Research on the Inspection Polices of 2-Failure-Mode Systems[1)]

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Abstract In this paper, a two-failure-mode system is discussed. It is assumed that while the system is working in a normal stage, it can enter failure 1 immediately or failure 2 after passing through an abnormal stage. Failure modes are self-announcing modes whereas normal modes and abnormal modes are non-self-announcing modes. While the system is working, it is inspected once every time interval to make sure it is normal or abnormal until it fails, or until the result of inspection is that it is abnormal. The duration of the inspection is a random variable. The reliability indices and the optimal inspection polices of the system are derived by using the density evolution method.

Key words Reliability, inspection, diagnosis

1 Introduction

Many productive systems usually have 2 kinds of failure modes——non-inspectable failure (F_1) and inspectable failure (F_2). Due to its immaturity in skills and expenses, the system is not inspected before F_1 appears. However, the system is inspected before F_2 occurs, and there are 2 stages, normal (N) and abnormal (A), in the working mode of the system. The system can not enter F_2 until it has passed A. A diagnostic parameter may be used to distinguish between N and A, and each inspection consists in measuring the value of the diagnostic parameter. The diagnostic parameter, which is a random variable, has a close relation with the working modes and can be observed easily. For instance, the diagnostic parameters of some electronic equipment include the power, amplitude, frequency, etc.

More than 100 papers have been dedicated to the research of inspection polices since 1963, more than ten of them by Chinese researchers. Inspection polices consist of 2 parts: the first, find out the optimum time interval between two inspections; the second, after getting the inspection results, try to take the most effective measures, such as keeping the system running or just repairing it. By taking these measures, minimum expense and maximum profit will be obtained. In this paper, by using probability analysis and the density evolution method, we studied the system comprehensively and obtained reliability indices and the optimal inspection period and critical value[1~7].

2 Assumptions

1) The system has a kind of inspection mode (I), 2 kinds of failure modes (F_1 and F_2) and 2 kinds of working modes (N and A), where I, F_1 and F_2 are the self-announcing modes whereas N and A are non-self-announcing modes. When the system is in N, it can transfer to F_1 with a constant failure rate λ_1 or to A with λ_{21}. While the system is in A, it can transfer to F_1 with a constant failure rate λ_1 or to F_2 with λ_{22}. As the system is operating, it is inspected once every time interval x_1 to make sure whether it is in N or A until it attains $F_i(i=1,2)$, or until the result of inspection is that the system is in A. The dura-

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tion of the inspection, X_1, is a random variable.

2) Each inspection consists in measuring the value of a diagnostic parameter. The diagnostic parameter, X_2, is a random variable. While the system is in N, c. d. f. of X_2 is $F_1(x)$ and $\int_{-\infty}^{\infty} x\mathrm{d}F_1(x)=\beta_1$; whereas as the system is in A, c. d. f. of X_2 is $F_2(x)$ and $\int_{-\infty}^{\infty} x\mathrm{d}F_2(x)=\beta_2$, where $\beta_1<\beta_2$. Denote x as the measured value of X_2 and x_2 as the critical value.

Diagnostic criterion. If $x\leqslant x_2$, we make the decision that the system is in N, and if $x>x_2$, in A alternately.

Obviously, $p_1=F_1(x_2)/p_2=1-F_2(x_2)$ is the probability that the inspection result is true when the system is in N/A. p_1, $q_1=1-p_1=1-F_1(x_2)$, p_2 and $q_2=1-p_2=F_2(x_2)$ are called accurate diagnostic probability of normal, wrong diagnostic probability of normal, accurate diagnostic probability of abnormal, and wrong diagnostic probability of abnormal, respectively. They are functions of variable x_2.

3) Once the result of inspection is that the system is in A or the system enters $F_i(i=1, 2)$, the system is repaired immediately. The repairs are perfect. The repair time distributions of the system are continuous, and the distribution of $X_i(i=1,2)$ is arbitrary. All random variables are mutually independent. Initially the system is working in N.

4) When the system is in N or A, the expected rewards per unit time generated by the system are R_1 or R_2, respectively. And when the system is in state (5, i) (which is defined below), the expected repair cost every time is E_i, $i=1,2,3,4,5$. The expected cost of each inspection is E_6.

Notations.

- $\bar{\ }$: $\bar{f}=1-f$.
- *: $f^*(s)=\int_0^{\infty} f(t)\exp(-st)\mathrm{d}t$ (Laplace transform).
- (i,j): The states of the system. $i=1$ means that the system is working in N; $i=2$ means that the system is in both N and I; $i=3$ means that the system is working in A; $i=4$ means that the system is in both A and I; $j=n$ means that the system has been inspected n times, $n=0, 1, 2, \cdots$.
- $(5,i)$: The states of the system. 5 means that the system is being repaired. $i=1/2/3/4/5$ means that the system is in F_1 (to which the system transfers from $(1,n)$, $n=0, 1,2,\cdots$)/the system is in F_1 (to which the system transfers from $(3,n)$, $n=0,1,2,\cdots$)/the system is in F_2/the system is in A/the system is in N (but the result of inspection is wrong).
- $h(t)$, $H(t)$, $\alpha(x)$, α^{-1}: $h(t)$ and $\alpha(x)$ are p. d. f. and the failure rate of X_1, respectively, and

$$H(t)=\int_0^t h(x)\mathrm{d}x=1-\exp\left[-\int_0^t \alpha(x)\mathrm{d}x\right],\ \alpha^{-1}=\int_0^{\infty} t\mathrm{d}H(t).$$

- $g_i(t)$, $G_i(t)$, $\mu_i(y)$, μ_i^{-1}: $g_i(t)$ and $\mu_i(y)$ are p. d. f. and the failure rate of the repair time when the system is in $(5,i)$, respectively, and

$$G_i(t)=\int_0^t g_i(y)\mathrm{d}y=1-\exp\left[-\int_0^t \mu_i(y)\mathrm{d}y\right],\ \mu_i^{-1}=\int_0^{\infty} t\mathrm{d}G_i(t),\ i=1,2,3,4,5.$$

- $P_{ij}(t,x)$: p. d. f. (with respect to x_1) that the system is in (i,j) and has an elapsed x_1 of x, $i=1,3$; 1, 2, $\cdots$.
- $P_{ij}(t;z)$: p. d. f. (with respect to X_1) that the system is in (i,j) and has an elapsed X_1 of z, $i=2, 4$; $j=0, 1, 2, \cdots$.
- $P_{5j}(t,y)$: p. d. f. (with respect to repair time) that the system is in $(5,j)$ and has an elapsed repair time of y, $j=1, 2, 3, 4, 5$.
- s_i,λ_{12i}: $s_1=s+\lambda_1+\lambda_{21}$, $s_2=s+\lambda_1+\lambda_{22}$, $\lambda_{121}=\lambda_1+\lambda_{21}$, $\lambda_{122}=\lambda_1+\lambda_{22}$.
- e_i, e_{i0}: $e_i=\exp[-(s+\lambda_1+\lambda_{2i})x_1]$, $e_{i0}=\exp[-(\lambda_1+\lambda_{2i})x_1]$, $i=1,2$.

3 State probabilities

The possible states of the system and the transitions among them are shown in Fig. 1. Using the method in [2,4~7], we can get the state probabilities of the system in terms of the Laplace transform as follows:

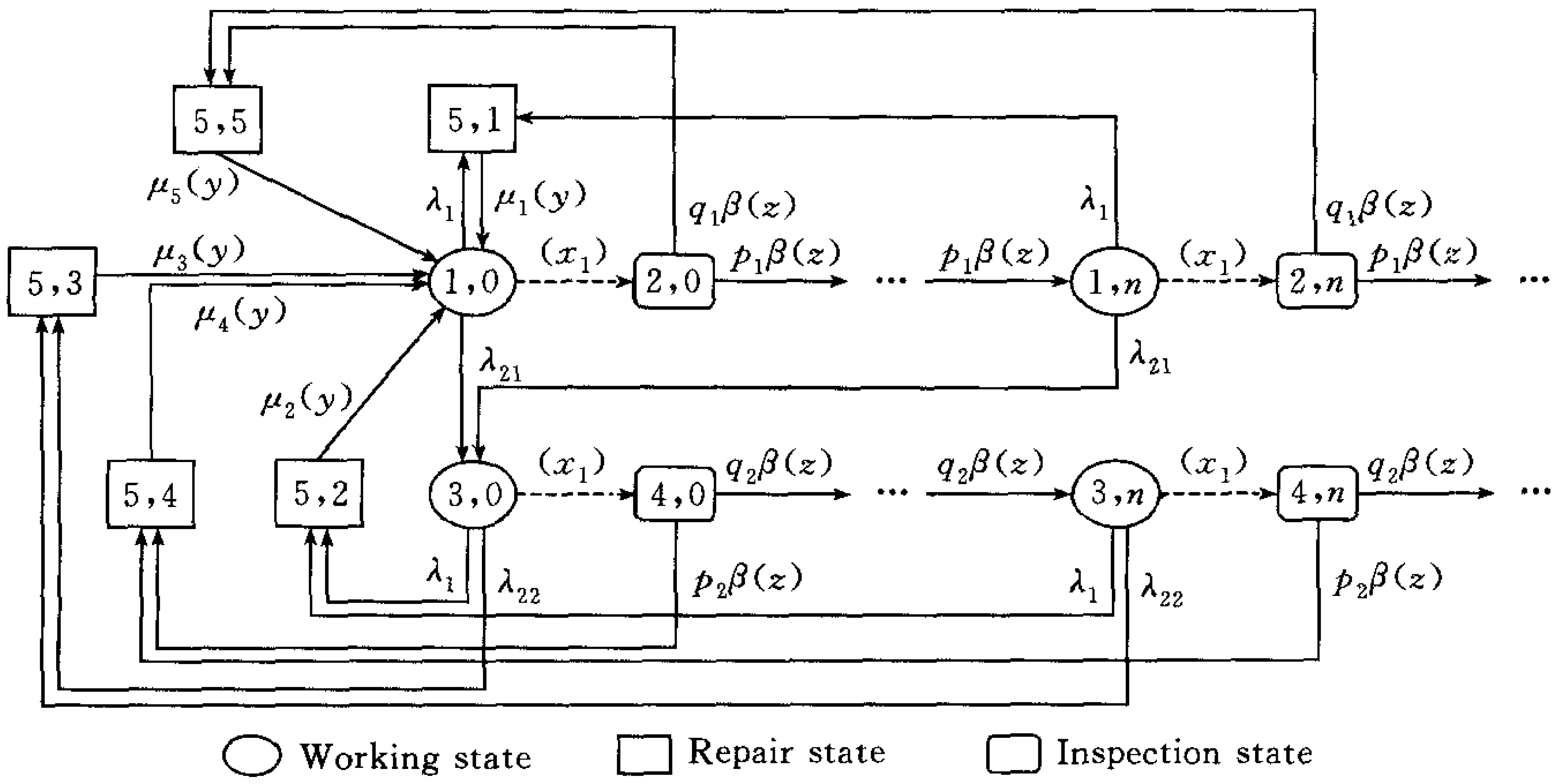

Fig. 1 Transition diagram

$$\sum_{n=0}^{\infty} P_{1n}^{*}(s,x) = (\lambda_{22} - \lambda_{21})[1 - q_2 h^{*}(s)e_2] \exp(-s_1 x)/B(s),\ 0 \leqslant x \leqslant x_1 \tag{1}$$

$$\sum_{n=0}^{\infty} P_{2n}^{*}(s,z) = (\lambda_{22} - \lambda_{21})e_1[1 - q_2 h^{*}(s)e_2]\overline{H}(z) \exp(-sz)/B(s) \tag{2}$$

$$\sum_{n=0}^{\infty} P_{3n}^{*}(s,x) = \lambda_{21}\{[1 - q_2 h^{*}(s)e_2] \exp(-s_1 x) - [1 - q_2 h^{*}(s)e_1] \exp(-s_2 x)\}/B(s),\quad 0 \leqslant x \leqslant x_1 \tag{3}$$

$$\sum_{n=0}^{\infty} P_{4n}^{*}(s,z) = \lambda_{21}(e_1 - e_2)\overline{H}(z) \exp(-sz)/B(s) \tag{4}$$

$$P_{51}^{*}(s,y) = \lambda_1(\lambda_{22} - \lambda_{21})s_1^{-1}(1 - e_1)[1 - q_2 h^{*}(s)e_2]\overline{G}_1(y) \exp(-sy)/B(s) \tag{5}$$

$$P_{52}^{*}(s,y) = \lambda_1\lambda_{21}\{s_1^{-1}(1 - e_1)[1 - q_2 h^{*}(s)e_2] - s_2^{-1}(1 - e_2)[1 - q_2 h^{*}(s)e_1]\}\overline{G}_2(y) \exp(-sy)/B(s) \tag{6}$$

$$P_{53}^{*}(s,y) = \lambda_{21}\lambda_{22}\{s_1^{-1}(1 - e_1)[1 - q_2 h^{*}(s)e_2] - s_2^{-1}(1 - e_2)[1 - q_2 h^{*}(s)e_1]\}\overline{G}_3(y) \exp(-sy)/B(s) \tag{7}$$

$$P_{54}^{*}(s,y) = p_2\lambda_{21}h^{*}(s)(e_1 - e_2)\overline{G}_4(y) \exp(-sy)/B(s) \tag{8}$$

$$P_{55}^{*}(s,y) = q_1(\lambda_{22} - \lambda_{21})h^{*}(s)e_1[1 - q_2 h^{*}(s)e_2]\overline{G}_5(y) \exp(-sy)/B(s) \tag{9}$$

where

$$\begin{aligned} B(s) = {} & (\lambda_{22} - \lambda_{21})[1 - p_1 h^{*}(s)e_1][1 - q_2 h^{*}(s)e_2] - \\ & \lambda_1(\lambda_{22} - \lambda_{21})s_1^{-1}(1 - e_1)[1 - q_2 h^{*}(s)e_2]g_1^{*}(s) - \\ & \lambda_1\lambda_{21}\{s_1^{-1}(1 - e_1)[1 - q_2 h^{*}(s)e_2] - s_2^{-1}(1 - e_2)[1 - q_2 h^{*}(s)e_1]\}g_2^{*}(s) - \\ & \lambda_{21}\lambda_{22}\{s_1^{-1}(1 - e_1)[1 - q_2 h^{*}(s)e_2] - s_2^{-1}(1 - e_2)[1 - q_2 h^{*}(s)e_1]\}g_3^{*}(s) - \\ & p_2\lambda_{21}h^{*}(s)(e_1 - e_2)g_4^{*}(s) - \\ & q_1(\lambda_{22} - \lambda_{21})h^{*}(s)e_1[1 - q_2 h^{*}(s)e_2]g_5^{*}(s) \end{aligned} \tag{10}$$

4 Reliability indices of the system

According to the assumptions of the system and the definitions of reliability indices, using Fig. 1 we can get reliability indices of the system.

4.1 N-availability and A-availability

The probability that the system is working in N is called N-availability, whereas the probability that the system is working in A is called A-availability. Denoting $A_1(t)$ and $A_2(t)$ as the instantaneous N-availability and A-availability at time t, respectively, we obtain

$$A_1(t) = \sum_{n=0}^{\infty}\int_0^{x_1} P_{1n}(t,x)\mathrm{d}x, \quad A_2(t) = \sum_{n=0}^{\infty}\int_0^{x_1} P_{3n}(t,x)\mathrm{d}x.$$

Taking the Laplace transforms on both sides of the above Equations and using Equations (1~10), we have

$$A_1^*(s) = (\lambda_{22}-\lambda_{21})s_1^{-1}(1-e_1)[1-q_2h^*(s)e_2]/B(s) \quad (11)$$

$$A_2^*(s) = \lambda_{21}\{[1-q_2h^*(s)][s_1^{-1}(1-e_1)-s_2^{-1}(1-e_2)] + q_2(\lambda_{22}-\lambda_{21})h^*(s)s_1^{-1}s_2^{-1}(1-e_1)(1-e_2)\}/B(s) \quad (12)$$

where $B(s)$ is given by Equation (10).

Let A_1 and A_2 represent the steady state N-availability and A-availability, respectively. By applying the limiting theorem of the Laplace transform, we get

$$A_1 = \lim_{t\to\infty}A_1(t) = \lim_{s\to 0}sA_1^*(s) = (\lambda_{22}-\lambda_{21})\lambda_{122}(1-e_{10})(1-q_2e_{20})/B \quad (13)$$

$$A_2 = \lambda_{21}[p_2\lambda_{122}(1-e_{10}) - p_2\lambda_{121}(1-e_{20}) + q_2(\lambda_{22}-\lambda_{21})(1-e_{10})(1-e_{20})]/B \quad (14)$$

where

$$\begin{aligned}B = {} & p_2(\lambda_{22}-\lambda_{21})\lambda_{121}\lambda_{122}\beta^{-1} + \lambda_{122}[p_2\lambda_{22} - \lambda_{121}(q_2\lambda_{21}+p_2\lambda_{22})\beta^{-1}](1-e_{10}) + \\ & \lambda_{121}[-p_2\lambda_{21} + \lambda_{122}(p_2\lambda_{21}+q_2\lambda_{22})\beta^{-1}](1-e_{20}) + \\ & q_2[\lambda_{22}\lambda_{122} - \lambda_{21}\lambda_{121} - (\lambda_{22}-\lambda_{21})\lambda_{121}\lambda_{122}\beta^{-1}](1-e_{10})(1-e_{20}) + \\ & \lambda_1(\lambda_{22}-\lambda_{21})\lambda_{122}(1-e_{10})(1-q_2e_{20})\mu_1^{-1} + \\ & \lambda_1\lambda_{21}[p_2\lambda_{122}(1-e_{10}) - p_2\lambda_{121}(1-e_{20}) + q_2(\lambda_{22}-\lambda_{21})(1-e_{10})(1-e_{20})]\mu_2^{-1} + \\ & \lambda_{21}\lambda_{22}[p_2\lambda_{122}(1-e_{10}) - p_2\lambda_{121}(1-e_{20}) + q_2(\lambda_{22}-\lambda_{21})(1-e_{10})(1-e_{20})]\mu_3^{-1} + \\ & p_2\lambda_{21}\lambda_{121}\lambda_{122}(e_{10}-e_{20})\mu_4^{-1} + q_1(\lambda_{22}-\lambda_{21})\lambda_{121}\lambda_{122}e_{10}(1-q_2e_{20})\mu_5^{-1}\end{aligned} \quad (15)$$

4.2 F_1N-failure frequency and F_1A-failure frequency

It is defined that the system is in F_1 N-failure if and only if it is in state (5, 1) whereas the system is in F_1 A-failure if and only if it is in state (5, 2). Denoting $W_1(t)$ and $W_2(t)$ as the instantaneous F_1 N-failure frequency and F_1 A-failure frequency at time t, respectively, from Fig. 1 we can obtain

$$W_1(t) = \sum_{n=0}^{\infty}\int_0^{x_1}\lambda_1 P_{1n}(t,x)\mathrm{d}x, \quad W_2(t) = \sum_{n=0}^{\infty}\int_0^{x_1}\lambda_1 P_{3n}(t,x)\mathrm{d}x.$$

Taking the Laplace transforms on both sides of the above Equation, we have

$$W_1^*(s) = \lambda_1(\lambda_{22}-\lambda_{21})s_1^{-1}(1-e_1)[1-q_2h^*(s)e_2]/B(s) \quad (16)$$

$$W_2^*(s) = \lambda_1\lambda_{21}\{[1-q_2h^*(s)]s_1^{-1}(1-e_1) - [1-q_2h^*(s)]s_2^{-1}(1-e_2) + q_2h^*(s)(\lambda_{22}-\lambda_{21})s_1^{-1}s_2^{-1}(1-e_1)(1-e_2)\}/B(s) \quad (17)$$

Let M_1 and M_2 represent the steady state F_1 N-failure frequency and F_1 A-failure frequency, respectively. Then

$$M_1 = \lambda_1(\lambda_{22}-\lambda_{21})\lambda_{122}(1-e_{10})(1-q_2e_{20})/B \quad (18)$$

$$M_2 = \lambda_1\lambda_{21}[p_2\lambda_{122}(1-e_{10}) - p_2\lambda_{121}(1-e_{20}) + q_2(\lambda_{22}-\lambda_{21})(1-e_{10})(1-e_{20})]/B \quad (19)$$

where B is given by Equation (15).

4.3 F_2-failure frequency and A-repair frequency

It is defined that the system is in F_2-failure if and only if it is in state (5, 3), whereas the system is in A-repair if and only if it is in state (5, 4). Denoting $W_3(t)$ and $W_4(t)$ as the instantaneous F_2-failure frequency and A-repair frequency at time t, respectively, from Fig. 1 we can obtain

$$W_3^*(s) = \lambda_{21}\lambda_{22}\{[1-q_2h^*(s)]s_1^{-1}(1-e_1) - [1-q_2h^*(s)]s_2^{-1}(1-e_2) + q_2h^*(s)(\lambda_{22}-\lambda_{21})s_1^{-1}s_2^{-1}(1-e_1)(1-e_2)\}/B(s) \quad (20)$$

$$W_4^*(s) = p_2\lambda_{21}h^*(s)(e_1 - e_2)/B(s) \tag{21}$$

Let M_3 and M_4 represent the steady state F_2-failure frequency and A-repair frequency, respectively. Then

$$M_3 = \lambda_{21}\lambda_{22}[p_2\lambda_{122}(1-e_{10}) - p_2\lambda_{121}(1-e_{20}) + q_2(\lambda_{22}-\lambda_{21})(1-e_{10})(1-e_{20})]/B \tag{22}$$

$$M_4 = p_2\lambda_{21}\lambda_{121}\lambda_{122}(e_{10} - e_{20})/B \tag{23}$$

4.4 N-repair frequency and inspection frequency

While the system is working, it is inspected once every time interval x_1 to make sure whether it is in N or A. When the system is working in N but inspection result is wrong, it should be repaired (or tested perfectly). The repair taken on the system in N is called N-repair, that is, the system is in N-repair if and only if it is in state (5, 5). As the system is in state (i, n) $(i=2,4;\ n=0,1,2,\cdots)$, it is being inspected. Denote $W_5(t)$ and $W_6(t)$ as the instantaneous N-repair frequency and inspection frequency at time t, respectively. By the definitions of $W_5(t)$ and $W_6(t)$, we obtain

$$W_5^*(s) = q_1(\lambda_{22}-\lambda_{21})h^*(s)e_1[1 - q_2h^*(s)e_2]/B(s) \tag{24}$$

$$W_6^*(s) = [\lambda_{22}e_1 - \lambda_{21}e_2 - q_2(\lambda_{22}-\lambda_{21})h^*(s)e_1e_2]/B(s) \tag{25}$$

Let M_5 and M_6 represent the steady state N-repair frequency and inspection frequency, respectively. Then

$$M_5 = q_1(\lambda_{22}-\lambda_{21})\lambda_{121}\lambda_{122}e_{10}(1-q_2e_{20})/B \tag{26}$$

$$M_6 = \lambda_{121}\lambda_{122}[\lambda_{22}e_{10} - \lambda_{21}e_{20} - q_2(\lambda_{22}-\lambda_{21})e_{10}e_{20}]/B \tag{27}$$

where B is given by Equation (15).

5 Optimal inspection policy

We are now in a position to obtain the profit function of the system by using the results obtained above. The expected total profits generated by the system during $(0, t]$ are

$$L(t) = R_1\int_0^t A_1(x)\mathrm{d}x + R_2\int_0^t A_2(x)\mathrm{d}x - \sum_{i=1}^{6}E_i\int_0^t W_i(x)\mathrm{d}x \tag{28}$$

Taking the Laplace transforms on both sides of (28), we have

$$L^*(s) = \left[R_1A_1^*(s) + R_2A_2^*(s) - \sum_{i=1}^{6}E_iW_i^*(s)\right]/s \tag{29}$$

Applying the limiting theorem of the Laplace transform, from Equation (29) we can search out the expected profits per unit time in the steady state:

$$L = \lim_{t\to\infty}L(t)/t = \lim_{s\to 0}s^2L^*(s) = R_1A_1 + R_2A_2 - \sum_{i=1}^{6}E_iM_i \tag{30}$$

where A_1, A_2, $M_i(i=1,2,3,4,6)$ and B are given by (13), (14), (18), (19), (22), (26), (27), (28) and (15), respectively. L is called the profit function of the system. Taking suitable values for the parameters to make L maximum is the optimal inspection policy.

According to the characteristics of the system, we have

$$p_1 = F_1(x_2),\ q_1 = 1 - F_1(x_2),\ p_2 = 1 - F_2(x_2),\ q_2 = F_2(x_2) \tag{31}$$

$$e_{i0} = \exp[-(\lambda_1 + \lambda_{2i})x_1],\ i = 1,2 \tag{32}$$

Substituting (31) and (32) into (30), the profit function L could be expressed as a function of two variables (x_1 and x_2), that is, $L=L(x_1, x_2)$. Using the analytical or numerical method, we can get the optimal inspection period and critical value $(x_1^{\#}, x_2^{\#})$, which make $L=L(x_1, x_2)$ maximum.

Numerical example.

Calculations are carried out using the following input data:

$\lambda_1 = 1/2470$, $\lambda_{21} = 1/1560$, $\lambda_{22} = 1/115$, $\beta^{-1} = 6$,

$\mu_1^{-1} = 60$, $\mu_2^{-1} = 66$, $\mu_3^{-1} = 156$, $\mu_4^{-1} = 21$, $\mu_5^{-1} = 9$,

$$R_1 = 1320,\quad R_2 = 1260,\quad E_1 = 4730,\quad E_2 = 12200,$$
$$E_3 = 399100,\quad E_4 = 10300,\quad E_5 = 1990,\quad E_6 = 380.$$

Let us assume that X_2 is $N(51, 12^2)$ when the system is in N, whereas X_2 is $N(83, 16^2)$ when the system is in A. With a microcomputer, from Equation (30) we can obtain the optimal inspection period and critical value, $(x_1^{\#}, x_2^{\#}) = (97.82, 65.23)$, and the maximum expected profits per unit time in the steady state $L(x_1^{\#}, x_2^{\#}) = L(97.82, 65.23) = 1064.59$.

6 Conclusion

This paper deals with the optimal inspection policies for a 2-failure-mode system whose modes can be known only through inspection. By using probability analysis and the density evolution method, the reliability indices and the optimal inspection period and critical value were obtained, which makes the expected profits per unit time generated by the system in the steady state maximum. The numerical example is served for demonstrating the feasibility of the method.

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2 类故障系统的检测策略研究

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摘 要 研究具有 2 类故障的可修系统的一个模型，假定系统工作时可能直接发生第 1 类故障，也可能经过异常后发生第 2 类故障. 系统故障时不需检测，系统工作时必须经过检测才能知道它是正常还是异常，并且检测时间是一个随机变量. 系统开始工作后，每隔一段时间对它检测一次，直到系统故障或者检测结果是系统处于异常状态为止. 利用密度演化方法，求出了系统的可靠性指标和最优检测策略.

关键词 可靠性，检测，诊断

中图分类号 TP202$^+$.1, N945.17, O213.2