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Accelerated reliability demonstration under competing failure modes

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ABSTRACT

The conventional reliability demonstration tests are difficult to apply to products with competing failure modes due to the complexity of the lifetime models. This paper develops a testing methodology based on the reliability target allocation for reliability demonstration under competing failure modes at accelerated conditions. The specified reliability at mission time and the risk caused by sampling of the reliability target for products are allocated for each failure mode. The risk caused by degradation measurement fitting of the target for a product involving performance degradation is equally allocated to each degradation failure mode. According to the allocated targets, the accelerated life reliability demonstration test (ALRDT) plans for the failure modes are designed. The accelerated degradation reliability demonstration test plans and the associated ALRDT plans for the degradation failure modes are also designed. Next, the test plan and the decision rules for the products are designed. Additionally, the effects of the discreteness of sample size and accepted number of failures for failure modes on the actual risks caused by sampling for the products are investigated.

1. Introduction

The reliability demonstration tests (RDTs) are suited for demonstrating the conformance of reliability measurements (i.e., MTBF, failure rate, reliability at mission time) to the specified reliability targets, which are determined by the requirements set in the design and development phase as well as in the production phase. The RDT, in combination with a test plan (also known as the variable sampling plan) and the decision rules, is concerned with either the acceptance or rejection of products based on the data from the test.

The literature on RDT can be classified according to the lifetime distribution assumed, the censoring scheme, the test condition, and the test data for decision-making. Exponential [1–8] and Weilbull [7–18] distributions are commonly employed to describe the statistical properties of life data in RDT. Time-censoring (Type-I censoring) instead of failure-censoring (Type-II censoring) is commonly adopted in RDT because many tests are conducted under time constraints. The test can be conducted either under the use or accelerated condition. Additionally, the prior knowledge can be utilized to design the test plan [5,12,18,19]. In many studies, only the life data are utilized for decision-making, but the performance degradation data can also be used to make decisions.

Because of the marketplace demands for decreased development time and cost, accelerated life testing (ALT) has been widely adopted in RDT to reduce test time, which is termed accelerated life reliability demonstration test (ALRDT). The literature on ALRDT mainly differs in terms of the censoring scheme and whether the parameters of the acceleration model and the shape parameter of the Weibull distribution are known [20–25]. This paper primarily focuses on time-censored ALRDT. Cui [21] proposed a test plan of time-censored ALRDT for a Weibull distribution with a known acceleration factor and shape parameter, and applied this test plan to demonstrate the reliability target of an electronic connector for space use. Kim and Yum [22] provided a plan for time-censored ALRDT using a Weibull distribution with unknown shape and scale parameters, but with known acceleration factor. Seo et al. [23] focused on the test plan for time-censored simple constant-stress ALT with a non-constant shape parameter, and the test plan depended on the initial estimates of the parameters of accelerated model. Turner [24] explored a reliability demonstration approach with quantitative accelerated life testing for power systems that was suitable for platform design and derived design with known and unknown acceleration factors, respectively. Bris [25] presented an optimum test plan with accelerated conditions using a Bayesian approach for exponential distribution.

For products whose performances degrade over time, it is possible to measure these performances during the test. These degradation measurements can be used to predict whether the test unit will fail at

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the censoring time. Consequently, the test duration is further reduced. Sohn and Jang [26] analyzed the degradation data of keyboards through an acceptance sampling test. Yang [27] discussed how to design an optimum test plan for the degradation bogey test (also known as zero-failure testing) to demonstrate the reliability target; this approach considered the risks caused by sampling and degradation measurement fitting. The optimum plan depended on prior knowledge of the degradation model parameters. However, the use of degradation testing instead of accelerated degradation testing was considered and the producer's risk caused by sampling required was not considered. Luo et al. [28] extended Yang's work to the accelerated condition with unknown model parameters in the plan design, where the method of two steps accelerated reliability demonstration test (TSARDT) was proposed. In [28], both the producer's and consumer's risks caused by sampling were considered and the risks caused by degradation measurement fitting were defined and formatted for the case in which the acceptable number of failures is larger than zero. Baussaron et al. [29] described an approach to designing the degradation demonstration test plan under the accelerated condition using the Wiener process. However, the uncertainty caused by the degradation extrapolation was not considered as part of the risk.

All the above studies for RDT can only be applied to products with single failure mode. However, competing failure mode situations occur frequently in engineering [30–35]. For example, Nelson [30] analyzed the data from ALT of the Class-H insulation system in motorettes subjected to three failure modes, namely Turn, Phase, and Ground failures. Tan [31] assessed the storage reliability of a safety valve under competing failure modes, which involved the performance degradation of compressed springs and O-rings. Huang and Askin [32] analyzed an electronic device with two types of major failure modes, including solder/Cu pad interface fracture (a failure mode) and light intensity degradation (a degradation failure mode). Very few studies exist on the reliability demonstration of products with competing failure modes. One exception is given by Balasooriya and Low [15] who provided a conservative Type-I progressively censored test plan of the RDT for multiple Weibull failure modes with equal scale parameters. However, the performance degradation data are not considered in the test plan design and the test is conducted under the use condition instead of the accelerated condition. Accelerated testing and degradation measurements may allow further reduction in the test time and effort, which are very useful and necessary for the cases that the mission time of the reliability target is very long under the use condition. Additionally, this study cannot solve the problem of multiple Weibull failure modes with different parameters. In fact, all the methods of RDT for products with single failure mode are based on a specified type of lifetime distribution. Thus, it is impossible to accomplish the reliability demonstration for products with competing failure modes directly by those methods because the lifetime distribution of the products with competing failure modes will not follow a specified distribution when the lifetime distributions of failure modes are different.

In this paper, accelerated reliability demonstration plans under competing failure modes are developed. The reliability target of the products is first allocated to each failure mode, and according to these allocations, the plan for each failure mode under the accelerated condition is designed. Then, the test plan and the decision rules for the products are obtained. The method of reliability target allocation proposed in the paper differs from the method adopted in the design and development phase of a product life cycle. In the design and development phase, depending on the degree of complexity associated with each element, the reliability targets are assigned to each element using the reliability model, thereby achieving a specified reliability target for the system [36–38]. However, this method cannot be applied to accomplish the reliability target allocation for products with competing failure modes because the risks required by the producer and the consumer cannot be considered. In this paper, the reliability target of the products, including the specified reliability at mission time as well as the risk caused by sampling, is allocated to each failure mode. The required risk caused by degradation measurement fitting of the target to the product involving the performance degradation is equally allocated to each degradation failure mode.

The competing failure model is first given. The accelerated reliability demonstration test plans are then developed, which are illustrated through case study. Additionally, error analysis is conducted. Finally, conclusions are presented.

2. Competing failures model

(1) A product experiences l failure modes simultaneously. All of the failure modes are independent of each other.
(2) For the failure mode, the failure time can be observed; for the degradation failure mode, the performance characteristic degrades over the life span, and the failure occurs when the performance crosses its threshold for the first time.
(3) The lifetime of the products is perceived to be the time to failure of a series system with l s-independent components, where component x represents the xth failure mode with failure time T_x for $x = 1, 2, \ldots, l$. The product life T_s is the minimum of these failure times; that is, $T_s = \min\{T_1, T_2, \ldots, T_l\}$.
(4) In many cases, the Weibull distribution is used to describe the statistical properties of the failure data, then $T_x \sim \text{Weibull}(\eta_x, \delta_x)$, η_x and δ_x denote the scale and the shape parameters for the xth failure mode. η_x is often a log linear function of a (possibly transformed) stress. And for the xth failure mode, the acceleration factor a_x is equal to $\eta_{0,x}/\eta_{a,x}$, where $\eta_{0,x}$ and $\eta_{a,x}$ are the scale parameters at use and accelerated stress respectively, and δ_x is constant and independent of stress.
(5) If a unit fails due to a failure mode, the test is terminated. Thus, the degradation processes for the degradation failure modes and the failure data for the other failure modes of the unit cannot be observed; however, if a unit fails due to a degradation failure mode, the test can be continued to observe the failure data or the degradation process for the other failure modes until the unit fails.

3. Design of accelerated reliability demonstration test plans

3.1. Reliability target for the product

Let $R_0^*(t_s)$ and $R_1^*(t_s)$ with the corresponding risks α and β denote the reliability target for the product required by the producer and the consumer, respectively, where t_s is the specified mission time under the use condition. The total risk required by the producer α comprises two parts: (1) the risk caused by sampling α_s; (2) the risk caused by degradation measurement fitting α_c, $\alpha = \alpha_s + \alpha_c$; as well as the total risk required by the consumer β is equal to $\beta_s + \beta_c$, β_s and β_c are the required consumer's risks caused by sampling and degradation measurements fitting, respectively. For the case that the product is only exposed to failure mode(s), the risk in the life test is only caused by sampling, then $\alpha_c = \beta_c = 0$, $\alpha = \alpha_s$, $\beta = \beta_s$.

3.2. Lot acceptance sampling and test procedure

According to the target, the test plan is designed through the optimization model. For the case that the product is only exposed to failure mode(s), the test plan includes sample size n, acceptable number of failures in the test c, and censoring time t_{a0}, the error between the required values and the actual values of the risks