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# Failure behavior modeling and reliability estimation of product based on vine-copula and accelerated degradation data

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ABSTRACT

Aiming at the characteristics of failure mechanism coupling of high-reliability and long-lifetime complex products, a method of multivariate failure behavior modeling and reliability assessment is proposed based on vine-copula and accelerated degradation data. The method, considering the coupling modeling under accelerated stress and the relevant acceleration mechanism consistency test, can not only clearly describe the multivariate coupling relationship of the product, but also can carry out the reliability assessment of the product within the affordable time and cost. The failure behavior modeling method consists of two parts which are degradation behavior and correlation relationship among variables. Firstly, degradation behavior description of failure behavior modeling is obtained from, the degradation data of product performance parameters based on the accelerated degradation test, the degradation path of each performance parameter by utilizing drift Brownian motion, then the implementation of accelerated consistency test ensures the true reliability information. Furthermore, the correlation description of failure behavior modeling is constructed by Vine-Copula based multivariate damage coupling modeling method describing the pairwise correlation relationship. Afterward, the exact solution of reliability joint distribution of the product with non-strictly monotonic degradation is figured out by Vine-Copula and the equation of reliability estimation based on conditional probability. Finally, the feasibility of the method is verified by utilizing smart electricity meter as the numerical example.



## 1. Introduction

The security service of important equipment such as aerospace, aviation, nuclear devices and power network plays a significant role in the national economic development and the national defense construction. However, malignant accidents are prone to take place due to the complicated operating condition of the equipment and the surrounding severe environment. Therefore, it is of great significance to identify malfunction, assess and predict its reliability in terms of guaranteeing the safe operation of equipment as well as enhancing economic efficiency. Failure behavior modeling, based on state of components and relevant failure mechanisms among them, can be used to predict the reliability of product and provide more reliable

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predictions, given that the hazard of failure can be reflected in the state of the components that make up the product. Due to the existence of the relevant failure mechanisms, it is more challenging to construct the failure behavior model and to evaluate the system reliability.

The term 'failure behavior' mainly appears in the description of the failure process of underlying mechanisms such as corrosion behavior [1] and fatigue behavior [2]. Zeng [3] defined the connotation of failure behavior and proposed the failure behavior model (FBM) and its classification. It was characterized by coupling multi-state model and multivariate coupling model based on performance parameter data.

When the relationship among failure mechanisms is available to be obtained, the coupling multi-state model is applied in failure behavior modeling. Zhao [4] theoretically established a systemic failure behavior model based on Petri network and physical structure of system in the condition of failure mechanisms with trigger correlation. Chen [5] discussed four kinds of correlation relationship among failure mechanisms based on Probabilistic Physics-of-Failure (PPOF). Under the condition of inter-competing failure mechanisms, traditional probabilistic risk assessment method was presented to model dependencies, but restricted to the fact that the redundancy configuration of the system must be the same components [6]. To overcome this deficiency, Mosleh [7] proposed the General Dependency Model (GDM) to describe the probabilistic dependencies between components based on Bayesian Network, eventually realizing the system explicit modeling method. In addition, the methods of generating function, Petri net, and reliability block diagram, were also used to describe the reliability model of system failure behavior [8–11].

When the coupling relationship of failure mechanisms is unknown, the observed performance parameters are always adopted to construct the FBM by identifying the model parameters and fitting the model forms, in which the difficulty lies in the acquisition and solution of the joint distribution. Multivariate distribution and copulas as flexible technique are gradually used to solve the problem. Peng et al. [12] established joint probability density function based on degradation process and solved it by using multiple integrals, where the relationship description was determined by covariance matrix of performance parameters. As for the problem of several dependent degradation processes and different marginal distributions, Liu et al. [13] presented the joint reliability distribution modeling and evaluation of marginal degradation process by utilizing multivariate copula method and adopting inverse Gaussian distribution with time scale transformation. Pham [14] established the competing risk model with dependent failure mechanisms based on time varying copula function. Moreover, due to the characteristics of high reliability and long lifetime of products, accelerated degradation data need to be applied in multivariate coupling modeling. Li et al. [15] constructed joint reliability distribution based on frank multivariate copula function and Wiener process where the parameters of degradation model under each stress level were described by the conversion function. Shen et al. [16] proposed a reliability assessment method under multiple-parameters accelerated degradation test based on multidimensional normal distribution. Compared with non-acceleration data, in the multivariate modeling of accelerated test, an acceleration model is introduced to increase the difficulty of parameter identification; moreover, the consistency test of failure mechanisms should be performed. However, the existing related work neglected the effect of consistency of failure mechanism and extrapolation of acceleration model caused by accelerated data, in addition, the application of n-dimensional copula or multivariate distribution fails to describe the correlation relationships between each two variables, thus a new modeling method based on Vine-Copula and accelerated degradation data is proposed in this paper to overcome the shortcomings.

The paper aims at high-reliability and long-lifetime products with multiple performance parameters, and carries out the failure behavior modeling based on performance parameters so as to achieve the estimation of system reliability. First of all, in the degradation behavior description model of the failure behavior, Brownian motion is introduced to fit the variable degradation trajectory, and then marginal distributions on the normal stress level are constructed on the basis of the consistency test of failure mechanism. Secondly, in the correlation description of failure behavior model, based on hierarchical thought and vine-copula method, pair bivariate Copula functions are used to describe the decoupling difficulty of multivariate damage joint distribution. Finally, in terms of reliability calculation, due to the fact that the current modeling of Copula function usually collocates with strictly monotonic degradation model as to estimate the lifetime, the solution method proposed in this paper based on conditional probability can also solve the non-strictly monotonic degradation model.

The rest of the paper are organized as follows. In Section 2, the methods of failure behavior modeling and reliability estimation of product are introduced. In Section 3, the proposed approach is illustrated by accelerated degradation data of smart electricity meter. Some conclusions are given in Section 4.

## 2. Failure behavior modeling and reliability estimation

### 2.1. Failure behavior modeling description

For systems subjected to temperature, vibration, humidity and other environmental stresses, there may be fatigue, corrosion, aging and other failure mechanisms. With regard to the single component of the system, it may be affected by single mechanism, or multiple mechanisms at the same time. It is possible for different mechanisms to have the independent competitive relation or coupling relation. When these failure mechanisms with relation to failure coupling, such as competition and triggering, act on the component, it will cause the interaction effect on failure mechanisms between the components, thus reflecting on the status of the components. State vector is used to describe the health condition of each component and can be represented in the following forms:

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