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Manufacturing process-based storage degradation modelling and reliability assessment

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ABSTRACT

Quality variations in manufacturing are significant factors for product's reliability. In this paper, a manufacturing process-based storage degradation modelling and reliability assessment approach is proposed to describe the uncertainty of product's storage degradation path caused by manufacturing process. Firstly, a storage degradation model of the output characteristic is constructed, by combining the functional relationship between output characteristic and bottom level performance (BLP for short, such as dimension, mechanical properties, material properties, etc.) with the storage degradation mechanism of products. This model is able to reflect the unit-to-unit variability of batch products. Secondly, based on finite element simulation and approximate modelling method, the unit-to-unit variability caused by manufacturing process is analysed, and the distribution characteristics of the random effect parameters (REPs) of the model are calculated accordingly. Finally, the storage reliability of the batch products is estimated based on the model and the calculated distribution characteristics of REPs. A case study of the aerospace relay is carried out to illustrate the effectiveness of the proposed approach.

1. Introduction

Non-operational storage is a common status in the lifecycle of most products [1, 2], such as replacement components, products in stock, etc. Even those products being used are also likely to be in the storage status. Single-shot products, such as airbags [3], aerospace equipment [4], missiles [5], etc., will be stored for the entire lifecycle prior to being operated. During the long-term storage (ranging from years to decades), due to exposure to temperature, humidity, and mechanical shocks, products will degrade step by step until failure. As a consequence, rising attention is put to the researches about storage degradation modelling and reliability assessment [6, 7].

Compared to working status, storage status is causing less degradation. In this case, the impact of unit-to-unit variability caused by quality variations in manufacturing on storage degradation will be relatively magnified and will become unignorable. Recent researches of quality variations in manufacturing-based reliability modelling [8–10] are primarily focused on the impact of these variations on failure distribution or reliability function of products. There are two problems in popularizing these researches to storage reliability research area directly. (1) Large amount of failure data are required to determine the exact form of failure distribution, as well as to calculate the corresponding distribution parameters. However, it is extremely difficult, maybe even impossible, to obtain storage failure data of products. (2) Studies about storage reliability are usually degradation-based, but the works mentioned above failed to establish the relationship between the degradation process and the quality variations in manufacturing.

In the well-known studies about degradation modelling [11], the general path model of a unit is described as a degradation function with fixed effect parameters (FEPs) and REPs. As a tangible manifestation of degradation process uncertainty, REPs lead to heterogeneity of the degradation paths, and the root cause of this heterogeneity is unit-to-unit variability, as stated in [12–14]. In Ref. [15, 16], unit-to-unit variability is considered to be caused by unobservable factors, and can't be quantified. Therefore, REPs have to be anticipated to follow a specific probability distribution [17–19]. However, with the development of finite element simulation and approximate modelling methods [20], unit-to-unit variability of numerous products could already be quantified based on their manufacturing process information.

In accordance with these problems, a novel approach of storage degradation modelling and reliability assessment is proposed in this paper, in which manufacturing process information is introduced to quantify the degradation variability of batch products. In Section 2, the basic procedure of the approach is given. Then, the key steps of this approach are illustrated in detail in Section 3. After that, storage degradation modelling and reliability assessment of a chosen aerospace

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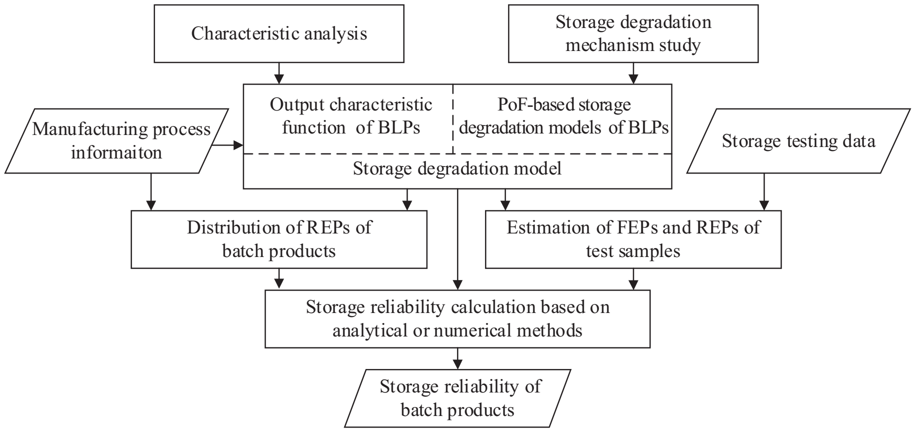

Fig. 1. Procedure of the proposed approach.

relay are performed in Section 4. Finally, the concluding remarks are given in the final section.

2. Procedure of the proposed approach

As it is displayed in Fig. 1, the key processes of this approach are: (a) the construction of the output characteristic's storage degradation model, (b) the calculation of the REPs' distribution based on manufacturing process information, (c) the reliability assessment based on the storage degradation model of output characteristic.

The simplified procedure for manufacturing process-based storage degradation modelling and reliability assessment is listed as follows.

(1) Construct the output characteristic function of BLPs, based on the manufacturing process information and composition characteristic of the product.
(2) Build the physics-of-failure (PoF)-based storage degradation models of BLPs, based on the degradation mechanism.
(3) Construct the storage degradation model of output characteristic by combining the output characteristic function with storage degradation models of BLPs together.
(4) Calculate the distribution of REPs of batch products, based on simulation techniques and the manufacturing process information of product.
(5) Estimate the FEPs of the output characteristic's storage degradation model and REPs of all testing samples, according to the storage testing data.
(6) Calculate the storage reliability of batch products through either analytical or numerical way, based on the storage degradation model of output characteristic, calculated REPs and estimated FEPs.

3. Approach for storage degradation modelling and reliability assessment

3.1. Manufacturing process-based storage degradation modelling

As a measurement of product's storage degradation process, output characteristic is determined by a number of BLPs. The functional relationship of output characteristic with respect to BLPs could be expressed as follows.

$$D = F(P\,|\Theta_1) \tag{1}$$

where D denotes the output characteristic, $P = \{p_1, p_2, \ldots, p_n\}$ represents the set of n BLPs, Θ_1 is the model parameter set determined by the manufacturing process, and represents unit-to-unit variability of batch products.

For any p_i in P, when it degrades due to the effect of storage environment stress. The PoF-based degradation path model could be described as:

$$p_i(t, S) = G(t, S\,|\Theta_2^i) \tag{2}$$

where $p_i(t,S)$ is the ith BLP at time t and stress level S, $\Theta_2{}^i$ is a parameter set which denotes the impact of the stress on p_i, and the parameters in $\Theta_2{}^i$ are determined by fixed factors, such as product materials, the type of the stress, storage degradation mechanisms, etc.

Let $\Theta_2 = \{\Theta_2{}^1, \Theta_2{}^2, \ldots, \Theta_2{}^n\}$. The storage degradation model of output characteristic that characterizes the degradation process of batch products can be obtained by combining Eqs. (1) with (2).

$$\begin{aligned} D(t, S) &= F(P(t, S)\,|\Theta_1) \\ &= F'(t, S \mid \Theta_1, \Theta_2) \end{aligned} \tag{3}$$

According to the indicated meanings, Θ_1 and Θ_2 correspond to the REPs and the FEPs [11], respectively.

3.2. Distribution characteristics calculation of REPs

REPs Θ_1 and FEPs Θ_2 of the testing samples can be obtained by parameter estimation. In order to describe the storage degradation paths of batch products, it is necessary to find the exact distribution characteristics of Θ_1. Therefore, with the manufacturing process information, a finite element simulation and approximate modelling-based method for calculating the distribution characteristics of Θ_1 is proposed.

The constructed manufacturing process-based approximate models for D and p_i are shown as follows.

$$\begin{cases} D = H(\Delta X) \\ p_i = H^i(\Delta X) \end{cases} \tag{4}$$

where $\Delta X = \{\Delta x_1, \Delta x_2, \cdots, \Delta x_m\}$ denotes the variation set of m manufacturing process parameters which determines the values of D and p_i.

Then, k variation sets can be obtained by random sampling, and the corresponding D and p_i will be evaluated by substituting these variation sets into Eq. (4). Finally, the k sets of evaluated $\{D, p_i\}$ should be substituted into Eq. (1) to estimate the corresponding $\{\Theta_1{}^1, \Theta_1{}^2, \ldots, \Theta_1{}^k\}$. In cases when k is large enough, the distribution characteristics of Θ_1 can be obtained.

3.3. Degradation model-based storage reliability assessment

When the formula of Eq. (3) is simple enough to be transformed to an inequality for the REPs with analytical methods, the reliability could be calculated with Eq. (5) directly.