding the predictive reliability of the system. At component level the decision rules aim at identifying optimally a group of several components to be preventively maintained when preventive maintenance is trigged due to the system level decision. Selecting optimal components is based on a cost-based group improvement factor taking into account the predictive reliability of the components, the economic dependencies as well as the location of the components in the system. Moreover, a cost model is developed to find the optimal maintenance decision variables. A 14-component system is finally introduced to illustrate the use and the performance of the proposed predictive maintenance policy. Different sensitivity analysis are also investigated and discussed. Indeed, the proposed policy provides more flexibility in maintenance decision-making for complex structure systems, hence leading to significant profits in terms of maintenance cost when compared with existing policies.

1. Introduction

The maintenance process includes preventive and corrective actions carried out to retain a system or restore it to an operating condition. It is a complex process of the utmost importance especially for the manufacturing firms. Maintenance costs may take from 15 to 70% of total production costs [1]. Optimal maintenance policies aim to provide optimal system reliability/availability and safety performance at the lowest possible maintenance cost [21]. In the literature, there are mainly two types of maintenance techniques including time-based maintenance (TBM) and condition-based maintenance (CBM). For TBM maintenance, preventive maintenance decision is based on the system age and on the knowledge of the statistical information on the system lifetime [6,9]. As a consequence, the realistic operating conditions of the system over time are not taken into account. Unlike TBM maintenance, CBM consists in advanced maintenance technique. It is popularly reported in the literature and the maintenance decision-making process relies on the diagnostic/prognostic of the system condition over time. It has been recently introduced and becomes nowadays an interesting approach for maintenance optimization [2,3,7,8,12].

A large number of CBM policies has been investigated, developed and successfully applied to mono-component system, e.g., [7,12,30] using the current equipment condition (deterioration level) and [15,31,8] taking the future equipment health state for making maintenance decision. However, these policies cannot be adapted directly to multi-component systems [4], in which interdependencies such as stochastic, structural and economic dependencies may exist between components [25]. In fact, the stochastic dependence implies that the deterioration process or failure of a component may affect the lifetime distribution of other ones. The structural dependence exists if components structurally form a part, so that maintenance of a failed component implies maintenance of working components, or at least dismantling them. Finally, the economic dependence involves (i) positive economic dependence (PED) implying that joint maintenance of a group of components is cheaper that performing maintenance on components separately, and (ii) negative economic dependence (NED) which exist if combining maintenance activities is more expensive than performing maintenance on components separately [6]. It is important to note that taking into account all these dependencies in maintenance optimization is necessary, but makes

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Abbreviation: CBM, condition-based maintenance; CM & OM & PM, corrective and opportunistic and preventive maintenance; MCS, minimal cut set; NED & PED, negative and positive economic dependence; RBD, reliability block diagram; RUL, remaining useful life

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Nomenclature

Notations

n	total number of components of considered system
i	index for components of the system, with $i=1,2,\ldots,n$
$s(t)$	system state at time t
$s_i(t)$	state of component i at time t
$X_{i,t}=x_{i,t}$	degradation level of component i measured at time t
$X_{1:n,t}=x_{1:n,t}$	degradation level of whole system measured at time t
$(X_{i,t})_{t\geq 0}$	stochastic process describing the degradation of component i over time t
α_i,β_i	shape and scale parameters of Gamma distribution for component i
Z_i	fixed failure threshold of component i
$c_{p,i}, c_{c,i}$	specific PM cost and specific CM cost of component i, with $c_{c,i}\geq c_{p,i}$
c_{insp}	inspection cost for a component
c_s	maintenance set-up cost
c_{psd}	planned shutdown cost
c_{usd}	unplanned shutdown cost
c_d	unplanned downtime cost rate
T, T^*	inter-inspection interval (or inspection cycle) and optimal value of T
T_k	k-th inspection time, with $T_k=k\,T$ and $k\in\mathbb{N}$
T_k^-, T_k^+	time just before/after the inspection date T_k
G_l	l-th group of components
$\lvert G_l\rvert$	cardinal number of the group G_l, $1\leq\lvert G_l\rvert\leq n$
$R_i(T_{k+1}\mid x_{i,T_k})$	predictive reliability of component i at the next inspection time T_k+T given its degradation level, x_{i,T_k}, at time T_k
$R(T_{k+1}\mid x_{1:n,T_k})$	predictive reliability of system at the next inspection time T_k+T given the degradation level of n components, $x_{1:n,T_k}$, at time T_k
$R^{G_l}(T_{k+1}\mid x_{1:n,T_k})$	system predictive reliability at the next inspection time T_k+T when all components of group G_l are replaced preventively at time T_k
$C_{G_l}^{GIF}(t)$	cost-based group improvement factor computed when all components of group G_l are replaced at time t
R_0, R_0^*	PM threshold and optimal value of R_0 defined for the policy (T,R_0)
R_p, R_p^*	PM threshold and optimal value of R_p defined for the policy (T,R_p,R_{op})
R_{op}, R_{op}^*	OM threshold and optimal value of R_{op} defined for the policy (T,R_p,R_{op})
N_b	total number of inspection times within $[0,T_{rep}]$
C_k	consists of the inspection cost, the running cost and the maintenance costs of the k-th inspection cycle (i.e. $(T_{k-1},T_k]$, with $k\geq 1$)
$C^\infty(T,R_0)$	long run maintenance cost per time unit of the policy (T,R_0)
$C^\infty(T,R_p,R_{op})$	long run maintenance cost per time unit of the policy (T,R_p,R_{op})
T_{rep}	time at which the system is completely replaced
$\mathcal{I}_{.}$	indicator function: $\mathcal{I}_{\{\cdot\}}=1$ if the condition $\{\cdot\}$ is true and 0 otherwise
Ω	set of all components of the system
Policy $(T,\ R_0)$	Multi-level predictive maintenance policy
Policy $(T,\ R_p,\ R_{op})$	opportunistic predictive maintenance policy

the maintenance models too complicated to solve or to analyze. This is specially true in CBM framework. In the literature most existing CBM maintenance policies for multi-component systems take advantage of PED to minimize the average maintenance cost, see for instance [2,3,13,26,16]. Nevertheless, these existing CBM policies addressing multi-component systems can be applied on several specific structures (i.e., series, parallel, series-parallel, parallel-series, k-out-of-n). However, actual system structures are more complex with a large number of components and very complex inter-connections between components which can be described as mixtures of basic connections [11,28,33]. It is shown in [29] that taking into account the complex structure in a maintenance model may lead to consider both PED and NED dependencies. However, the maintenance policy proposed in [29] is based on TBM technique. Recently, a CBM policy has been introduced for complex structure systems using Birnbaum importance measure which can help to take into account effectively the system structure in maintenance decision-making [19]. Each component is individually selected to be preventively maintained at discrete times but the maintenance grouping impacts (PED and/or NED between components) are not really highlighted.

To face this issue, in the present paper, a predictive maintenance policy with multi-level decision-making process is proposed for complex structure systems. The main idea is to jointly consider prognostic information (i.e., predictive reliability or RUL) of components and system, PED and NED dependencies as well as system structure in the maintenance decision-making process. More precisely, the proposed maintenance policy is divided into two levels:

- At system level and at each inspection time, the reliability of components is firstly predicted. Based on the predictive reliability of components, the predictive reliability of the system is secondly determined and compared with a prefixed reliability threshold. Preventive maintenance is needed if the predictive reliability of the system is lower than the prefixed threshold.
- At component level: the main idea is to find an optimal grouping of several components to be preventively maintained when maintenance decision at system level is triggered. Decision making is made on the basis of a "cost-based group improvement factor" taking into account the predictive reliability of components, the economic dependencies as well as the location of components in the system. The later is the first original contribution of the paper.

The proposed maintenance policy has two decision variables including inter-inspection interval and PM threshold at system level. These decision variables need to be optimized. The second contribution of the paper is to develop a cost model in order to find the optimal maintenance decision variables. In addition, Monte Carlo simulation technique is used to evaluate the maintenance cost rate.

The rest of this paper is organized as follows. Section 2 is devoted to the description of the general model of degradation and failure of a multi-component system. The complex structure of the system is also investigated. Section 3 focuses on the predictive reliability/RUL at both component and system level for a complex structure system. Additionally, the cost-based group improvement factor is also introduced. Section 4 describes the maintenance costs structure and the proposed multi-level predictive maintenance policy. The global cost model is also developed here. To illustrate the use and advantage of the proposed policy, a 14-component system with complex structure is introduced. A comparison on the performance of the proposed policy and an existing policy is investigated through different sensitivity analyses. Finally, the present paper ends with some conclusions and outlines for possible future works.