Numerical Solution of Integral Equations for Reliability Quantification

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Key Words—Failure and repair intensities, Integral equation.

Reader Aids—
Purpose: Report a mathematical technique
Special math needed for explanations: Advanced probability, Advanced numerical analysis
Special math needed to use results: Same
Results useful to: Reliability theoreticians

Abstract—This paper gives a numerical method for solving a linear system of integral equations whose solution is the set of unconditional failure and repair intensities of a component, where the component life and repair times are arbitrarily distributed. Our method gives a sequence of solutions that converges to the true solution of the system of integral equations. An example illustrates our method.

1. INTRODUCTION

Fault tree analysis is a widely used technique for evaluating the reliability and safety of complex systems. The methods by Vesely [1] and Inagaki & Henley [2] can perform rigorous probabilistic evaluation of top-events for s-coherent and non-coherent systems, respectively. Both of these methods assume that unconditional failure and repair intensities of relevant components in the system are known.

The unconditional failure and repair intensities of a component are given as solutions to a linear system of integral equations [3, p 193] that is difficult to solve analytically except when the component life and repair times are exponentially distributed. This paper gives a numerical method for solving the linear system of integral equations when the component life and repair times are arbitrarily distributed. A sequence of solutions obtained by our method converges to the true solution of the integral equations. This paper uses a rather abstract mathematics in developing the theory of our method of solution. In executing our approach, however, we only have to solve a matrix equation. A conventional method such as Gauss-Seidel directly applies to solve the matrix equation.

2. NOTATION, NOMENCLATURE, AND ASSUMPTIONS

Notation

E_0 event that the component was up and new at the initial time ($t = 0$)

$w(t)$ unconditional failure intensity of the component; viz, $w(t) = \lim_{dt \to 0} \frac{1}{dt} \Pr\{\text{component is up at time } t \text{ and fails in } (t, t + dt) | E_0\}$

$v(t)$ unconditional repair intensity of the component; viz. $v(t) = \lim_{dt \to 0} \frac{1}{dt} \Pr\{\text{component is under repair at time } t \text{ and the repair completes in } (t, t + dt) | E_0\}$

X_i random length of working period i of the component

Y_i random length of repair period i of the component

$f(t), F(t)$ common pdf, Cdf for X_i

$g(t), G(t)$ common pdf, Cdf for Y_i

A_a Volterra operator; defined in the text

I identity operator such that $I\{a(t)\} = a(t)$; or identity matrix

$C[0, T]$ Banach space of real-valued functions that are continuous on the interval $[0, T]$

P_n bounded linear projections, ie, $P_n^2 = P_n$, of $C[0, T]$ onto n-dimensional subspace S_n of $C[0, T]$

$\{e_i(t): i = 1, ..., n\}$ basis for n-dimensional subspace S_n; viz, $P_n z \in S_n$ for $z \in C[0, T]$, and $P_n z$ is represented as $P_n z = e_1^*(z)e_1(t) + ... + e_n^*(z)e_n(t)$

$e_i^*(z)$ the $e_i(t)$-component of $P_n z$ when $P_n z$ is expanded as a linear combination of $e_1(t), ..., e_n(t)$

$|\cdot|$ norm; vector norm and matrix norm are defined in the text

$\text{col}(x_1, ..., x_n)$ n-dimensional column vector with elements $x_1, ..., x_n$

δ_{ij} Kronecker delta; viz, $\delta_{ij} = 1$ for $i = j$, $\delta_{ij} = 0$ for $i \neq j$

F_n $n \times n$ matrix with $e_i^* A_f e_j$ as its (i, j)-element

G_n $n \times n$ matrix with $e_i^* A_g e_j$ as its (i, j)-element

c, d $c = \text{col}(c_1, ..., c_n)$, $d = \text{col}(d_1, ..., d_n)$

h $\text{col}(e_1^* f, ..., e_n^* f)$

λ, μ constant failure and repair rates

Nomenclature

spectral radius — Let $\varrho_i (i = 1, ..., n)$ be eigenvalues of an $n \times n$ matrix A. The spectral radius $\varrho(A)$ of matrix A is $\varrho(A) = \max\{|\varrho_i| : i = 1, ..., n\}$

acceleration parameter — parameters that are chosen to make the convergence interative process rapid

Assumptions

1. The component starts working at the initial time ($t = 0$). The component is perfect (up and new) at $t = 0$.
2. Repair begins immediately upon failure of the component.

Numerical Solution Of Integral Equations

Mike Jess

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