Reliability Analysis for Multiple Dependent Failure Processes: An MEMS Application

QIANMEI FENG* and DAVID W. COIT

*Department of Industrial Engineering, University of Houston, Houston, TX, USA
bDepartment of Industrial & Systems Engineering, Rutgers University, Piscataway, NJ, USA

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Abstract: Widespread acceptance of micro-electro-mechanical systems (MEMS) depends highly on their reliability, both for large-volume commercialization and for critical applications. The problem of multiple dependent failure processes is of particular interest to MEMS researchers. For MEMS devices subjected to both wear degradation and random shocks that are dependent and competing, we propose a new reliability model based on the combination of random-shock and degradation modeling. The models developed in this research can be applied directly or customized for most current and evolving MEMS designs with multiple dependent failure processes.

Keywords: MEMS reliability, degradation, random shocks, dependent competing failure processes

1. Introduction

The prime focus of micro-electro-mechanical systems (MEMS) development has been on the functionality, manufacturing and implementation of these devices. Less consideration has been given to reliability for larger production quantities over longer usage times. MEMS reliability research becomes increasingly important to achieve widespread acceptance of such technologies, both for large-volume commercialization and for critical applications. MEMS reliability problems are challenging since each device has its own unique failure modes and mechanisms [1]. Previous studies in MEMS reliability focused on deterministic models for specific failure mechanisms and physical analysis of failed MEMS devices [2]. Well-developed probabilistic models for MEMS are required by leveraging the expertise from quality and reliability professionals.

Failure of MEMS may arise from forces generated by the devices themselves or from external sources. Common MEMS failure mechanisms and causes are identified as wear degradation, stiction, shock loads, fatigue, etc [3]. The problem of multiple dependent failure processes is of particular interest to MEMS researchers, as it is a critical problem that MEMS have experienced in the field. For MEMS devices subjected to multiple dependent failure processes including both the wear degradation process and random shocks, we propose a new probability model based on the combination of random-shock and degradation modeling. Although some studies have developed reliability models for degradation and random shock [4-6], no existing research has investigated the case when these two failure processes are dependent and competing, especially for MEMS reliability. The models developed in this research can be applied directly or customized for most current and evolving MEMS designs with multiple dependent failure processes.

*Corresponding author’s email: qmfeng@uh.edu
2. Modeling of Multiple Dependent Failure Processes

According to the reliability tests conducted by Sandia National Laboratories [7], a micro-actuator system may fail due to two competing yet dependent failure processes: (1) catastrophic failures caused by extreme shocks from a random shock process, and (2) soft failures caused by wear degradation and cumulative wear damages from the same random shock process. The system fails when either of the two failure processes reaches its threshold value. These two competing failure processes are dependent in a way that the same random shock process impacts both cumulative wear damage and catastrophic failures.

Hard/catastrophic failure occurs when the shock load/stress exceeds the maximal fracture strength $D$, according to an extreme shock model [7]. Random shocks arrive according to a Poisson process $\{N(t), t \geq 0\}$ with rate $\lambda$. As shown in Fig. 1 (bottom), shock loads arriving at $t_1$, $t_2$, ..., $t_n$ are denoted as $\{W_1, W_2, ..., W_n\}$, which are assumed to be i.i.d. random variables distributed as a normal distribution, $W_i \sim N(\mu_w, \sigma_w^2)$. The mean of $W_i$ is relatively much larger than the standard deviation, such that the negative portion of the normal distribution is negligible. The device experiences a hard failure when the applied stress exceeds the fracture strength $D$. For each shock, the probability that the device survives the applied stress is $L_i = \Phi\left(\frac{D - \mu_w}{\sigma_w}\right)$.

Soft failure occurs when the overall wear volume is beyond a threshold value $H$. The wear degradation paths $X_s(t)$ are illustrated in Fig. 1 (top), which results from both aging degradation and instantaneous damages (in the form of debris) due to random shocks, according to a cumulative shock model [5]. The aging wear process follows a linear degradation path $X(t) = \phi + \beta t$ [8,9]. Every random shock during operation causes an instantaneous step increase on the wear volume, measured by the shock damage sizes $\{Y_1, Y_2, ..., Y_n\}$ that are assumed to be random i.i.d. variables. The cumulative damage size due to random shocks until time $t$, $S(t)$, is given as $S(t) = \sum_{i=1}^{N(t)} Y_i$, if $N(t) > 0$. Therefore, $X(t) = X(t) + S(t)$, and the cumulative distribution function (cdf) of $X(t)$ can be derived as

$$F_X(x, t) = P(\phi + \beta t + S(t) < x) = \sum_{n=0}^{N(t)} P(\phi + \beta t + S(t) < x | N(t) = n) P(N(t) = n).$$

Consider the two dependent competing failure processes, the system reliability function can be expressed as

$$R(t) = \sum_{n=0}^{N(t)} L^n S^n X(t) + S(t) < H | N(t) = n) P(N(t) = n).$$

If the distribution of shock damage sizes $\{Y_1, Y_2, ..., Y_n\}$ are i.i.d. normal random variables, $Y_i \sim N(\mu_y, \sigma_y^2)$, and $\beta$ follows a normal distribution, $\beta \sim N(\mu_\beta, \sigma_\beta^2)$, then the reliability function can be further derived as [10]
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\[ R(t) = \sum_{n=1}^{\infty} P_n \Phi \left( \frac{H - (\mu_p + \phi + n\mu_\lambda)}{\sqrt{\sigma_p^2 + n\sigma_\lambda^2}} \right) \frac{\exp(-\lambda t)(\lambda t)^{n}}{n!} + \Phi \left( \frac{H - \mu_p - \theta}{\sigma_p} \right) \exp(-\lambda t). \]

3. Conclusions

We studied the reliability model for MEMS subjected to multiple dependent failure processes. These failure processes include instantaneous wear damages and catastrophic failures caused by random shocks, as well as aging wear degradation process. The reliability model developed in this research can then be used to study maintenance policies and other reliability decisions.

References


Qianmei (May) Feng is an Assistant Professor in the Department of Industrial Engineering at the University of Houston. Her research has been in reliability & quality engineering, and applications in manufacturing and healthcare systems.

David W. Coit is an Associate Professor in the Department of Industrial & Systems Engineering at Rutgers University. His research involves reliability prediction & optimization, risk analysis, and multi-criteria optimization considering uncertainty.