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A MC-PSO approach to the failure probability evaluation of risky plant components: The maintenance design

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ABSTRACT

A mandatory feature of the risky plants is the high reliability obtained through a careful engineering design joined with a well planned maintenance program. This latter aims at decreasing the wear thus rejuvenating the component age as if it had operated for a shorter time. The variable appearing in the failure distribution which rules the failures is then switched from chronological time to age and the (few) observed failures always occur during the early age of the component, i.e. from the lower tail of the true unknown distribution. Correspondingly, a first guess distribution based on the observed failures is strongly biased towards lower ages. In the present paper, we firstly consider the problem of estimating the true failure probability and then we apply the results to a maintenance design. In order to recover the true distribution, we propound resorting to the Particle Swarm Optimization (PSO) technique joined with a Monte Carlo (MC) simulation. We assume that the failures obey a Weibull distribution and that a set of real data has been observed from which a reference distribution has been guessed. In the PSO approach a set of agents move within the space of the two Weibull parameters: in correspondence of each location of each agent the corresponding distribution is computed and a sequence of failures is Monte Carlo sampled. The distribution thereby estimated is compared with the reference one until a match is found. The true distribution is then that corresponding to the coordinates of the agent which realized the match. Knowledge of the true failure distribution allows us to optimize the maintenance design and also to correctly compute quantities of interest involving the plant economy and the safety.

1. Introduction

The safety of complex and risky plants such as the nuclear or the aerospace ones, is strongly affected by the reliability of their main components which depend, besides an efficient engineering design, on the maintenance program [1–4]. The maintenance decreases the wear and rejuvenates the component age as if it had operated for a shorter time, thus switching the variable which rules the failures from chronological time to age, here called "time" and "age", respectively. Assuming that the component must safely function for a given mission time, the problem is how to design the maintenance so that the objective could be achieved without failures or – more realistically – with a low failure probability. The solution to this problem depends on the knowledge of the failure probability of the component: when this is overestimated, the maintenance periods are kept shorter than needed, with a waste of economical resources. The opposite case is worst, since too long maintenance periods directly involve the safety.

Here, we consider the evaluation of the failure probability of a component of a risky plant, subject to periodic imperfect maintenance with proportional repairs [5,6]. We assume that at the start of the plant operation the designer establishes the maintenance parameters and states that the corresponding failure probability will remain valid throughout the mission time or up to the first failure. In this latter case, the initial probability will be replaced by a conditioned one, the condition being the occurred failure. An alternative approach to the problem, e.g. as in [6], would consist in assuming that in correspondence of every plant maintenance the failure probability be updated by a conditioned one, the condition being that the plant is in safe state at the maintenance time. In this approach, which implies a flow of information from the plant to the designer, there will be not a single analytic expression for the probability distribution to be used for further use, e.g. for plant reliability-cost optimizations. Moreover, we assume that (i) the failure probability follows a Weibull distribution of the age, and that (ii) a first guess of this probability has been obtained by resorting to the maximum likelihood estimate (MLE) method, based on the failures observed in a set of similar components which functioned under known maintenance conditions. However, the accuracy of a guess so

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Nomenclature

u, S	component age and right censored age
t	clock time
τ	component maintenance period
N	number of maintenance periods
$W(u;\ \eta,\beta)$	Weibull component failure cumulative distribution function (cdf) with scale parameter η and shape parameter β
$w(u;\eta,\beta)$	Weibull component failure probability density function (pdf)
W_0, w_0	biased Weibull cdf and pdf as estimated from component failures
W^*,w^*	true Weibull cdf and pdf, also here called *root cdf* and *root pdf*
w^{PSO}	MC-PSO estimate of the Weibull pdf from the failures sampled from a biased W
$h_m(t)$	component hazard rate (failure rate) in the m-th time period
$R_m(t)$	component reliability in the m-th time period
$F_m(t)$	component failure distribution in the m-th time period
x_i	coordinates of an agent in the swarm procedure (vector of the (η,β) parameters)
$\varphi(x)$	fitness of a swarm agent in location x: closeness of $w^{PSO}(x)$ to w_0

obtained is scarce not only because in risky plants the number of failures is–luckily–very low, but basically because the maintenance prevents the occurrence of high ages. Since the few observed failures come from the lower tail of the true distribution, we may a priori say that this first guess distribution is biased towards lower ages. To recover the underlying true distribution, we propound to resort to the Particle Swarm Optimization (PSO) technique [7] joined with a Monte Carlo (MC) simulation. In our PSO approach a set of agents spans the 2D space of the Weibull parameters and for each location of each agent the corresponding distribution is computed and a sequence of failures is Monte Carlo sampled. The distribution thereby estimated is compared with the initial guess and the search is continued until a match is found. The true distribution is then that corresponding to the coordinates of the agent which realized the match. Knowledge of the true failure distribution allows us to optimize the maintenance design and also to correctly compute quantities of interest involving the plant economy and the safety.

The remainder of the paper is structured as follows: in Section 2 we recall the maintenance model here investigated [5]. In Section 3, by means of a Monte Carlo (MC) simulation approach, we show that the above mentioned first guess distribution cannot be accepted since it is actually shifted towards lower ages. In Section 4, after giving a short summary of the standard PSO method, we attempt to recover the true Weibull distribution. In Section 5 some maintenance designs are presented and finally, in Section 6, some conclusions are drawn.

2. The periodic imperfect maintenance model and the failure probability.

It is assumed [5] that at the start the component has zero age and that its chronological life is constituted by a sequence of periods of length τ during which the age increases with time, separated by instantaneous preventive maintenances at times $t_m=m\tau$, $(m=1,2,\ldots)$. The maintenance is called proportional if its effect is that of multiplying the current age at the end of each period by a factor $(1-\varepsilon)$, where $\varepsilon\in(0,1)$ is the maintenance efficiency. In the extreme cases $\varepsilon=0$ and $\varepsilon=1$, the effect of the maintenance is either null or such that the age is restored to zero, respectively. Correspondingly, after the maintenance, in the first case, the component is as bad as old (BAO), whereas it is as good as new (GAN) in the second case. All the intermediate cases are called of imperfect maintenance (IM). At the start of the m-th period (t_{m-1},t_m), at time t^+_{m-1}, the age is u^+_{m-1} and increases with time up to the final value $u^-_m=u^+_{m-1}+\tau$ at t^-_m; at t^+_m the age is suddenly reduced to $u^+_m=(1-\varepsilon)u^-_m$:

$$u^-_1=\tau,\quad \text{and}\quad u^+_1=(1-\varepsilon)u^-_1$$

$$u^-_2=u^+_1+\tau=(1-\varepsilon)\tau+\tau \quad\text{and}\quad u^+_2=(1-\varepsilon)u^-_2=[(1-\varepsilon)+(1-\varepsilon)^2]\tau$$

$$u^-_m=u^+_{m-1}+\tau=\sum_{k=0}^{m-1}(1-\varepsilon)^k\tau=\left[1-(1-\varepsilon)^m\right]\frac{\tau}{\varepsilon}\quad\text{and}$$
$$u^+_m=(1-\varepsilon)u^-_m=(1-\varepsilon)\left[1-(1-\varepsilon)^m\right]\frac{\tau}{\varepsilon}$$

Within the generic m-th interval, i.e. for $t\in(t_{m-1},t_m)$ the age is

$$u_m(t)=t-(m-1)\tau+u^+_{m-1} \tag{1}$$

As usual in reliability studies, we assume that the failure ages follow a Weibull distribution with shape parameter β and scale parameter η: the cumulative distribution function (cdf) and the associated probability density functions (pdf) are

$$W(u)=1-\exp\left(-\left(\frac{u}{\eta}\right)^{\beta}\right)\quad\text{and}$$
$$w(u)=\frac{\partial W}{\partial u}=\frac{\beta}{\eta}\left(\frac{u}{\eta}\right)^{\beta-1}\exp\left(-\left(\frac{u}{\eta}\right)^{\beta}\right)$$

In the present case, the independent variable is the time t, but the failures occur according to the component age u at t. The functions of interest in the m-th time interval are

- the hazard rate

$$h_m(t)=\frac{\beta}{\eta}\left(\frac{u_m(t)}{\eta}\right)^{\beta-1} \tag{2}$$

- the partial reliability

$$R_{p,m}(t)=\exp\left(-\int_{(m-1)\tau}^{t}h_m(u)du\right)=\cdots$$
$$=\exp\left[-\left(\frac{t-(m-1)\tau+u^+_{m-1}}{\eta}\right)^{\beta}+\left(\frac{u^+_{m-1}}{\eta}\right)^{\beta}\right]$$

the total reliability is then

$$R_m(t)=\left[\prod_{j=1}^{m-1}R_{p,j}(j\tau)\right]R_{p,m}(t)=\left\{\prod_{j=1}^{m-1}\exp\left[-\left(\frac{\tau+u^+_{j-1}}{\eta}\right)^{\beta}+\left(\frac{u^+_{j-1}}{\eta}\right)^{\beta}\right]\right\}R_{p,m}(t)$$

- the failure distribution function is

$$F_m(t)=1-R_m(t) \tag{3}$$