Review of Reliability Analysis Based on Degradation Modeling

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Abstract. Reliability analysis based on degradation modeling is an effective method to estimate the reliability of some highly reliable components or systems. This paper first introduces the advantages and disadvantages of degradation modeling, and then summarizes the related research of degradation modeling according to the two cases of no stress factor and stress factor. Finally, it briefly analyzes the hot issues in the field of degradation modeling, and looks forward to the next research.

Introduction

With the development of science and technology, a large number of products with long service life and high reliability have appeared in the fields of electronic industry, aerospace industry and so on. For such high reliability and long life products, the traditional life test and accelerated life test are difficult to obtain the failure time data in a relatively short period of time. However, the failure mechanism of high reliability and long life products can be traced back to the potential performance degradation process of the product, which can be considered that the performance degradation eventually led to the failure of the product. Therefore, the idea of using product degradation data to estimate its reliability and life is proposed.

In recent years, more and more engineers and statisticians, degradation data through a measurement of performance parameters of products, and to predict the reliability of storage or use of products, thereby opening up a use of failure time data, and use only the degradation of new ways of data analysis of product reliability. Meeker [1-3] et al provide a comprehensive review of degradation models and related inference methods.

The reliability analysis based on the degradation model is an effective method to estimate the reliability of some high reliability components or systems when the failure concept measurement is very little or no failure. When important performance parameters are gradually degraded to a critical threshold level, the system and its components are defined as degradation failures. The degradation model is based on the probability model of failure mechanism degradation trajectory, and the projection distribution is compared to the predetermined failure threshold [4]. One of the most important advantages of degradation modeling is the ability to record multiple degradation quantities for each individual unit in the population. Therefore, there is no need to wait for failure to obtain and analyze failure time data. Compared with the traditional life test, the degradation test will produce more useful reliability information. For high reliability, long life components or systems, degradation modeling may be the only feasible reliability analysis method.

Reliability analysis based on degradation modeling mainly includes: degradation data modeling, failure criteria, connection degradation model and failure time distribution and reliability analysis algorithm. In order to achieve reliability analysis under normal stress level, it is necessary to combine the stress covariate in the degradation model for accelerated degradation test. In this paper, the reliability evaluation methods based on performance degradation data and the commonly used degradation modeling methods are introduced respectively.
Advantages and Disadvantages of Reliability Assessment Methods Based on Performance Degradation Data

In reliability theory, the failure of products can be divided into two types: degradation failure and sudden failure. Because of the failure mechanism of most of the products can be traced back to the final performance of the product potential degradation process, the actual failure time can be determined by the stress at a given the degradation path estimate, the performance degradation data analysis can be used to replace the traditional reliability evaluation of failure data analysis to product.

Product degradation test or state monitoring is used to obtain performance degradation data, and the use of degradation data instead of failure time data for product reliability analysis has the following advantages:

1. In the application of expected failure or minimal failure, the degradation data can provide more reliability information than the traditional truncated failure time data, and the degradation process can also help us to find the physical model between the product degradation and the accelerated stress.
2. Direct observation of the degradation process will allow direct modeling of the failure mechanism and provide more reliable and accurate estimates and solid foundations for reliability statistical inference.
3. Degeneration is the natural response of some tests. Degradation data can provide better degradation process information, and then help to find the appropriate function formula, and get more accurate life estimation.
4. Degradation data can be analyzed earlier before failure occurs.
5. Compared with the failure time data, the degradation data modeling is more close to the failure physics, and the inference will be more effective and credible. However, the above advantages have a potential premise, that is, the acquisition of the degradation quantity is non-breaking. In fact, the degradation of a unit often requires destructive measurements or potentially disruptive quantities that change the process of degradation.

When the degradation quantity is contaminated by a large number of measurement errors, or when the degradation quantity is not closely related to failure, the advantages of the degraded data will be discounted. Therefore, in addition to the advantages mentioned above, there are still some shortcomings in the degradation failure analysis:

1. The degradation modeling of component or subsystem performance output will be useful, but the modeling may be more complicated because the output may be affected by multiple unknown physical/chemical processes.
2. Degradation data may be difficult or impossible to obtain.
3. Obtaining degraded data may affect the future degradation of the product.
4. The measurement error may eliminate the information in the degraded data.
5. Degradation level may not be closely related to failure.

Normal Degradation Model

In the literature, the normal degradation (ND) model can be divided into two categories: parametric model and nonparametric/semi-parametric model. In parametric models, the form of degenerate trajectories or the distribution of degradation quantities are specified; however, they are not specified or partially specified in nonparametric/semi-parametric models and degradation estimates.

Parametric ND Model

Degeneracy is a stochastic process, which can be simulated in many ways. For example, the real degradation of temporal observations defines a set of sample functions (degradation trajectories); on the other hand, the true degradation rate or degradation rate is a random variable at the specific moment. Usually, the existing parameter ND model uses the following methods:

1. Degradation trajectory method;
(2) Time dependent parameter distribution method (referred to as "stochastic process" in some papers);

(3) A stochastic process with independent increments.

Specifically, the regression model with random degradation path by using the method of coefficient
degradation measurements; time related parameter distribution by using the method of specific
degradation distribution at each observation time with time related parameters; is completely different,
the incremental amount between the adjacent degradation simulation and the distribution fitting
parameters may change with time or change them the stochastic process method with independent
increment.

Simple linear regression models and nonlinear regression models are often used in the modeling of
degradation trajectories. Linear degradation occurs in some simple wear processes, and in some
engineering applications, the degenerate quantity may be represented by a simple linear time function.
In the linear regression model, the simplest model assumes that the intercept of the model is constant.
Lu et al. proposed a linear degradation trajectory model with random intercept and slope, intercept
and slope obey normal distribution and correlation, and for repeated observation degraded data, it
contains an error term[5] with very low standard deviation. Degenerate trajectories are often nonlinear
time functions, and sometimes linearization is infeasible. Therefore, the nonlinear regression method
is developed. Lu and Meeker proposed a general nonlinear mixed effect model and two step methods
to estimate the model parameters, and the model parameters obey the multivariate normal distribution.
They also propose a parameter Bootstrap method to obtain the confidence interval[6] of the failure
time distribution. Wu and Shao study the asymptotic behavior of the least squares estimator of the
degenerate quantity in the nonlinear mixed effect model[7].

The basic idea of the degradation trajectory model is to limit the sample space of the degradation
process and assume that all sample functions allow the same functional form but have different
parameters. However, when some sample degradation trajectories are inconsistent with others, it may
be caused by the inherent variability in individual units, which is quite restrictive. In the field
application, this situation is naturally encountered. Based on the optimal fuzzy clustering, Wu and Tai
[8] process those special units as "outliers", and assign smaller weights to them when estimating the
model parameters. Their method provides a closer confidence interval than the two step method for
the failure time distribution.

The time dependent parameter distribution method appears because the degradation quantity is a
random variable, and its distribution is a time function. In this method, multiple degradation data at a
certain moment must be collected and treated as a non directional scatter point.

Yang and Xue[9] simulated the degradation data based on the normal distribution with time
dependent parameters, and estimated the model parameters by regression analysis. Zuo et al.[10]
extends this idea to the process of general distribution and develops other methods in the case of
various data formats. As a general method, the time dependent parameter distribution method can be
flexibly used to estimate reliability without the need to make assumptions about the degradation
trajectory. However, this method ignores the directionality of the degradation data and requires
multiple observations, which will not be suitable for predicting the residual life of individual units. In
the stochastic process model with independent increments, there are basically two types: cumulative
damage model and continuous time model. The former is based on the cumulative damage theory
describing the degradation process under discrete stresses, and sometimes the state of the process is
assumed to be discrete. The model takes the probability of damage increment and their arrival time
interval or increment in a time interval as the modeling object. The latter is suitable for simulating the
continuous degradation process showing variability. The degradation of the product is caused by
aging and/or persistent stress. Based on the model should hold for a cumulative damage model (CD).
The earliest CD model was deterministic. The current CD model is a probabilistic model, such as a
compound Poisson process.
Unlike the CD model, the continuous time model, such as the Brown motion and the Gamma process, is used to describe the continuous degradation by considering each degradation trajectory as a potential continuous time stochastic process.

**Nonparametric ND Model**

Non parametric regression techniques are used to simulate the degradation trajectories without having to assume that their forms are intuitive; however, due to the localization properties of nonparametric regression, long-term extrapolation will be questionable. This limits the development of nonparametric regression degradation models.

An alternative method is to use the time dependent parameter distribution method in nonparametric form. Eghbali \[11\] proposed a degradation hazard method based on this concept. This method relaxes the requirement of choosing the form of degenerate trajectory and is easily extended to ADT model.

**Accelerated Degradation Test Model**

Nelson \[3\] briefly studies the degradation behavior of various degradation products and materials, ADT model and inference method, and gives the basic accelerated degradation model under constant stress. Meeker and Escobar \[1\] reviewed some references to describe the application of ADT model. They proposed a mathematical model for analyzing ADT data and suggested a method to estimate the failure time distribution, distribution quantiles and confidence intervals. Deng Aimin et al \[12\] briefly reviewed the existing ADT models and looked forward to the future development of model.

Elsayed \[13\] provides a brief review of the degradation model and divides the ADT model into two categories: physical statistics based model and statistical based model. Moreover, he divides the models based on statistics into two categories: parametric model and nonparametric model. The following will introduce the relevant ADT model based on this classification.

**Based on Physics Statistical Model**

Degradation of insulating materials under different stress levels was analyzed by Nelson \[14\]. He assumed that temperature is the only acceleration factor for determining the degradation profiles with time, and the relationship between absolute temperature, median breakdown voltage and time is given. Then, he estimates the lifetime distribution based on the performance degradation model. Whitmore and Schenkelberg \[15\] accelerate the degradation process by a Brown motion simulation with time scale transformation. The model is combined with Arrhenius law for high stress test, and they also propose a model parameter inference method based on ADT data. Meeker et al. \[16\] uses the Arrhenius law to describe the effect of temperature on the first-order first-order chemical reaction rate, and a scale accelerated failure time model is obtained. The confidence interval of the failure time distribution is obtained by simulation method.

**Based on Statistical Model**

Statistics based models include parametric models and nonparametric models. The parameter model assumes that the degradation trajectory of the element obeys a specific function form with random parameters or the degradation quantity obeys a hypothesis distribution with time dependent parameters. Moreover, these models assume that only degenerate trajectories or scaled distributions are scaled at different stress levels, but their forms remain unchanged. The nonparametric model relaxes the assumptions about the form of degenerate trajectories or the distribution of degradation quantities and establishes them in a nonparametric manner. Compared with parametric regression models, nonparametric models have greater flexibility, but they may not have clear physical meaning.

(1) The parametric model is based on the degenerated trajectory, and Crk \[17\] extends the idea of the general degradation trajectory method, and develops the multivariate regression analysis of the functional parameters on the applied stress.
Tang and Chang \cite{18} simulate non-destructive accelerated degradation data as a set of stochastic processes with parameter dependent stress levels. In the degenerate modeling method of Brown motion, Doksum and Hoyland \cite{19} discussed the ADT model of the stress situation, and introduced a kind of flexible model based on the concept of cumulative recession. Simple step stress, multi-step stress and progressive stress are considered. The proposed model is a time shift drift Brown motion model.

(2) Nonparametric model

Shiau and Lin \cite{20} proposed a nonparametric regression accelerated life stress (NPRALS) model for a set of accelerated degradation curves. It is assumed that different stress levels affect only the degradation rate without affecting the shape of the degradation curve. An algorithm for estimating NPRALS components is proposed. By studying the relationship between the acceleration factor and the stress level, the estimation of the average failure time of the product under normal conditions is obtained.

Compared with the parametric model, the nonparametric model performs better than the parameter model if the assumed trajectory function is far away from the real trajectory in the parameter modeling. However, the efficiency of nonparametric models is relatively low. Moreover, in order to use the nonparametric regression model, the range of the degradation curve under normal conditions must be covered by the range of accelerated degradation data converted by time, and the ADT must be implemented until the test unit fails.

Another nonparametric model is the use of degradation hazard functions. Eghbali \cite{11} proposed an ADT model called proportional degradation hazard model (PDHM). MLE is used to estimate model parameters. The model is applied to the ADT data of light emitting diodes to predict the reliability under normal operating conditions.

**Development Trend**

In today's industrial and aerospace applications, reliability analysis based on product performance degradation data has become more and more important. Although the reliability analysis technology for product performance degradation has been well developed, there are still a lot of mature areas to be studied. Considering the research background of this subject and considering the characteristics of the storage and working environment profile of gyroscope, it is considered that there are some important problems worthy of study:

(1) Reliability analysis of products with competing hard failure modes and soft failure modes

For some products, the degradation of the product will occur in the process of degradation of the product function over time, and the failure may occur (hard failure). Product failure is the result of the competition between the two failure modes, and the reliability analysis of this type of product needs to consider both of these two failures simultaneously.

In Yao Zengqi's \cite{21} doctoral dissertation, a hybrid degenerate mathematical expression with two failure modes is presented by combining the density distribution function of the degradation quantity with the probability of burst failure. Under the assumption that the two failure modes are independent of each other, Huang and Askin \cite{22} have studied the competitive failure problem with performance degradation. Under the assumption that the failure modes are independent of each other, Zhao and Elsayed \cite{23} study a competitive failure problem under accelerated stress conditions. Li & Pham \cite{24} studies the reliability modeling of multistate deteriorating systems with multiple failure modes and random shocks, but still assumes that each failure mode is independent of. Bagdonavičius studied multiple failure modes of linear degradation data and statistical inference of general degenerate trajectory model \cite{25} \cite{26}. On the basis of determining the distribution model of product performance degradation quantity, Zhao Jianyin et al. \cite{27} gives a general model of competition failure between sudden and degenerate failure, and analyzes the reliability of metallized film pulse capacitor. N. D.
Singpurwalla \cite{28} uses the concept of "hazard potential" to explain the cause of dependence between lifetimes, and studies the failure problem with multiple correlated risks in dynamic environment.

In this field, the main focus is to study techniques to estimate the distribution parameters corresponding to each failure mode. These technologies should be based on composite performance degradation data and life test data. In addition, the correlation between the failure modes should be considered for the working objects in complex environments.

(2) Reliability estimation of joint degradation and failure time data is an important part of modern reliability theory and survival analysis. It is the modeling and statistical analysis of aging, wear, damage accumulation and degradation process of technical units or systems \cite{11}.

Recently, a method for developing joint degradation failure time data analysis is being developed. Wang and Taylor \cite{29}, Tsiatis and Davidian \cite{30} use the Cox model to expand the strength of the failure time, including the degradation of the additional covariates and the application of the semi parametric estimation method for survival data. Bagdonavi IUS and Nikulin when considering the degradation process simulation of the Gamma parameter estimation method \cite{31}, Padgett and Tomlinson study the reliability inference problem of degradation and failure time in degradation process simulated by Gauss process \cite{32}. Lehmann takes into account the parameter estimation \cite{33} \cite{34} in the case of the degenerate process defined by Wiener diffusion. Bagdonavi IUS and Bikelia are considered \cite{35} \cite{36} estimation problem without covariates and with covariates when combined with degradation and failure time data reliability.

(3) Reliability prediction based on degradation modeling under stochastic stress

For accelerated degradation tests in laboratory or other controlled environments, the degradation model under deterministic and static stress is better. A new modeling method is needed to adapt to the case of random or multiple changes of stress which obviously affect the degradation process.

Tseng & Wen studies the accelerated degradation failure problem of high reliability products under step stress \cite{37}. Wang and Coit used the cumulative damage model combined with a variety of variation stress to expand the proportional degradation hazard method proposed by Eghbali and Elsayed. The system reliability prediction problem based on degradation data under the stress was studied, but the analytical method \cite{38} was not given. Park and Padget are used to study the stochastic degradation model \cite{50} under multi step stress. E.A. Elsayed and H.T. Liao \cite{40} proposed a geometric Brown motion degradation rate model and simulated the variability of under field working conditions by using the approximation method. Jong In Park and Suk Joo Bae proposed a Delta approximation to achieve field reliability prediction based on ADT data, and no need to make any assumptions about the degradation model \cite{41}. Chan and Meeker \cite{42}, Meeker and Escobar \cite{43} study the degradation modeling problem in highly variable environments, and propose a general degradation trajectory model that combines multiple variations of environmental stresses, but requires time series data of environmental processes.

(4) Degradation reliability analysis under stochastic and uncertain failure thresholds

In engineering practice, the degradation failure threshold is usually a fixed known value, but in some cases, the failure threshold is a random variable, and the strength degradation stress strength interference failure model is one of them. The degradation failure problem under random failure threshold is simply discussed by Wang and Coit, and a simulation method is presented to solve the failure distribution \cite{38} \cite{44}. Lewis and Chen study the stress intensity interference failure problem of deterministic stress and stochastic strength degradation and stochastic stress and deterministic strength degradation \cite{45}. When \cite{46} and \cite{47} are assumed to be independent of stress and strength, the stress intensity interference failure problem of stochastic discrete stress and degradation strength is studied. Zhao Jianyin et al. \cite{48} proposed a periodic stochastic stress strength degradation reliability model considering the degradation of strength under the influence of random stress. The correlation between stress and strength degradation was considered. Alexander Usynin, Wesley Hineshe and Aleksey Urmanov are used to study the uncertainty failure threshold problem in the cumulative
damage model [49]. Zhang Deng [50] studies the statistical inference problem for a class of discrete degenerate data under random failure threshold.

(5) Reliability prediction based on periodic inspection data of gyroscope

Generally, during the period of storage and transportation loss, the degradation data obtained from field tests show considerable variability, and the data are affected by sampling uncertainty and time uncertainty. There is a deterministic function relationship between model response regression and independent variables based on the traditional form, function selection is usually implemented according to some empirical relations to obtain the existing in scientific research, and by adding an error characterization of additional random response. The model parameter [51] is estimated by ordinary / generalized least squares technique based on the assumption of error structure.

Although regression models may be one of the most skilled statistical techniques for engineers, the limitations in reliability prediction have recently been reported [52]. In addition, some common modeling difficulties, such as: error diagnosis and normality test, an important limitation is that the repeated measurements from the same components are regarded as independent observations in linear or nonlinear regression models. The mixed effects model can be used to simulate the covariance structure of repeated measurements, but the stochastic change characteristics of the regression model prevent the proper consideration of time uncertainty in residual life prediction. This motivates inference based on stochastic process models to account for the time uncertainty in aging gyroscopes.

In short, in order to study the reliability prediction method based on performance degradation modeling, the above aspects will be an important problem to be solved urgently.

Summary

Reliability analysis based on degradation modeling is an effective method to estimate the reliability of highly reliable components or systems. This paper makes a periodic summary of the related theoretical research and engineering practice in the field of degradation modeling. In summary, reliability modeling based on performance degradation modeling is gaining more attention and development, and has been widely used in more and more engineering fields. Further development of this research direction will provide strong support for national economy and technology development.

Reference


