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A literature review on the planning and analysis of accelerated degradation testing for mechanical products

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Abstract. High reliability and long life are typical requirements for mechanical products. The performance requirements of mechanical products are increasing as science and technology develop, and the environment and working stress they bear are becoming more diverse. This issue has become one of the bottlenecks for mechanical products in lifespan and reliability generally. The aim of this study is to categorize, examine, and review the most applicable accelerated testing methods for mechanical products. The research status of accelerated modeling methods, statistical analysis, and design optimization of accelerated degradation testing(ADT) technology are reviewed. On the basis of literature analysis, the deficiencies and possible development directions of ADT were summarized and prospected. This work is anticipated to serve as a reference and provide important insights into the reliability of mechanical products.

Keywords: mechanical products, reliability, reliability acceleration testing, accelerated degradation testing

1. Introduction

With the acceleration of the upgrading of mechanical products, industrial sectors are faced with the requirement to develop new products with more complex structures and higher reliability level within a relatively shorter time. The increasing high reliability of products poses new requirements for testing the materials, components, and systems of products. Traditional reliability testing techniques, such as reliability qualification testing and environmental stress screening, typically require long testing time or a large test sample size to obtain their reliability information, and the testing cost is exceedingly high [1-3]. The vast majority of modern mechanical products are carefully designed and manufactured to

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operate without failure for a couple of year, more than a decade, or longer. Few components in actual field testing will exhibit significant degradation or failure under normal usage conditions [4]. Therefore, to achieve rapid and low-cost reliability growth and evaluation of mechanical products, accelerated degradation testing (ADT), as one new development direction of reliability accelerated testing technology [5], is receiving increasing attention from many international researchers.

ADT is an accelerated test method that accelerates product performance degradation by increasing stress levels, collects performance degradation data for products, and uses these data to estimate the life characteristics of products under normal stress without changing the product failure mechanism [6]. ADT measures the degradation amount of a product through its performance or characteristics. Degradation amount should be modeled mathematically when it reaches a specified degradation threshold based on the failure mode. Then, an estimate of the reliability and life parameters of products under normal working stress levels will be obtained by establishing an acceleration model and using performance degradation data under high stress to extrapolate reasonably [7]. ADT is a significant manner for solving the life prediction problem of products with complex failure mechanisms and changing environments, contributing to obtaining product life and reliability indicators with less time cost and higher estimation accuracy [8].

On the basis of the characteristics of reliability accelerated testing for high-reliability products, an overall review of the current research status of ADT is presented in this paper, along with a summary of the research deficiencies and a discussion of possible development directions.

2. Current research status of ADT technology

Research on ADT technology began in the 1980s [9], and since then, ADT has been widely used in mechanical products and other degradation failure products. The accelerated degradation data obtained during testing become more complex with the increasing performance of products, promoting the continuous development and improvement of acceleration degradation modeling, statistics, and optimization methods of ADT technology for products, particularly mechanical products.

2.1. Research status of accelerated degradation data modeling

The key to reliability evaluation lies in the in-depth analysis of physical failure mechanisms and the establishment of appropriate degradation models by using degradation data. At present, three methods are used for characterizing degradation in reliability assessment. The first method is a degradation model based on physical failure. It makes achieving reliability modeling easier. Another method is a degradation model based on regression model. It exhibits the advantage of quickly establishing a degradation trajectory, but has the disadvantage of poor accuracy. The third method is a degradation model based on random processes. It can describe the time dependence of product degradation paths.

The degradation model based on physical failure is established by further analyzing the physical failure principles and chemical reaction laws of products further on the foundation of a thorough understanding of product failure mechanisms. The most representative physical failure models include the cumulative damage model [10], response theory model [11], and stress intensity model [12]. Walker [13] studied the effect of strain ratio on fatigue crack growth by using a cumulative damage model. The pairs model is one of the commonly used physical failure models in fatigue failure. It is primarily used to describe the growth of microcracks in products over time. Forman et al. [14] put forward a new theory on the basis of the Walker model that uses the response theory model. This theory considers instability when the load ratio and stress intensity factor approach the fracture toughness of materials. It exhibits excellent correlation with general experimental data. Salcedo et al. [15] discovered a new method for defining the threshold voltage of field-effect transistors and proposed a stress intensity model by deriving the relationship between stress loading and material strain. Surles et al. [16] studied a stress intensity model based on Fisher information matrix, developed an asymptotic inference process for a general function of parameters by using carbon fiber strength data and simulation analysis. Reliability evaluation through physical failure models exhibits high reliability, but such modeling methods are limited to products with complex failure mechanisms.

The regression model is used to explore the relationship between predictive factors and response variables, including artificial intelligence algorithms, degradation trajectory fitting methods, and graphical methods. Artificial intelligence algorithms is divided into neural networks and least-squares support vector machines, which can directly fit degradation data without restrictions but have high requirements for sample size and degradation data size. Chinnam [17] first monitored the torque and axial force of a drill in real time and then used the monitored data to model performance degradation based on neural network algorithms. Gebraeel et al. [18] proposed a product performance degradation modeling method based on least-squares support vector machines. This method uses historical degradation data to train the vector machine and estimate parameter values. Then, it predicts the remaining life of products through real-time degradation data. The degradation trajectory fitting method takes the relevant parameters of the product degradation amount distribution as a function of time and performs curve fitting on the data to obtain the degradation trajectory. Joseph et al. [19] presented a differential form of the degenerate trajectory model. Graphical methods can be used to evaluate product reliability when the degradation trend is not changing significantly. A graphical method selects a distribution function to characterize the degradation data collected at each period, setting some parameters in the life distribution function as a function of stress level and test time. In 1981, Newson [1] proposed a graphical method for reliability evaluation that fits accelerated degradation data by using lognormal distribution. Huang et al. [20] proposed a degradation modeling method that uses truncated Weibull distributions to analyze the natural order of performance degradation data. The advantage of a graphical method is that it is more accurate than the reliability prediction of general models. However, its disadvantage is that it disregards individual differences and requires simultaneous measurement of performance degradation data.

The evaluation results of using regression models to model degradation are not as accurate as those of random processes, as the degradation of products exhibits a trend of diffusion over time. Random processes include the Wiener process, gamma process, inverse Gaussian process, and Markov process. The Wiener process can describe the time uncertainty and measurement error of product degradation process and the influence of external random factors on product performance during the test. Doksom et al. [21] first applied the Wiener process to reliability engineering and studied the degradation test model of products under variable accelerated stress of the Wiener process. Park et al. [22] developed a new accelerated test model based on the generalized cumulative damage method for the Wiener process that characterizes degradation phenomena. Shemehsavar et al. [23] proposed a step stress acceleration model based on the binary Wiener process, and then further discussed parameter inference on the basis of the proposed model.

Products with monotonic degradation trajectories are modeled using the gamma process. Abdel-Hamed [24] introduced the gamma process into the field of reliability in 1975. Srivastava et al. [25] studied the design of partially degradation testing under optimal binary step stress based on gamma process, and modeled the dependency between two performance degradation quantities of products. Ling et al. [26] proposed an accelerated degradation analysis method for monotonic and bounded degradation systems based on the gamma process and evaluated the performance of the proposed method. Shat et al. [27] extended the univariate degradation model in the gamma process to characterize accelerated degradation testing with different bivariate degradation models.

The inverse Gaussian process is a continuous probability distribution, and it currently has no intuitive physical explanation. In some cases, it is more accurate than Wiener process and gamma process. Peng [28] proposed an arc-wise gamma mixed degradation model based on the inverse Gaussian process. The effectiveness of different random processes was evaluated by using the characteristics of lifetime distribution and parameter estimation of the EM-type algorithm. Case studies demonstrate that the model exhibits the advantages of random effects and explanatory variables. Ye et al. [29] systematically studied the inverse Gaussian process and discussed statistical inference and model selection methods for three random effect models. The inverse Gaussian process has been proven to be a limited composite Poisson process, providing a meaningful physical explanation for simulating product degradation in a random environment.

The Markov process is an important method for studying the state space of discrete event dynamic systems. Using Markov process modeling can calculate the probability of a system with multiple degradation states and accurately predict the degradation trend of products. Papamichael et al. [30] used a Markov process to simulate the perturbation process of a degenerate evolution system and proposed a new analytical solution based on Markov renewal theory. The test results of this method exhibit good agreement with those estimated using the Monte Carlo method. Mokhov et al. [31] modeled the operation of industrial equipment based on the Markov process to estimate the state transition probability of equipment and predict the final operating state of such systems. The effectiveness of this method was proven through practical cases. However, the Markov process has limitations, such as the transition probability of state changes must be fixed and the complex matrix operation.

At present, no universal method is available for judging the pros and cons of a model. Misjudgment frequently occurs when modeling performance degradation. Tsai et al. [32] studied the effect of the incorrect fitting of a degradation model on the prediction of average product failure time under laser data excitation and described in detail a quantitative analysis method for the effect of mistakenly designating the gamma process as a Wiener process on average product life. Yu [33] proposed the problem of erroneously specifying normal and extreme value distributions for complete data and studied the effect of irregularities between normal and extreme value distributions on the level of estimating independent variables. Ling et al. [34] studied the effects of model error specifications between the gamma model and Weibull model on likelihood estimation, inferred mean life, and reliability level on the basis of disposable equipment test data, and evaluated the bias and coverage probability of confidence interval under model error specifications through simulation.

In summary, scholars' research on degradation models has focused more on degradation models based on the regression model and random process, and significant results have been achieved. However, some problems, such as a general model, inconsistent modeling basis for accelerated degradation data and lack of in-depth analysis of product failure mechanisms, must still be addressed.

2.2. Statistical analysis status of accelerated degradation data

The statistical analysis of accelerated degradation data includes parameter estimation and inferring the service life of system from degradation amount. Parameter estimation is used to obtain the point value or confidence interval of unknown parameters in a model. Inferring the service life of system from degradation amount is established for the calculation of reliability characterization quantities.

Obtaining a point estimation for the target value is necessary, along with establishing a confidence interval for the estimated value in the statistical analysis. Nowadays, commonly used parameter estimation methods include moment estimation, maximum likelihood estimation, Bayesian method, and bootstrap sampling method. Maximum likelihood estimation has been widely applied in statistics, but the calculation results are inaccurate when the degradation data have errors. Ruud [35] extended the EM algorithm to the problem of data loss and simulation estimation, obtaining the maximum likelihood estimation parameters of the model. Jiang et al. [36] proposed a degradation gamma model based on the invariance principle of the degradation mechanism and derived the maximum likelihood estimation of the parameters of the proposed model. The superiority of the established model was verified through Monte Carlo simulation. The Bayesian method combines multisource information, such as fault reports and historical data, in reliability modeling, improving the efficiency of reliability evaluation and considering the uncertainty of a model. Therefore, the Bayesian method is widely used in ADT optimization and random process modeling. Weaver et al. [37] proposed an accelerated degradation test method to find the optimal test scheme on the basis of Bayesian criteria for the estimation accuracy of failure time quantile under service conditions. Li et al. [38] developed a step stress accelerated degradation test based on the Bayesian method. After comparing with the local optimal design for maximum likelihood theory, the results showed that this method can provide better experimental schemes for engineering applications. Bootstrap sampling is an effective method for interval estimation. It fits the distribution characteristics of the sample population through sample data in the case of less degraded data. Wang et al. [39] used the bootstrap sampling method to obtain a confidence interval for the estimated value of the model parameters of a power supply module for a certain type of communication equipment.

The failure threshold determines whether a sample in ADT has failed. Product failure is determined when the performance degradation amount of product reaches the failure threshold for the first time. The general definition of life distribution is

$$T = \operatorname{Inf}\{t: Y(t) = \omega; t \geq 0\} \tag{1}$$

where T is the service life, $Y(t)$ is the performance degradation amount, and ω is the failure threshold.

The expression for life distribution of a random process model is established by the relationship among degradation amount, failure time distribution, and reliability function. In response to the limitations of sequential Monte Carlo methods for approximate estimation, Li et al. [40] inputted the state values of the fitted degradation trajectory into the analytical solution to estimate the PDF of the remaining service life.They validated the effectiveness of this method by using fatigue crack growth data. Zhang et al. [41] described the nonlinear degradation trend of random degradation modeling based on Wiener process, where drift increment is a weighted sum of the kernel function, and then derived the numerical approximation distribution of the remaining service life. Park et al. [42] discovered an accelerated degradation failure model of inverse Gaussian distribution on grounds of geometric Brownian motion, and verified it using actual data of fatigue crack size.

The relation between degradation and life is established in accordance with the fact that the performance degradation amount of products is a linear function over time in the aforementioned studies. However, the performance degradation amount of some products is a nonlinear function over time in engineering. In addition, individual degradation rates are different due to the effects of random factors on products. Therefore, when establishing the relationship between a degradation model and life distribution, the processing methods for nonlinear data and differences in individual performance degradation must be further studied.

2.3. Research status of ADT design and optimization

The advantages and disadvantages of ADT schemes take a great impact on the final test results. Considering aspects, such as accelerated stress level, sample number, test cost, sample detection frequency, test cutoff time, and sample size distribution, is typically necessary at each stress level when designing and optimizing ADT.

The design methods of ADT include the D-optimal, C-optimal, and M-optimal criteria. Omshi et al. [43] used the D-optimal criterion to conduct a constant stress accelerated degradation testing with a degradation path following the inverse Gaussian process. They obtained the optimal sample allocation for each stress level and determined the effect of stress level on the objective function. Shat et al. [44] proposed the C-optimal criterion for the optimal design of constant stress ADT when the degradation path follows a linear mixed effect model. The optimal design is primarily based on time variables rather than commonly considered stress variables. In addition, ADT is designed with the majorization goal of minimizing the variance of the reliability index estimated value. Hamada [45] minimized the variance of a single life assessment of maintenance requirements, significantly reducing the uncertainty of certain indicators related to reliability estimation. Srivastava et al. [46] explored the project of an optimal modified slope stress ADT with the degradation path following the Wiener process. The optimal samples number, the optimal stress change point, and the optimal stress rate were obtained by minimizing the asymptotic variance of the qth quantile life estimation under service conditions.

3. Research deficiencies and development direction

Numerous studies have been conducted on the theories, methods, and applications of ADT technology. However, the overall system is not yet perfect due to the requirement of high reliability for mechanical products. On the basis of the preceding analysis, several issues must be resolved. (1) System-level ADT design and analysis. A system-level product has a complex structure and is not suitable for large sample sizes and multiple measurements of performance indicators. Therefore, the technical specifications of

ADT for materials and components are not fully applicable. To standardize the test process, technical guidance documents for system-level products should be established. (2) Statistical analysis of multivariate accelerated degradation data. A widespread phenomenon of multiple performance degradation in system-level products occurs, and multiple degradation processes are correlated in engineering practice. A single performance parameter is incapable of judging whether a product meets work requirements. Establishing an accelerated degradation model with multiple stress coupling effects is necessary to make it more applicable to multiple degradation failure products in engineering. (3) Analysis and model solving of small sample degradation data. Complex systems in ADT frequently have a small number of samples and insufficient performance degradation data, presenting a small sample characteristic. Relying solely on traditional reliability analysis methods is difficult when completing high-precision reliability evaluation. One feasible approach is to combine the degradation data in experimental design with actual field data, compile a natural environment load spectrum, and then convert the natural environment spectrum into an equivalent accelerated test spectrum. (4) Analysis of performance parameter fluctuations and measurement errors. Performance parameter fluctuations and measurement errors directly affect the evaluation accuracy of degradation. Comprehensively considering the performance parameter fluctuations and measurement errors of products is necessary when selecting the stress level, sample size, failure threshold, and accelerated degradation model in the test.

4. Conclusion

ADT technology is a practical and efficient test method for achieving the reliability evaluation of mechanical products with high reliability and long lifespan. It has become a research hot areas of the reliability for mechanical products in recent years. This article summarized the basic concepts and theories of ADT technology, along with its design and optimization. The current weaknesses and development directions of ADT technology are proposed through a discussion. ADT technology has achieved significant results in the reliability evaluation of materials and components, but it still has shortcomings, such as the lack of system-level ADT design and analysis, the statistical analysis of multivariate accelerated degradation data, and the analysis of measurement errors. Although ADT still has its problems and limitations, it will play an increasingly important roles in promoting the development of reliability engineering with further research of numerous scholars.

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Conflicts of Interest

The authors declare that there are no conflicts of interest.

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