Optimal Design of Multi-Stress Accelerated Degradation Test within Irregular Test Region

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Abstract. Motorized spindle is the key functional part of the computer numerical control machine tool and its lifetime determines the reliability level of the machine tool to a great extent. Many efficient plans have been obtained for electronic products but how to design an efficient accelerated degradation test plan for the motorized spindle is still a problem to be solved. In this paper, considering the condition that the loaded stresses of the motorized spindle in practice may not reach their highest levels simultaneously, a novel optimization design method of the accelerated degradation test is proposed within the irregular test region. The orthogonal design theory and the uniform design theory are applied to determine the alternative test plans within the irregular test region for different numbers of stress levels. A numerical example is presented to illustrate the effectiveness of the proposed method. Finally, the sensitivity analysis is conducted to assess the robustness of the optimum plan on parameter variation.

1. Introduction

Computer numerical control (CNC) machine tool is the foundational equipment to realize the modernization of the manufacturing industry. The reliability of the CNC machine tool has a great influence on the manufacturing process and relates to the product’s reliability [1-2].

Motorized spindle is the key functional part of the CNC machine tool and its lifetime determines the reliability level of the CNC machine tool to a great extent. With the rapid development of the high-speed machining technology, the machining level has been continuously improved, so people put forward higher requirements for the reliability of the motorized spindle [3].

Motorized spindle is a complex mechanical-electrical-hydraulic system with multiple failure modes and failure causes [4]. The reliability test of the motorized spindle is the main technological approach to design and improve its reliability. However, as a highly reliable product, the failure data of the motorized spindle that can be obtained from the field test or life test within a short time are not enough for the reliability assessment. For this issue, some scholars have proposed the degradation test (DT) of the motorized spindle based on the performance indicators which gradually degrade over
time. The lifetime of the motorized spindle is defined as the working time until the key performance indicator reaches a certain threshold under the normal condition. Qiu [5] established the Weibull distribution model of the motorized spindle based on the degradation data of the radial run-out. Jiang [6] proposed the DT method of the motorized spindle based on the virtual augmented sample method. However, these DTs are carried out under the normal stress level. They also take much time and money to obtain sufficient information for the reliability assessment.

Accelerated degradation test (ADT) is an alternative approach to collect the degradation data under the higher stress level. In a common ADT, units are allocated to several stress levels, and the degradation process is measured, analyzed, and extrapolated to the failure threshold to estimate the lifetime of the product under the normal condition [7]. The effectiveness of ADT and the accuracy of reliability assessment depend on the efficient test plan, including the sample size, stress level, test time, and so on. Many researchers have obtained the optimal ADT plans for electronic products. For example, Zhao [8] presented the ADT framework for mission-oriented systems subject to degradation and shock. Limon [9] designed the optimal ADT plan of carbon film resistors considering the stochastic gamma process with constant stress loading. Liang [10] compared three ADT plans with temperature and driving currents as stepwise increasing loads to determine an appropriate test strategy for UV LEDs. Omshi [11] obtained the ADT plan of the electrical connector when the degradation path follows the inverse Gaussian process. Tseng [12] proposed the design method of SSADT and the degradation data of the light-emitting diodes were used to illustrate the proposed procedure. Wang [13] studied the maximum likelihood estimation of the accelerated degradation model for the light output of the GaAs laser device. Zhang [14] established the ADT model based on the real ILL data collected from an in-service pipeline. Ye [15] applied the accelerated degradation model without random effects to fit the stress relaxation data of the electrical connectors.

However, when designing the ADT, researchers always assumed that all the stress levels between the normal stress and the highest stress could be loaded on the test unit. Accordingly, if one establishes a Cartesian coordinates system with the multiple stresses to be axed, the range of test stress, called test region, is a rectangular area [16-18]. But in the practice, one stress may be limited by the other stress, which will lead to the condition that the loaded stresses cannot reach the highest stress levels simultaneously, and the test region becomes irregular. For the motorized spindle, under a certain power, the rotating speed and the torque are in the inverse proportion, that is to say, the higher the rotating speed is, the smaller the torque is. On the contrary, the lower the rotating speed is, the higher the torque is. The rotating speed and the torque cannot reach their highest condition. To solve this problem, the optimal design method of the multi-stress ADT is proposed in this paper. The orthogonal design theory and uniform design theory are used to select the alternative test plans within the irregular test region.

The rest of paper is organized as follows. Basic assumptions of models are described in Section 2. The optimization model is established in Section 3. The optimal design method based on the orthogonal design and the uniform design is described in Section 4. The proposed method is applied to a certain type of motorized spindles to demonstrate its effectiveness and the sensitivity analysis is conducted to assess the robustness of the optimum plan in Section 5. Some concluding remarks are addressed in Section 6.

2. Model Assumptions

2.1. Degradation Model
Assuming that the degradation process is irreversible, the degradation model is established based on cumulative damage theory [19],

\[ c(X_{n+1}) = c(X_n) + D_n h(X_n), \]  

(1)
where $X_n$ is the measured value of the performance index at $t_n$, $c(\cdot)$ is the continuous cumulative damage function, $D_n$ is the degradation amount of the performance index during $(t_n, t_{n+1}]$, $h(\cdot)$ is the function of damage model.

The different form of equation (1) is

$$dc(X_n) = h(X_n)dD_n.$$  \hfill (2)

Thus, the degradation amount during $(0, t]$ is

$$\int_0^t \frac{1}{h(X_n)} dc(X_n) = \int_0^t dD_n = D_t - D_0. \hfill (3)$$

In equation (3), if $c(\cdot) \neq h(\cdot)$, the random process $\{D_u: 0 \leq u \leq t\}$ and the degradation model will be different. Considering the failure characteristics of complex electrometrical products, let $c(u)=u$, $h(u)=1$. $\{D_u: 0 \leq u \leq t\}$ is the Wiener process with parameters $\mu > 0$ and $\sigma^2$. The degradation amount before $t$ is

$$X_t - X_0 = D_t, \hfill (4)$$

where $X_0$ is the initial value of the performance index.

When $\{D_u: 0 \leq u \leq t\}$ is taken into equation (4), there is

$$X_t = X_0 + \mu t + \sigma B(t). \hfill (5)$$

In general, assuming that the standard Brownian motion $B(t) - N(0, t)$, equation (5) is equal to

$$X_t = X_0 + \mu \delta + \sigma B(\delta), \hfill (6)$$

where $\delta(t)$ is the scale function, $\delta = t^k$, and $k$ is the scale parameter.

$Y$ is defined as the degradation threshold. The degradation failure time $T$ of the performance index can be regarded as the time when a certain point of Brownian motion reaches the predetermined value $Y$ for the first time, and $T$ obeys the standard inverse Gaussian distribution.

2.2. Acceleration Model

The acceleration model is generally used to describe the relationship between the parameters of the degradation model and the accelerated stresses. For the motorized spindle, the performance indexes are often related to multiple stresses [20]. To establish a universal model, the generalized log-linear accelerated model is applied as

$$\ln \mu = \gamma_0 + \gamma_1 \ln S_1 + \gamma_2 \ln S_2 + \ldots + \gamma_s \ln S_s, \hfill (7)$$

where $\gamma_0, \gamma_1, \gamma_2, \ldots, \gamma_s$ are unknown parameters, $S_1, S_2, \ldots, S_s$ are different kinds of stresses that effect performance indexes, and $s$ is the total number of stresses.

3. Establishment of Optimization Model

3.1. Design Variables

All factors of ADT can be taken as design variables as follows:

- The total stress levels $L_i$ ($i=1, 2, \ldots, s$) of the stress $S_i$ and the stress combination $\left(S_{i_1}, \ldots, S_{i_l}\right)$, $l=1, 2, \ldots, L_s$, where $s$ is the total number of stresses.
- The sample size $n_{\left[S_{i_1}, \ldots, S_{i_l}\right]}$ under the stress combination $\left(S_{i_1}, \ldots, S_{i_l}\right)$.
- The inspection interval $f_{\left[S_{i_1}, \ldots, S_{i_l}\right]}$ under the stress combination $\left(S_{i_1}, \ldots, S_{i_l}\right)$.
• The inspection times $m_{\left(s^i_l,...,s^i_r\right)}$ under the stress combination $\left(S^i_l,...,S^i_r\right)$.

In practical applications, the number of design variables can be reduced referring to the engineering experience so that the optimization algorithm can be simplified.

3.2. Constraints
The test cost is always concerned by researchers, which consists of the sample cost, the inspection cost, the operation cost and the salary of operators.

Therefore, the total cost of ADT could not exceed the test budget, which can be expressed as

$$C_T = C_T \sum_{l=1}^{l_s} \sum_{s=1}^{s_s} n_{\left[s^i_l,...,s^i_r\right]} + C_M \sum_{l=1}^{l_s} \sum_{s=1}^{s_s} n_{\left[s^i_l,...,s^i_r\right]} m_{\left[s^i_l,...,s^i_r\right]}$$

$$+ C_O \sum_{l=1}^{l_s} \sum_{s=1}^{s_s} f_{\left[s^i_l,...,s^i_r\right]} m_{\left[s^i_l,...,s^i_r\right]} + C_W \max_{l=1,...,l_s} \sum_{s=1}^{s_s} f_{\left[s^i_l,...,s^i_r\right]} m_{\left[s^i_l,...,s^i_r\right]} \leq C_b,$$

where $C_T$ denotes the total test cost, $C_T$ denotes the unit cost of sample, $C_M$ denotes the unit cost of measurement, $C_O$ denotes the depreciation of testing samples and the consumption of utilities such as water and electricity in unit time, $C_W$ denotes the salary of operators in unit time, $C_b$ denotes the total pre-fixed budget of tests, and $m_{\left[s^i_l,...,s^i_r\right]}$ denotes inspection times.

3.3. Optimization Objective
The optimization design of ADT is to improve the prediction accuracy of the reliability indexes under the limited test budget. In this paper, the optimization objective is to minimize the mean square error (MSE) of the estimated value of the average life $t_0$ under the normal condition, i.e.,

$$MSE\left(\hat{t}_0\right) = E\left[\left(\hat{t}_0 - t_0\right)^2\right],$$

where $\hat{t}_0$ is the estimated value of the average life $t_0$ under the normal condition.

Owing to the introduction of the acceleration model and the difficulty to obtain the MSE in its analytical form, MSE is calculated by the Monte Carlo simulation to take place of $MSE\left(\hat{t}_0\right)$, that is

$$Z = \frac{1}{N_{MC}} \sum_{\omega=1}^{N_{MC}} \left[\hat{t}_\omega - t_0\right]^2,$$

where $Z$ is the function of the optimization objective, $N_{MC}$ is the times of the Monte Carlo simulation, $\hat{t}_\omega$ is the mean lifetime of the $\omega$th simulation under the normal condition and $t$ is the assumed true value.

4. Optimization Design Method
4.1. Standardization of Irregular Test Region
Firstly, standardize the irregular test region. As in figure 1, $O \left(0, 0, 0\right)$ is the stress level point under the normal condition, and $Q_{EFG}$ is the boundary surface of the irregular region. The surface function of $Q_{EFG}$ is $z=f(x, y)$, where $0 < x < 1, 0 < y < 1, 0 < z < 1$. 


Figure 1. Irregular test region

Figure 2. Test region of alternative test plans

And then, as shown in figure 2, \( S(x_L, y_L, f(x_L, y_L)) \) in the boundary surface \( Q_{EFG} \) is selected as the highest stress level point. The lowest stress level point is optimized based on the optimization objective. \( LMNP-QRST \) is the test region to determine the alternative test plans.

Given the total number \( K \) of stress levels, other stress levels can be determined by the following principle of equal-interval distribution according to the highest stress level point \( S \) and the lowest stress level point \( L(x_L, y_L, f(x_L, y_L)) \), that is

\[
\begin{align*}
    x_i &= \frac{(K-1)x_L + (i-1)x_S}{K-1}, \\
    y_i &= \frac{(K-1)y_L + (i-1)x_L}{K-1}, \\
    z_i &= \frac{(K-1)f(x_S, y_S) + (i-1)f(x_L, y_L)}{K-1},
\end{align*}
\]

where \((x_i, y_i, z_i)\) are equal interval points within the irregular test region, and \(i=1, 2, ..., K\).

**4.2. Optimization Method Based on Orthogonal Design**

There are many combinations of test points in accordance with orthogonal design. The orthogonal characteristics of different combinations are different. For the orthogonal design of different stress levels and different combination of stress points, the optimization result is different, so it is necessary to find out the best combination of stress points for each stress level. Computer simulation tests are conducted and the best stress combinations with the smallest value of variance factor are determined in figure 3 and tables 1-3, when \( K \) are selected as 2, 3 and 4. \( A_i, B_i, C_i \) are the stress levels of each stress \( A, B, C \).
Figure 3. Best stress combinations when $K=2$, 3 and 4

Table 1. Best stress combinations when $K=2$

|   | A     | B     | C     |
|---|-------|-------|-------|
| 1 | (1) $A_1$ | (1) $B_1$ | (1) $C_1$ |
| 2 | (1) $A_1$ | (2) $B_2$ | (2) $C_2$ |
| 3 | (2) $A_2$ | (1) $B_1$ | (2) $C_2$ |
| 4 | (2) $A_2$ | (2) $B_2$ | (1) $C_1$ |

Table 2. Best stress combinations when $K=3$

|   | A     | B     | C     |
|---|-------|-------|-------|
| 1 | (1) $A_1$ | (1) $B_1$ | (1) $C_1$ |
| 2 | (1) $A_1$ | (2) $B_2$ | (2) $C_2$ |
| 3 | (1) $A_1$ | (3) $B_3$ | (3) $C_3$ |
| 4 | (2) $A_2$ | (1) $B_1$ | (2) $C_2$ |
| 5 | (2) $A_2$ | (2) $B_2$ | (3) $C_3$ |
| 6 | (2) $A_2$ | (3) $B_3$ | (1) $C_1$ |
| 7 | (3) $A_3$ | (1) $B_1$ | (3) $C_3$ |
| 8 | (3) $A_3$ | (2) $B_2$ | (1) $C_1$ |
| 9 | (3) $A_3$ | (3) $B_3$ | (2) $C_2$ |

Table 3. Best stress combinations when $K=4$

|   | A     | B     | C     |
|---|-------|-------|-------|
| 1 | (1) $A_1$ | (1) $B_1$ | (1) $C_1$ |
| 2 | (1) $A_1$ | (2) $B_2$ | (2) $C_2$ |
| 3 | (1) $A_1$ | (3) $B_3$ | (3) $C_3$ |
| 4 | (1) $A_1$ | (4) $B_4$ | (4) $C_4$ |
| 5 | (2) $A_2$ | (1) $B_2$ | (2) $C_2$ |
All points in the boundary surface $QEFG$ are selected to be the highest stress level, and the point $S^*$ is selected as the optimal stress point based on the optimization model. Meanwhile, the plan under the stress point $S_1^*$ is determined as the optimal test plan.

4.3. Optimization Method Based on Uniform Design

The starting point of uniform design theory is to make test points to be dispersed uniformly within a test range and ensure the uniformity adequately, which can not only reduce the number of test points, but also obtain the result that reflects the major characteristic of the test system. Therefore, when loading stresses of ADT have more than four levels, the uniform design theory has a better optimization effect.

ADT with three kinks of loaded stresses is taken as an example in this paper. According to uniform design theory, the best stress combinations with the smallest value of variance factor are determined in tables 4-6 when $K=5$, 6 and 7.

**Table 4. Best stress combinations when $K=5$**

|   | (1) A | (2) B | (3) C |
|---|-------|-------|-------|
| 1 | $A_1$ | $B_2$ | $C_4$ |
| 2 | $A_2$ | $B_4$ | $C_3$ |
| 3 | $A_3$ | $B_1$ | $C_2$ |
| 4 | $A_4$ | $B_3$ | $C_1$ |
| 5 | $A_5$ | $B_3$ | $C_5$ |

**Table 5. Best stress combinations when $K=6$**

|   | (1) A | (2) B | (3) C |
|---|-------|-------|-------|
| 1 | $A_1$ | $B_2$ | $C_3$ |
| 2 | $A_2$ | $B_4$ | $C_6$ |
Table 6. Best stress combinations when $K=7$

|   | (1) $A$ | (2) $B$ | (3) $C$ |
|---|---------|---------|---------|
| 1 | (1) $A_1$ | (2) $B_2$ | (3) $C_3$ |
| 2 | (2) $A_2$ | (4) $B_4$ | (6) $C_6$ |
| 3 | (3) $A_3$ | (6) $B_6$ | (2) $C_2$ |
| 4 | (4) $A_4$ | (1) $B_1$ | (5) $C_5$ |
| 5 | (5) $A_5$ | (3) $B_3$ | (1) $C_1$ |
| 6 | (6) $A_6$ | (5) $B_5$ | (4) $C_4$ |
| 7 | (7) $A_7$ | (7) $B_7$ | (7) $C_7$ |

All points in the boundary surface $Q_{EFG}$ are selected to be the highest stress level, and the point $S^*$ is selected as the optimal stress point based on the optimization model. Meanwhile, the plan under the stress point $S_{x}^*$ is determined as the optimal test plan.

5. Numerical Example

5.1. Test Description
To illustrate the effectiveness of the proposed optimization method, a certain type of motorized spindle is used to carry out ADT. The rotating speed, torque, and cutting force are three essential stresses of the motorized spindle in the using conditions. However, the torque and the cutting force decrease gradually with the increase of the rotating speed, which is shown in figure 4.

![Figure 4. Relationship between rotating speed, torque and cutting force](image)
In the ADT of the motorized spindle, these three stresses cannot reach the highest level at the same time, that is, the test region is irregular. Therefore, the proposed method in this paper is used to design the ADT of motorized spindles with the inspection interval and inspection times as design variables. Because the lifetime of the motorized spindle is highly correlated with the radial run-out, the radial run-out is set as the observation index of the degradation in the ADT of the motorized spindle.

Assuming that the initial radial run-out is 4.5μm, the lifetime of the motorized spindle is defined as the time when the value of the radial run-out reaches 30μm. The stress levels of the rotating speed, torque, and cutting force at the normal condition are $S_{10}=4000$ rpm, $S_{20}=10$ Nm, and $S_{30}=2800$ N.

The predetermined budget $C_b$ is set as 750 thousand yuan. According to the actual situation, other costs of ADT are itemized in table 7.

| Item   | Value (thousand yuan) |
|--------|-----------------------|
| Expected expense | 750 |
| $C_P$   | 25 |
| $C_M$   | 0.2 |
| $C_O$   | 0.02 |
| $C_W$   | 0.01 |

### 5.2. Optimum Test Plan

Under the $\xi$th combination of three stresses ($S_{1\xi}$, $S_{2\xi}$, $S_{3\xi}$), when the $\alpha$th test sample is performed for the $k$th inspection, the inspection time is $t_{k,\alpha}^{(S_{1\xi},S_{2\xi},S_{3\xi})}$ and the degradation amount at this time is $X_{k,\alpha}^{(S_{1\xi},S_{2\xi},S_{3\xi})}$. The degradation increment between $t_{k,\alpha-1}^{(S_{1\xi},S_{2\xi},S_{3\xi})}$ and $t_{k,\alpha}^{(S_{1\xi},S_{2\xi},S_{3\xi})}$ is $\Delta X_{k,\alpha}^{(S_{1\xi},S_{2\xi},S_{3\xi})}$.

Thus, there is

$$
\Delta X_{k,\alpha}^{(S_{1\xi},S_{2\xi},S_{3\xi})} \sim N \left( \mu(S_{1\xi},S_{2\xi},S_{3\xi}), \sigma^2 \left( \delta_{k,\alpha}^{(S_{1\xi},S_{2\xi},S_{3\xi})} - \delta_{k,\alpha-1}^{(S_{1\xi},S_{2\xi},S_{3\xi})} \right) \right),
$$

where $\sigma=0.008476$, $\delta = \mu^{1.506}$.

The accelerated model is

$$
\ln \mu(S_{1\xi},S_{2\xi},S_{3\xi}) = \gamma_0 + \gamma_1 \ln S_{1\xi} + \gamma_2 \ln S_{2\xi} + \gamma_3 \ln S_{3\xi}
$$

where $(-11.6428, 0.0875, 0.3423, 0.0914)$.

The log likelihood function is
The average life of products at using conditions is

\[ t_0 = E(t) = \frac{Y - X_0}{\exp(\gamma_0 + \gamma_1 \ln S_{\gamma_0} + \gamma_2 \ln S_{\gamma_2} + \gamma_3 \ln S_{\gamma_3})}. \]

The optimal design of ADT, with the stress level \( K \) being 4 and 5, is taken as examples to demonstrate the optimization method in this paper. According to the orthogonal design theory in table 3 and the uniform design theory in table 6, all points in the boundary surface Q\(_{EFG}\) are seleted as the highest stress level point \( S(x_S, y_S, f(x_S, y_S)) \). And then, the lowest stress level point is optimized by the given number \( K \) of stress levels within the test region \( LMNP_{-QRST} \) based on the optimization model. Finally, the optimum test plan is determined in table 8.

### Table 8. Optimum test plan of motorized spindle

| Lowest stress level | Highest stress level | \( f \) | \( m \) | \( Z \) | \( C_T \) |
|---------------------|----------------------|--------|--------|------|--------|
| \( K=4 \)           | (5582, 16, 4331)      | (15, 17, 20, 23) | (25, 24, 22, 21) | 1.58\times10^{17} | 64.51 |
| \( K=5 \)           | (4907, 18, 4200)      | (11, 13, 14, 16, 19) | (22, 21, 20, 18, 16) | 1.63\times10^{17} | 68.20 |

#### 5.3. Sensitivity Analysis

To observe the sensitivity of the optimum plan, the effect of the prior parameters on the optimal result is evaluated, and the relative ratio of \( \text{MSE}(\hat{t}_0) \) in the two cases is used as the evaluation standard, that is,

\[ RV = \left| \frac{\text{MSE}(\hat{t}_0)}{\text{MSE}^*} \right| \times 100\%, \tag{14} \]

where \( \text{MSE} \) is the value of asymptotic variance when model parameters are not changed and \( (\text{MSE})^* \) is the value of asymptotic variance after model parameters are changed.

To obtain the sensitivity of individual model parameters to the optimal result and exclude the mutual effect between parameters, only one parameter is changed every time, while other parameters remain unchanged. The deviations of the parameters are defined as \( \varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4 \), so that the model parameters after changed are \( (1+\varepsilon_1)\gamma_0, (1+\varepsilon_2)\gamma_1, (1+\varepsilon_3)\gamma_2, \) and \( (1+\varepsilon_4)\gamma_3 \). Let \( \varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \varepsilon_4 = 10\% \), then the result of sensitivity analysis is shown in table 9.

### Table 9. Sensitivity analysis for the effect of parameters on the optimal result

| Deviation of model parameters | Relative ratio |
|------------------------------|---------------|
| +10%                         | 1.45          |
It is shown in table 9 that the fluctuation of MSE is acceptable when the deviation of model parameters is ±10%, implying that the optimum test plan of the motorized spindle is less sensitive to the parameter deviation and has a good robustness.

6. Conclusion
In this paper, the optimization method of the motorized spindle is proposed for the ADT with an irregular test region. In the method, the orthogonal design theory and the uniform design theory is used to determine the alternative test plans within the irregular test region for different numbers of stress levels. And then, the optimum test plan is obtained to minimize the MSE of the estimated value of the average life under the normal condition, under the constraints that the test cost does not exceed the test budget.

The main original contributions of this work are as follows.
(1) The irregular test region formed by loaded stresses in the engineering practice is highlighted and the problem of irregular test region has been effectively dealt with by the orthogonal design theory and the uniform design theory, which can be applied in the case of the different numbers of stress levels.
(2) The numerical example is used to illustrate the effectiveness of the proposed optimization method, which will give advice on the reliability test of other products in the future.

Acknowledgments
Supported by National Science and Technology Major Project (Grant No. 2019ZX04024001), National Natural Science Foundation of China (Grant No. 51975249 and 51675227), Jilin Province Science and Technology Development Funds (Grant No. 20180201007GX and 20190302017GX), Technology Development and Research of Jilin Province (Grant No. 2019C037-01), Changchun Science and Technology Planning Project (Grant No. 19SS011), finally, the paper is supported by Program for JLU Science and Technology Innovative Research Team (JLUSTIRT).

References
[1] Mu Z, Zhang G, Ran Y and Zhang S 2019 Reliability Statistical Evaluation Method of CNC Machine Tools Considering the Mission and Load Profile IEEE Access 7 115594 - 115602
[2] Liu Y, Peng H and Yang Y 2018 Reliability Modeling and Evaluation Method of CNC Grinding Machine Tool Appl Sci 9 2076-3417
[3] Huang H, Liu Z, Mi J and Li Y 2018 Reliability modeling and analysis of heavy-duty CNC machine tool spindle under hybrid uncertainty Sci Sin Phys Mech Astron 1 42-53
[4] Yang Z, Li X, Chen C and et.al. 2018 Reliability assessment of the spindle systems with a competing risk model P I Mech Eng O J Ris 233 226-34
[5] Qiu R, Ju K, Dong Y and et.al. 2016 Research on reliability test based on small sample motorized spindle performance degradation China Mech Eng 27 2738-42
[6] Jiang X, Liu H, Liu L and et.al. 2013 Extrmely small-scale sample’s reliability of an electric spindle based on distribution of false lifetime J Vib Shock 10.13465/j.cnki.jvs.2013.19.014
[7] Duan F and Wang, G 2019 Optimal design for constant-stress accelerated degradation test based on gamma process Commun Stat Theor M 48 2229-53
[8] Zhao X, He K, Kuo W and et.al. 2019 Planning Accelerated Reliability Tests for Mission-Oriented Systems Subject to Degradation and Shocks IIE Trans 52 91-103
[9] Limon S, Rezaei E, Yadav OP and et.al. 2019 Designing an accelerated degradation test plan considering the gamma degradation process with multi-stress factors and interaction effects Wual Technol Quant M 10.1080/16843703.2019.1696010
[10] Liang B, Wang Z, Qian C and et.al. 2019 Investigation of Step-Stress Accelerated Degradation Test Strategy for Ultraviolet Light Emitting Diodes Materials 12 1996-44
[11] Omshi EM and Shemehsavar S 2019 Optimal Design for Accelerated Degradation Test Based on D-Optimality Iran J Sci Technol A 43 1811-8
[12] Tseng S and Wen Z 2000 Step-stress accelerated degradation analysis for highly reliable products. J Qual Technol 32 209-16
[13] Wang X and Xu D 2010 An inverse Gaussian process model for degradation data Technometrics 52 188-97
[14] Zhang S, Zhou Q and Qin H 2013 Inverse Gaussian process-based corrosion growth model for energy pipelines considering the sizing error in inspection data Corros Sci 73 309-20
[15] Ye Z, Chen L, Tang L and Xie M 2014 Accelerated degradation test planning using the inverse Gaussian process IEEE T Reliab 63 750–63
[16] Wang Y, Chen X and Tan Y 2017 Optimal Design of Step-stress Accelerated Degradation Test with Multiple Stresses and Multiple Degradation Measures Qual Reliab Eng Int 33 1655-68
[17] Ge Z, Jin T, Han S and et.al. 2012 Design of accelerated degradation testing with multiple stresses based on D optimality Syst Eng Electron 34 846-53
[18] Chen Y, Sun W and Xu D 2017 Multi-Stress Equivalent Optimum Design for Ramp-Stress Accelerated Life Test Plans Based on D-Efficiency IEEE Access 5 25854-62.
[19] Park C and Padgett W J 1997 New cumulative damage model for system failure with application to carbon fibers and composites Technometrics 39 34-44
[20] Ye X and et.al. 2016 Online condition monitoring of power MOSFET gate oxide degradation based on Miller Platform Voltage IEEE Trans Power Electr 32 4776-84