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Assessment of the Effect of Predictive Maintenance on the System Reliability

Avaliação do Efeito da Manutenção Preditiva sobre a Confiabilidade de Sistemas

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Abstract

In this work, we assess the effect of predictive maintenance on the reliability of repairable systems. In reparable systems, the reliability assessment considering corrective and preventive maintenance is well defined, but not considering predictive one. The effect of predictive maintenance is taken into account through a finite probability that the system is found in degraded condition. If the predictive maintenance evidences the degradation, then the repair is carried out. All the repairs are considered perfects, which means that the system is restored to an as-good-as-new condition each time the repair is carried out. The measure of system reliability under predictive maintenance is found to be between that of a maintenance-free strategy and preventive maintenance. The effect on the system reliability depends on the value of the probability that the system is found in degraded condition. We propose an expression for the reliability that is convenient when values of such probability are less than 15%. By using the proposed expression, one can estimate how much improvement in reliability any system gains by the predictive maintenance.

Keywords

System reliability • Predictive maintenance • Aging effects

Resumo

Neste trabalho, avaliou-se o efeito da manutenção preditiva na confiabilidade de sistemas reparáveis. Em sistemas reparáveis, a avaliação da confiabilidade considerando as manutenções corretivas e preventivas está bem definida, mas não considerando as preditivas. O efeito da manutenção preditiva é levado em consideração através de uma probabilidade finita de que o sistema seja encontrado em condições degradadas. Caso a manutenção preditiva evidencie a degradação, então o reparo é realizado. Todos os reparos são considerados perfeitos, o que significa que o sistema é restaurado para uma condição tão boa quanto novo, cada vez que o reparo seja realizado. A confiabilidade do sistema sob manutenção preditiva está entre o nivel da estratégia sem manutenção e o nível da manutenção preventiva. O efeito na confiabilidade do sistem depende do valor da probabilidade do sistema ser encontrado em condição degradada. Propou-se uma expressão para a confiabilidade que é conveniente quando os valores dessa probabilidade são inferiores a 15%. Usando a expressão proposta, pode-se estimar o quanto de melhoria na confiabilidade qualquer sistema ganha com a manutenção preditiva.

Palavras-chave

Confiabilidade de sistema • Manutenção preditiva • Efeitos de desgaste

1 Introduction

In the corporate world, especially in industrial sectors, preserving the functional state of their systems is essential for the operation and continuity of production and profit of the organizations [1]. In this context, the industrial maintenance is no longer considered an operational cost, and it increasingly plays a strategic role in the organizations [2].

The emergence of industrial maintenance occurred alongside the creation of the first industries. However, maintenance strategies date back to the beginning of the 19th century, coinciding with the beginning of the series production [3]. Some authors divide the strategies into three generations, characterized by corrective, preventive, and predictive maintenances [4,5]. Other authors still regard reliability-centered maintenance (RCM) as being the fourth generation [6,7]. The RCM is defined by a set of engineering techniques that aim at excellence in maintenance activities, increasing the reliability of assets, and reducing the respective costs [1].

System reliability is defined as the probability that the system performs its function properly during a certain time interval, subjected to a certain operational condition. The goal of this work is to propose a mathematical expression for assessing the system reliability considering the predictive maintenance associated with a degradation factor that means the probability that the system is found in degraded condition. The degradation factor denotes the possibility of making repairs after system testing is carried out. The system reliability considering predictive maintenance is found between the one with maintenance-free strategy and another with preventive maintenance. The effect of the predictive maintenance on the system reliability depends on the value of the degradation fator. Such degradation fator is considered small when its value is less than 15%.

This work is presented by this introduction, followed by the theoretical framework in which the concepts necessary for understanding the proposal are discussed in more detail, and by the development of the proposed expresssion for the reliability. Finally, the results are presented together with the respective discussions, and the conclusions addresses the final considerations.

2 Materials and Methods

The theoretical framework as well as other issues are addressed in this section to clarify and elucidate fundamental points for a better understanding of the research proposal.

2.1 The probability distribution

Each system has a corresponding failure probability distribution model, which is related to the time to failure random variable $\boldsymbol{t}$ [8]. Several distribution models appear in the literature, and among them the most common are the normal, exponential and Weibull distributions [9, 10, 11].

The probability density function indicating a probable time t comprised in the interval between t and $t + dt$, in which one failure occurs, is given by [12]

$$f(t)\, dt = P\{t < \boldsymbol{t} \leq t + dt\}\,. \tag{1}$$

The above expression represents the probability of failure in an infinitesimal time interval. Considering a mission time t, the probability that one failure occurs before a time t is given by the cumulative distribution function given by [1]

$$F(t) = \int_0^t f(t')dt' = P\{\boldsymbol{t} \leq t\}. \tag{2}$$

The Weibull distribution is widely used because it can represent diverse failure rate curves over a time interval. The Weibull distribution was proposed by Waloddi Weibull in 1951. It represents the behavior of a system when there is competition between different failure modes. This characteristic is typical of several industrial systems. Its probability density function is described by

$$f(t) = \frac{\beta}{\theta}\left(\frac{t-t_0}{\theta}\right)^{\beta-1} exp\left[-\left(\frac{t-t_0}{\theta}\right)^{\beta}\right]. \quad (3)$$

The parameters of the Weibull distribution can be obtained by several statistical methods, and their descriptions are presented in Table 1.

Table 1: The parameters of the Weibull distribution.

Parameter	Description
t_0	The location parameter, $-\infty < t_0 < \infty$.
θ	The scale parameter, $\theta > 0$.
β	The shape parameter, $\beta > 0$.

2.2 Maintenance strategies

The maintenance is an action that tries to guarantee the availability and operation of facilities and equipment [14], reducing the probability of failure or minimizing their impacts if the failure occurs [15]. With the development of applied technologies over the time, maintenance strategies have advanced in terms of their techniques and complexity [8]. Among the important strategies are the corrective, preventive and predictive maintenances [16].

The corrective maintenance is the unscheduled repair that occurs when the failure is identified [17], seeking to restore the operation immediately after the failure [18]. It is also called maintenance-free strategy. The corrective maintenance is the most common, oldest and non-profitable maintenance, The corrective maintenance by logic does not need any programming.

The most profitable and recent strategy is the time-based maintenance or preventive maintenance. A preventive maintenance program must be based on a technique that allows establishing optimal maintenance intervals to carry out maintenance of assets. The preventive maintenance aims to carry out repairs based on periodicity, either by time or by use [19]. The adoption of the preventive maintenance sometimes raises the costs associated with maintenance, as there is the possibility of the repair in the system still with residual life.

As an improvement of these maintenance strategies, the predictive maintenance has emerged, which uses measurement techniques (system testing) to predict the ideal moment for doing repairs based on the condition of the system [20]. Predictive maintenance is a more recent maintenance strategy that aims to increase the asset's life expectancy and ensure sustainable operational management while also enhancing the performance and efficiency of the system.

2.2.1 Maintenance-free strategy

Reliability is a mathematical principle based on probabilistic and statistical theories for pragmatically assessing the performance of systems [21]. The reliability value is given by the probability that the system works perfectly for a specified time interval. Thus, the system reliability is defined as

$$R(t) = 1 - F(t) = \int_t^{\infty} f(t')dt'. \quad (4)$$

The definition of reliability is central to all the assessments in this work, with or without maintenance. Relatively few systems are design to operate without maintenance of any kind. When considering low failure costs and few human factors the maintenance-free stragegy can be the best one. The system reliability will be the criteria for judging the effectiveness of the maintenance-free strategy.

2.2.2 Preventive maintenance strategy

Considering that preventive maintenance is performed on a system at each time interval τ, the reliability differs from the one with the maintenance-free strategy after the first interval. Assuming that the repair is perfect (the system is brought to as-good-as-new condition after the repair), the reliability curve in next intervals has the same profile of the first interval, however starting from the end point of the last interval. The reliability curve can be seen in the Fig. 1, in which the preventive maintenance reliability is denoted by $R_{PV}(t)$. If there is not repair, the relliability curve continues as the free-maintenance reliability $R(t)$.

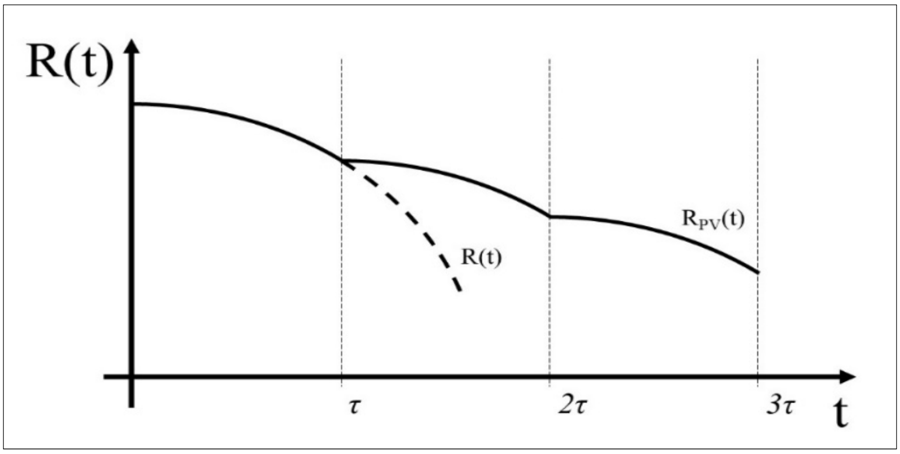

Figura 1: The reliability curve for the preventive maintenance, illustrating the changes in reliability after each maintenance interval.

In the first interval $0 < t \leq \tau$, when any repair has not yet been done, the preventive maintenance reliability is defined as

$$R_{PV}^{(1)}(t) = R(t)\,. \tag{5}$$

After the first repair, the reliability is the result of the product of the preventive maintenance reliability at the instant τ and the maintenance-free reliability in the additional interval $t - \tau$. Thus, the preventive maintenance reliability in the general interval $N\tau < t \leq (N+1)\tau$, where $N = 1, 2, \ldots$, can be obtained by the following recursive expression:

$$R_{PV}^{(N+1)}(t) = R_{PV}^{(N)}(N\tau)R(t - N\tau). \tag{6}$$

2.2.3 Predictive maintenance strategy

In the predictive maintenance, system testing are carried out to predict the ideal moment for doing the preventive repair. In this paper, we propose a general expression for the predictive maintenance reliability that considers the folowing conditions:

- system testing are immediately carried out;
- after the system testing, repairs may or may not be done; and
- repairs are immediately done.

Due to the mutually exclusive nature of the result after carrying out system testing, a factor p, called degradation factor, should be used to represent the probability that a system is operationally compromised to the point of need of repair. In a practical way, the degradation factor represents the wear condition of the system. For presentation purposes, another factor $\tilde{p}$ will be defined complementarily to the degradation factor; that is,

$$\tilde{p} = 1 - p\,. \tag{7}$$

After carrying out system testing, if there is no need of repair, the reliability goes on as the previous reliability curve. On the other hand, when system testing demonstrates that there is a need of preventive repair, the reliability follows the curve of the as-good-as-new condition. In the Fig. 2 a graph illustrates the reliability curve for the predictive maintenance in any interval, where the predictive maintenance reliability is denoted by $R_{PD}(t)$. After carrying out system testing, both the effects of doing the preventive repair and of not doing so can be seen in the reliability curve.

In the first interval $0 < t \leq \tau$, when any system testing has not yet been done, the predictive maintenance reliability is

$$R_{PD}^{(1)}(t) = R(t). \tag{8}$$

After the first system testing, the predictive maintenance reliability can be averaged over both the effects of doing the preventive repair and of not doing so, respectively being weighted by the factors p and $\tilde{p}$. The predictive maintenance reliability in the general interval $N\tau < t \leq (N+1)\tau$, where $N = 1, 2, \ldots$, can be obtained by the following recursive expression:

$$R_{PD}^{(N+1)}(t) = R_{PD}^{(N)}(N\tau)R(t - N\tau)p + R_{PD}^{(N)}(t)\tilde{p}\,. \tag{9}$$

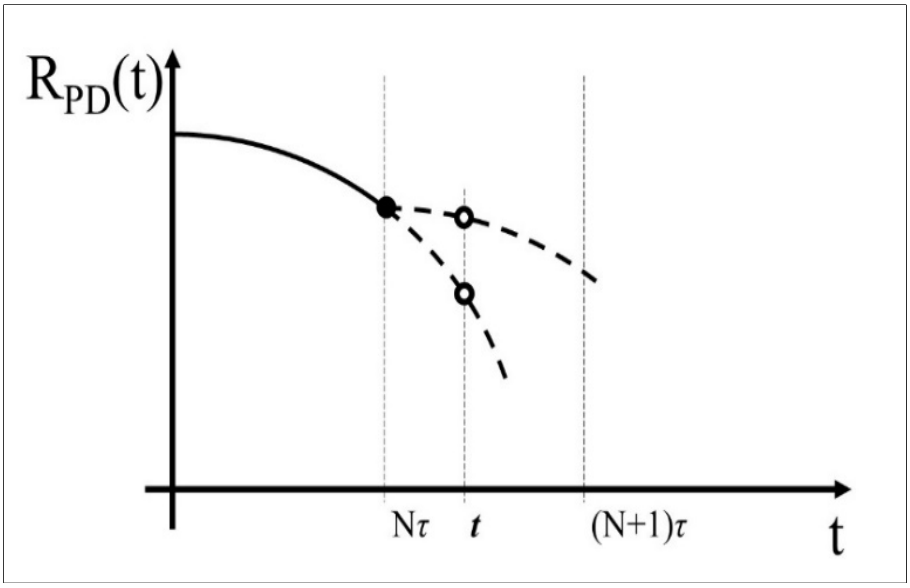

Figure 2: The reliability curve for the predictive maintenance strategy, illustrating the effects of doing or not doing the preventive repair.

3 Results and Discussions

To check the general expression for the predictive maintenance reliability, we used the data found in [22], in which the Weibull distribution is the model for the failure time interval. The values of the distribution and maintenance parameters are presented in Table 2.

Table 2: The values of the distribution and maintenance parameters.

Parameter	**Value**
t_0 (h)	691.0548
θ (h)	1410.0
β	3.317
τ (h)	1000.0
p	0.25

According to the values of the distribution and maintenance parameters, the curves for the probability density function and the maintenance-free reliability are shown in the graphs in the Fig. 3. The reliability corresponds to the complementary cumulative failure distribution function.

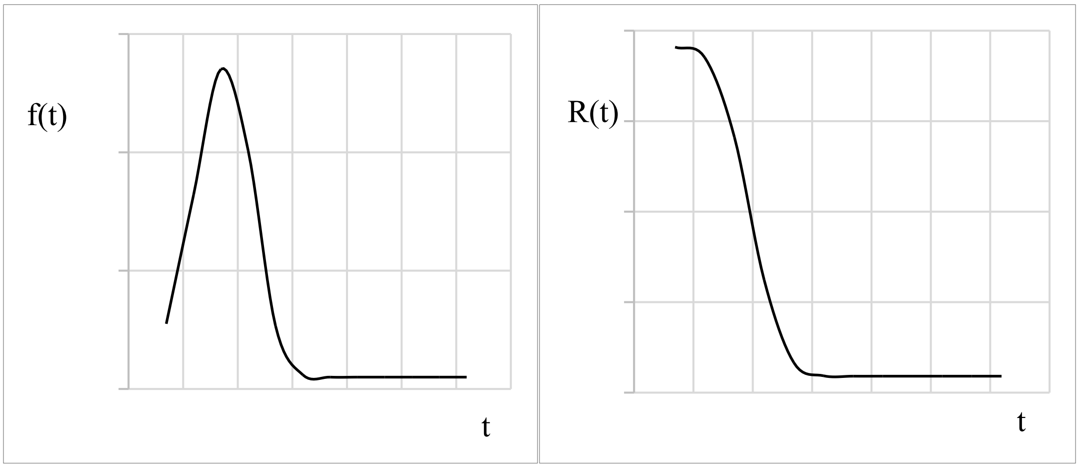

Figure 3: The curves of the failure probability density function (left) and maintenance-free reliability (right).

By the expressions presented above, it was possible to compare the curve for the predictive maintenance reliability, $R_{PD}(t)$, with the curves for the maintenance-free reliability, $R(t)$, and the preventive maintenance reliability, $R_{PV}(t)$. This comparison was done through the graph in the Fig. 4. In the graph, it is noted that the curve of the predictive maintenance reliability is located at the region between the curves of the maintenance-free reliability and preventive maintenance reliability. In other words, when adopting the predictive maintenance strategy for a system, there is a gain in reliability over the maintenance-free strategy. On the other hand, as far as reliability is concerned, the gain for the predictive maintenance strategy does not reach the same level as in the preventive maintenance strategy.

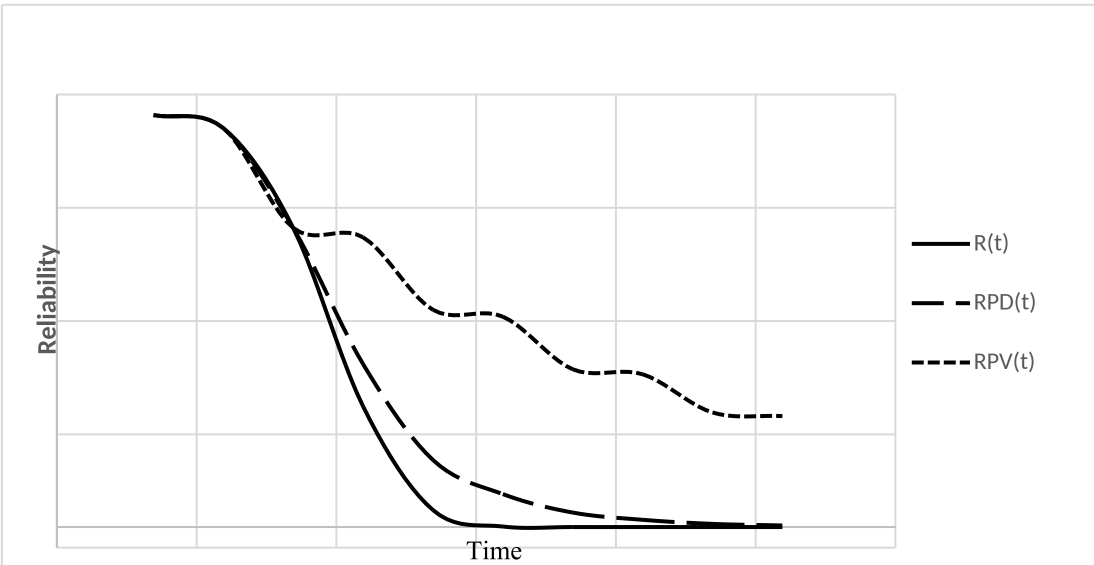

Figure 4: Comparison between the reliability curves for the maintenance strategies.

The shape of the reliability curve for a system operating under predictive maintenance strategy depends on the value of the degradation factor p. The reliability curve for different factor p can be seen in the Fig. 5. By varying the degradation factor, it can be observed that when $p = 1$ the curve for the predictive maintenance reliability becomes the same of the preventive maintenance one. The $p = 1$ means that every system testing performed on the system requires subsequent repair. This situation corresponds to the preventive maintenance itself, in which prenvientive repairs are done during the whole mission time. This result corroborates the validation of the proposed expression for the predictive maintenance reliability.

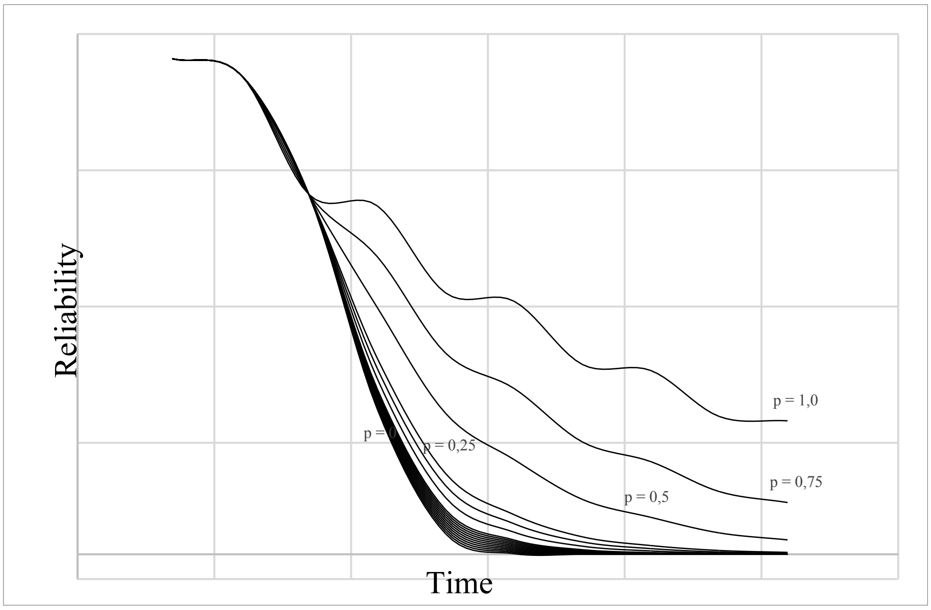

Figure 5: The reliability curves as a function of the degradation factor. Source: Authors (2024).

On the other hand, the $p = 0$ means that the test indicates no need of preventive repair. Thus, it is easy to verify that the predictive maintenance reliability corresponds to the maintenance-free reliability, as the overlap of the respective curves can be observed.

A correlation analysis of the curves with different values of p was performed in relation to the curve with $p = 0.01$ for establishing which curves would be statistically equivalent to one with small degradation factor ($p \ll 1$). The results of the correlation coefficient R^2 with respect to the value of p are presented in Table 3.

Table 3: The correlation analysis of the reliability curves for the predictive maintenance.

p	R^2
0.02	99.99%
0.05	99.97%
0.10	99.86%
0.15	99.66%
0.20	99.37%
0.25	99.01%
0.50	99.13%

A level of equivalence can be established when $R^2 > 99.5\%$. Thus, the curves for the values of p up to 0.15 are statistically equivalent to the curve with $p = 0.01$ (which can be considered a small degradation factor).

4 Conclusions

This work has led to the proposition of a mathematical expression for the reliability of a system operating under a predictive maintenance strategy. Through the proposed expression, it was possible to estimate the probability of a system being operated along any time of the interest.

Maintenances that adopt the predictive strategy to extend the useful life of systems have been gaining ground both in the literature and industry. This paper presented supports to the development of such strategy. By using the proposed expression, it is possible to generate greater predictability on the behavior of the systems, exercise control over the systems, plan more assertive maintenance and, with that, obtain a better use of resources.

Clearly, the expected behavior of the proposed expression was verified using data from the literature, validating the results. The general expression for the reliability of systems operating under the predictive maintenance strategy proved to be effective, fulfilling the objective of this work. The authors suggest the use of the proposed expression to estimate costs associated with the predictive maintenance, providing an effective comparison tool in distinct maintenance strategies.

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