Reliability evaluation of electro spindle based on no-failure data

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Abstract. Electric spindle is a key functional component of CNC machining equipment including CNC machine tools, and its reliability level is a key bottleneck factor restricting the reliability of high-end CNC equipment. So far, the research on the reliability evaluation method of electric spindle is still in its infancy, and there is a lack of Systematic and complete theoretical support. The motorized spindle is a typical high-reliability and long-life product, and it is difficult to fail or fail due to obvious performance degradation within a limited test time. Therefore, the traditional reliability evaluation method based on statistical theory is not effective. Therefore, it is of great significance to carry out the early reliability test of the motorized spindle and the reliability evaluation of the motorized spindle without failure data, which is of great significance to reasonably evaluate the reliability level of the motorized spindle. At present, when there is no failure data or very little failure data for the motorized spindle of the machine tool, only the point estimate of the parameter or the one-sided confidence interval of the parameter can be calculated, and it is extremely difficult to obtain the point estimate and the interval estimate at the same time, which will affect the reliability analysis results. Consistency. In order to solve this problem, this paper takes a certain type of CNC machine tool motorized spindle as the research object, and determines the monitoring points and monitoring information according to the failure analysis of similar motorized spindles; combines the test information to evaluate the reliability of the motorized spindle without failure data. The reliability evaluation method of the motorized spindle proposed in this paper can effectively avoid the problem that the traditional method cannot be analyzed when there is no failure data, and provides a new idea for the reliability evaluation of the motorized spindle.

Keywords: Electro Spindle, E-Bayes Method, No-failure Data, Reliability Estimation.

1. Introduction

The early CNC machine tool spindles mainly used two different transmission modes: gear transmission and belt transmission. These two modes are simple in structure, but have the disadvantages of large vibration and strong noise in practical applications, and the speed is low, which cannot meet today's production[1, 2]. High-speed and high-precision machining requirements in manufacturing requirements. Therefore, with the continuous improvement of high-speed and high-precision machining and manufacturing requirements, motorized spindles with more compact structure, high rotational speed and small moment of inertia are widely used in high-speed CNC machine tools and CNC machining equipment. The motorized spindles used in high-speed CNC machine tools and CNC machining equipment use frequency conversion motors and machine tool spindles to drive the motorized spindles, through this method and design, the electric spindle can realize the "zero transmission" between the frequency conversion motor and the machine tool spindle.[3]

Reliability evaluation of mechanical and electronic products refers to a method of evaluating the reliability level of a product through a certain reliability test at a specified time and under a specified working condition. The basic idea is to design a series of accelerated life reliability tests or field failure data collection to analyze the function or reliability characteristics of the product under specific circumstances, so as to expose the defects and deficiencies of the product in the process of design and manufacturing. , to provide methods and opinions for product optimization and improvement, and improve the reliability and life of related products. Among them, the accelerated

life reliability test mainly involves the construction of the test bench, the design of the test hardware system and the monitoring system[4].

Considering the characteristics of high reliability and long test time of the motorized spindle, sometimes small samples of fault data or even no failure data will be encountered during the accelerated degradation test, which brings the traditional reliability analysis method. Challenge. For the non-failure data of a certain type of aero-engine, [5]under the condition that the shape parameters of the Weibull function are known, a new life prediction method is used to analyze the reliability lower confidence limit and life confidence lower limit of this type of aero-engine calculation, and an example is given. [6] al. proposed a method to convert the constant accelerated stress into normal stress to calculate the life information of key performance components based on the failure-free accelerated life test results of key performance components of a certain type of satellite. In his paper, used the optimal confidence limit and the one-sided confidence limit to calculate and compare the reliability of rolling bearings without failure data, and obtained the scope of application of the two methods. In his paper, [7]used the modified Bayesian method to calculate the failure probability of each point when using the distribution curve method for rolling bearings without failure data, and completed the reliability assessment.

All of the above methods can be used to evaluate the reliability of related high-reliability products including aero engines, rocket engines and bearings under small samples or even no failure data. However, it is obvious that these methods all have a common shortcoming, which is that they require a long time to test with multiple samples. However, considering the high cost of the electro spindle, these methods have some limitations in analyzing the reliability of the electro spindle. Under the condition of no failure data, the use of Bayesian method can make full use of the prior information of product information, thereby improving the accuracy of reliability assessment. [8]used the multi-layer Bayesian method to calculate the failure probability of a certain type of bearing at each truncation time, and then used the distribution curve method to estimate the reliability of the product. [9]et al. conducted a reliability test of successive timing truncation on the test bench for two samples of grinding motorized spindles and used the method of virtual augmented samples to truncate the tails of the two experimental grinding motorized spindles. The test life is virtually extended in order to improve the accuracy of the evaluation of the electro spindle, and finally the reliability evaluation of the very small sample is carried out using the Bayesian method. [10]took the Beta function as the prior distribution of the product after analyzing the reasons why the reliability evaluation of non-failure data was considered "adventurous", and comprehensively considered the failure information, and proposed a "synthetic method" for reliability parameter calculation. Bayesian Estimation". [11]proposed the E - Bayes method based on the Bayesian method. The E - Bayes method overcomes the computational complexity of the multi-layer Bayesian method and the Bayesian method and improves the computing speed. , and analyzed and compared the calculation results of the multi-layer Bayesian and E-Bayes methods. The final results show that when the sample size is sufficient, the calculation results of the two methods are very close. The E- Bayes method is not only simple and convenient in the operation process, but also it is almost the same as the multi-layer Bayesian method.

According to the above analysis content, on the basis of analyzing the basic principle and degradation mechanism of the motorized spindle, and comprehensively considering the time and economic cost, according to the early reliability experiment of the motorized spindle on this motorized spindle accelerated degradation test bench for a certain period of time, the collection And analyze the test data, and finally use the E- Bayes method and Bootstrap method to evaluate the reliability of the motorized spindle without failure data.

According to the collected experimental data, a reliability evaluation model that does not reduce the credibility of the evaluation results is proposed for the case where there is no failure data in the accelerated degradation test of the electric spindle. The new motor-spindle reliability evaluation model can obtain the point estimation and interval estimation of the reliability of the motor-spindle at the same time. Firstly, the E- Bayes method is used to calculate the failure probability estimates of the electric spindle at different truncation times. At the same time, the distribution curve of the electric

spindle is fitted to obtain the cumulative fault distribution curve of the electric spindle, so as to obtain the reliability point estimation value of the electric spindle system. . Then, the idea of Bootstrap sample self-help method is used to extract samples from the accumulated fault distribution curve that has been obtained, and the confidence interval estimation of the reliability of this model of motorized spindle is obtained by estimating the new samples obtained. At the end, a comparative analysis with other methods is given to verify that the model is not only simple to calculate, but also can obtain a higher-precision confidence interval estimate at the same time.

2. Reliability evaluation of electro spindle without failure data

Firstly, the combination distribution curve method is proposed, and based on the E- Bayes method, the product failure probability estimation under each truncation time is calculated, and then the point estimation of the reliability of the machine tool electric spindle is calculated. Then, the method of parameter Bootstrap was introduced to re-sample randomly and repeatedly from the cumulative fault distribution curve of the motorized spindle, and the confidence interval of the motorized spindle was estimated through many new samples (more than 5 000 samples).

2.1. Monte Carlo method to generate no-failure data samples of electro-spindle

Monte Carlo method was first proposed by members of the Los Alamos National Laboratory in the 1940s. During the Second World War, the Monte Carlo method was mainly used for the development and production of nuclear weapons. The Monte Carlo method used Probability and statistics are the guiding ideology, inspired by a simple random number generator - roulette, so the method is named after the world-famous casino in Morocco. The core idea of Monte Carlo method is to use random sampling techniques and statistical sampling experiments to provide approximate solutions to different mathematical problems. This process includes the probability of obtaining an approximate solution to a problem by performing a large number of simulations using random numbers obtained by sampling. According to the relevant knowledge of the theorem of large numbers and statistics [12], when the sample size T tends to infinity, the average value of the sampling sample is:

$$\frac{1}{T}\sum_{t=1}^{T} h(x_t), (x_t \sim f(x)) \tag{1}$$

This average will converge to the expected value $E_f\left[h(x)\right]$.

In order to evaluate the operation reliability of the motorized spindle system of a certain type of machine tool, the reliability timing censoring test under *j* groups of constant stress tests was carried out on m groups of electric spindles, and the timing censoring times were arranged in the order from small to large :

$$T_1, T_2, T_3, ..., T_j \quad (T_1 < T_2 < ... < T_j) \tag{2}$$

And each group of experiments has a total $n_1, n_2, ...n_j$ of one electric spindle experimental sample.

Assuming that at the end of the test, there is no failure of the electric spindle system, the data obtained at this time are the failure samples of the electric spindle without fault failure. At this time, the no-failure data of the electro-spindle is expressed as: $(T_i, n_i)(i = 1, 2, ... j)$ where T_i denotes the censoring time of the experiment.

At the same time, we believe that the following rules exist for the non-failure data information of the electro-spindle, that is, during the test process, the corresponding product failure probability at each censoring time is p_i, it is obvious that there is $p_1 < p_2 < ... < p_j$, and has:

$$s_i = n_i + n_{i+1} + ... + n_j \tag{3}$$

s_i Represents the total number of samples whose running time of the electro spindle is greater than or equal to the censoring time T_i.

To verify the wide applicability of the new model in the absence of failure data, and to estimate the gap between the evaluation results under the new model and the real value and the evaluation effect, a set of data containing a large amount of data was generated according to the Monte Carlo method using related software. Random numbers, this group of random numbers should obey Weibull distribution, and the sample size of random numbers should be much larger than the sample size of electric spindle reliability test.

According to the distribution parameters that can be obtained after eliminating the early fault data of the electro-spindle as $\beta = 1.716$, η=1811.9 Use the distribution parameters to generate random numbers containing 600 random numbers then sort them according to the method from small to large, and then divide each 10 data into a group, a total of 60 groups data. This set of data is processed at the same time. Only the first 10 groups of the group of data are taken, and for each group of data, the minimum value in the data in the group is selected. Then take a number slightly smaller than this value as a truncation time point t_i, and it can be considered that failure must not occur at this time node t_i. In this example, it is assumed that a total of 55 sets of electro-spindle systems have been tested, and the number of electro-spindle sets participating in the test n_i at each truncation time is t_i and decreases sequentially, so that a set of no-failure data of electro-spindle systems can be obtained, as shown in Table 1.

Table 1. No-failure data for electro spindles.

Serial number i	Censoring time T_i / h	Number of motorized spindle n_i / sleeves	Number of samples of electro spindle not failing s_i
1	30.8	10	55
2	193.6	9	45
3	283.9	8	36
4	344.9	7	28
5	396.7	6	21
6	455.7	5	15
7	524.2	4	10
8	578	3	6
9	652.9	2	3
10	701.7	1	1

2.2. Point Estimation of Electric Spindle Reliability

2.2.1 Distribution curve method

[13] Proposed a processing method based on non-failure data, the distribution curve method. The basic processing process is shown in Figure 1.

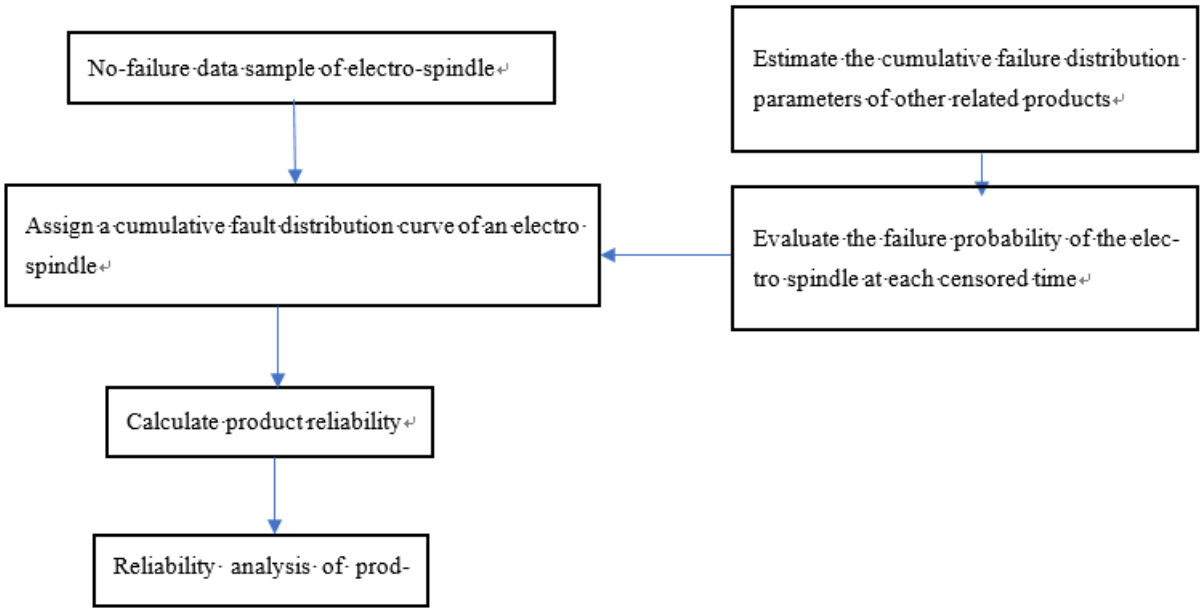


Figure 1. The frame of the distribution curve method.

From Figure 1 that the basic processing process of this method is: (1). Obtain the point estimate $\hat{p}_i$ of the failure probability p_i at the censored time t_i; (2). Use the least squares method to assign a $(t_i, \hat{p}_i)$ cumulative pass point Fault distribution curve, where $i = 1, 2, 3, ...m$ (3). Other reliability index estimates are made according to the generated cumulative fault distribution curve. The analysis shows that in the above process, the most important thing is to get the proper failure probability $\hat{p}_i$ at the censored time instant t_i.

2.2.2 E-Bayes estimation of electric spindle failure probability

Because of the failure probability of the electro-spindle system $p_i \in (0,1)$, many previous literatures used Bayes to solve related problems, and p_i defaulted the prior distribution to conform to the uniform distribution $U \in (0,1)$. However, this will lead to a small possibility of a high failure probability in the case of no failure of the electro-spindle, and a high possibility of a small failure probability. Therefore, the uniform distribution as $U \in (0,1)$ the prior distribution will have significant errors.

Therefore, the prior distribution p_i in this paper is selected as the conjugate distribution of the double hyper parameter Beta distribution, and the density function of this conjugate distribution is

$$\pi(p_i | a,b) = \frac{p_i^{a-1}(1-p_i)^{b-1}}{B(a,b)} \tag{4}$$

$a > 0, b > 0$ And both are hyper parameters, where $B(a,b) = \int_0^1 t^{a-1}(1-t)^{b-1}dt$ is the beta function.

Take derivation of the above formula, we can get:

$$\frac{d\pi(p_i | a,b)}{dp_i} = \frac{p_i^{(a-2)}[(a-1)(1-p_i)-(b-1)p_i]}{B(a,b)} \tag{5}$$

Since a, b are two hyper parameters and make it difficult to observe a, b under practical conditions. Therefore, two hyper parameters of a, b are defined as models that follow the uniform distribution.

$$\pi_1(a) = U(0,1) \tag{6}$$

$$\pi_2(b) = U(1,c) \tag{7}$$

In the above distribution, it is worth noting that c is constants greater than 1. The definition formula of the E- Bayes estimate (Expected Bayesian Estimation) p_i can be obtained from this is:

$$\hat{p}_{iE} = \iint_D \hat{p}_i(a,b)\hat{\pi}(a,b)dadb = E\left[\hat{p}_i(a,b)\right] \tag{8}$$

From the properties of the Beta function, at $a=1$, the probability density of p_i is:

$$\pi\left(p_i \middle| b\right) = b(1-p_i)^{b-1} \tag{9}$$

For parameters b, there is $1<b<c$. Bringing the above formula into the definition of E- Bayes, the definition can be simplified to:

$$\hat{p}_i = \int_D \hat{p}_i(b)\pi(b)db = E\left[\hat{p}_i(b)\right] \tag{10}$$

Where: $\hat{p}(b)$ is the Bayes estimator of p_i; $D=\{b:1<b<c, c>1\}$ which can represent the density function in the interval of $\pi(b)$ from the above equation, the estimated value $\hat{p}_i$ is the mathematical expectation of the hyper parameter under the b bayes estimate of p_i.

According to E-Bayes' related theorem[14], under the squared loss, when the prior distribution of b is:

$$\pi(b) = \frac{1}{c-1} \tag{11}$$

Combined with equation (10), the failure probability value under the E-Bayes estimation can be obtained as:

$$\hat{p}_i = \frac{1}{1-c}\ln\frac{s_i+c+1}{s_i+2} \tag{12}$$

At the same time, let the parameters $c=4$ and combined into the above formula, by using the E-Bayes method, the failure probability of the electro-spindle at each truncation time can be calculated in Table 2.

Table 2. E- Bayes Estimated Electro spindle Failure Probabilities.

serial number i	censoring time T_i / h	Failure probability estimates $\hat{p}_i$
1	30.8	0.017098
2	193.6	0.020625
3	283.9	0.025329
4	344.9	0.03177
5	396.7	0.040867
6	455.7	0.054173
7	524.2	0.074381
8	578	0.106151
9	652.9	0.156668
10	701.7	0.231049

2.2.3 Multilayer Bayes Estimation of Electric Spindle

According to the relevant content of Section 2.2.2, to compare the advantages of E-Bayes under the new model and the multi-layer Bayes method used in the traditional calculation process, the calculation of the multi-layer Bayes formula for the failure probability of the electric spindle is introduced here.

If the prior density function of failure probability p_i is:

$$\pi(p_i|b) = b(1-p_i)^{b-1} \tag{13}$$

The multi-layer prior density function of p_i is:

$$\pi(p_i) = \int_1^c \pi(p_i|b)\pi(b)db \tag{14}$$

According to the relevant lemma of Bayes' theorem, p_i the multi-layer posterior density function of failure probability can be obtained as:

$$\hat{p}_{iHB} = \int_0^1 p_i h(p_i|s_i)dp_i = \frac{\int_1^c b\left\{\int_0^1 p_i(1-p_i)^{s_i+b-1}dp_i\right\}db}{(c-1)-s_i\ln(\frac{s_i+c}{s_i+1})} = \frac{(s_i+1)\ln(\frac{s_i+c+1}{s_i+2})-s_i\ln(\frac{s_i+c}{s_i+1})}{(c-1)-s_i\ln(\frac{s_i+c}{s_i+1})} \tag{15}$$

According to the above formula, the failure probability at each truncation time T_i can be calculated, which is listed in Table 3.

Table 3. Electric Spindle Failure Probability Estimation under MBE.

censoring time T_i / h	Failure probability estimates $\hat{p}_i$
30.8	0.017013
193.6	0.020503
283.9	0.025147
344.9	0.031489
396.7	0.040413
455.7	0.053403
524.2	0.073012
578	0.103641
652.9	0.152266
701.7	0.225561

2.2.4 Point Estimation of Reliability

During the test time, at that time $t_i = T_i$, the failure probability of the electro-spindle system satisfies:

$$p_i = 1-\exp\left[-\left(\frac{T_i}{\eta}\right)^{\beta}\right] \tag{16}$$

Among them, $i = 1,2,...k$ taking the logarithm of both sides of the above equation, we get:

$$\ln T_i = \ln\eta + \beta^{-1}\ln\ln(1-p_i)^{-1} \tag{17}$$

Substituting equivalently p_i with $\hat{p}_i$, we have:

$$y_i = \mu + \sigma x_i + \varepsilon_i \tag{18}$$

Which have $y_i = \ln T_i$, $x_i = \ln\ln(1-p_i)^{-1}$, $\mu = \ln\eta$, $\sigma = \beta^{-1}$.

When the $\sum_{i=1}^{k} \omega(y_i - \hat{\mu} + \hat{\sigma} x_i)^2$ value is the smallest, the estimated value of the $\hat{\mu}$ and $\hat{\sigma}$ can be obtained, namely: $\hat{\mu} = \frac{BC - AD}{B - A^2}, \sigma = \frac{D - AC}{B - A^2}$ In the above formula, there are $A=\sum_{i=1}^{k} \omega_i x_i$, $B=\sum_{i=1}^{k} \omega_i x_i^2$, $C=\sum_{i=1}^{k} \omega_i y_i$, $D=\sum_{i=1}^{k} \omega_i x_i y_i$.

Substituting the data in 3 into Equation 18, the parameter estimates under the E-Bayes estimation can be obtained by calculation in Table 4.

Table 4. E-Bayes parameter estimates calculation results.

p_i	x_i	y_i	ω_i	A	B	C	D
0.01710	-4.06020	3.42751	0.01787	-0.07257	0.29464	0.06126	-0.24872
0.02063	-3.87084	5.26579	0.10111	-0.39138	1.51496	0.53242	-2.06091
0.02533	-3.66302	5.64862	0.13179	-0.48277	1.76838	0.74446	-2.72696
0.03177	-3.43313	5.84325	0.14010	-0.48098	1.65125	0.81863	-2.81046
0.04087	-3.17663	5.98318	0.13812	-0.43875	1.39376	0.82639	-2.62515
0.05417	-2.88785	6.12183	0.13222	-0.38183	1.10266	0.80942	-2.33748
0.07438	-2.56015	6.26187	0.12167	-0.31150	0.79750	0.76191	-1.95060
0.10615	-2.18731	6.35957	0.10062	-0.22009	0.48140	0.63991	-1.39968
0.15667	-1.76964	6.48142	0.07577	-0.13409	0.23729	0.49112	-0.86911
0.23105	-1.33664	6.55351	0.04072	-0.05443	0.07275	0.26685	-0.35668

Then the summation of the above values and combined to equation (19), we can get $\hat{\mu}_1$=7.6221, σ_1=0.5625 and thus get $\hat{\eta}_1$=exp($\hat{\mu}$)=2042.8, $\hat{\beta}_1 = \frac{1}{\hat{\sigma}} = 1.78$

The reliability point estimation under the E-Bayes estimation can be obtained as:

$$R_1(t) = \exp[-(\frac{t}{\hat{\eta}_1})^{\hat{\beta}_1}] = \exp[-(\frac{t}{2042.8})^{1.78}] \tag{19}$$

Substituting the data in Table 4.4 into formula 18, the estimated value of the parameter β under the multi-layer Bayes can be obtained. By using the same method, we have $\hat{\mu}_2$=7.649, σ_2=0.569 and $\hat{\eta}_2$=exp($\hat{\mu}$)=2100, $\hat{\beta}_2 = \frac{1}{\hat{\sigma}} = 1.758$

The reliability point estimation under the multi-layer Bayes estimation can be obtained as:

$$R_2(t) = \exp[-(\frac{t}{\hat{\eta}_2})^{\hat{\beta}_2}] = \exp[-(\frac{t}{2100})^{1.758}] \tag{20}$$

Relative error (MRE) is a method that can reflect the credibility of parameter estimation. In order to compare the credibility of parameter estimation, the relative error and the true value are used for comparative analysis here, and the relative error of the parameter is:

$$MRE = \frac{|\psi - \hat{\psi}|}{\psi} \tag{21}$$

Where, ψ represents the real value of the parameter η and β; $\hat{\psi}$ - parameters estimates of parameter η and β.

Table 5. Parameter estimates for the cumulative fault distribution function of the electro-spindle.

Project	Truth value	Multilayer Bayes Method		E-Bayes Method	
		EV	error/%	EV	error/%
β	1.716	1.76	2.42	1.78	3.6
η	1811.9	2100	15.9	2043	12.7

It can be seen from Table 5 that the difference between the estimated value obtained using E-Bayes and the multi-layer Bayes method and the true value is very small, especially the characteristic life value is very close. From the overall point of view of reliability R, the estimation value based on E-Bayes is simpler to calculate and has smaller error, which is better than multi-layer Bayes estimation. Therefore, we use the failure rate calculated by E-Bayes as the estimated value.

2.3. Confidence interval estimation of the reliability of the electro spindle

From the content of the previous section, it can be known that the cumulative fault distribution of the electro-spindle can be obtained through parameter estimation as:

$$\hat{F}(t,\hat{\beta},\hat{\eta}) = 1 - e^{-(\frac{t}{2043})^{1.78}} \tag{22}$$

According to the contents of the previous sections, all the reliability point estimates of the electro-spindle can be analyzed and obtained. Using the Boot strap method to process the non-failure data of the electro-spindle can evaluate the reliability under different methods while obtaining the interval estimation of reliability. The precision of the reliability estimate.

2.3.1 Reliability interval estimation of motorized spindle based on Bootstrap method

First, multiple data are randomly selected through the cumulative probability distribution function $\hat{F}(t,\beta,\eta) = 1 - \exp[-\left(\frac{t}{\hat{\eta}}\right)^{\hat{\beta}}]$,the obtained data sample is $t^* = [t_1^*,...,t_m^*]$.At the same time, according to the idea of the Bootstrap method, the extracted samples still obey the original distribution, that is:

$$F(t^*) = 1 - \exp[-\left(\frac{t^*}{\eta}\right)^{\beta}] \tag{23}$$

It should be noted that when calculating the failure probability p_i after resampling, the Bayes method cannot be used instead with:

$$\hat{F}\left(t_i^*\right) = \frac{i - 0.35}{m} \tag{24}$$

Bring it into Equation 24, take the logarithm of both sides at the same time, and obtain the linear model $y_i^* = \mu^* + \sigma^* x_i^* + \xi$, with $y_i^* = \ln t_i^*$, $x_i^* = \ln\ln(1 - \hat{F}(t_i^*))^{-1}$

Also, we have:

$$\begin{cases} \hat{\mu}^* = \dfrac{B^*C^* - A^*D^*}{mB^* - A^{*2}} \\ \hat{\sigma}^* = \dfrac{mD^* - A^*C^*}{mB^* - A^{*2}} \end{cases} \tag{25}$$

Among them $A^*=\sum_{i=1}^{m}x_i^*$, $B^*=\sum_{i=1}^{m}x_i^{*2}$, $C^*=\sum_{i=1}^{m}y_i^*$, $D^*=\sum_{i=1}^{m}x_i^*y_i^*$

Thus, the sample distribution function under Bootstrap is obtained as:

$$\hat{F}^*(t^*)=1-\exp[-(\frac{t^*}{\hat{\eta}^*})^{\hat{\beta}^*}] \tag{26}$$

Among them $\hat{\beta}^*=\frac{1}{\hat{\sigma}^*}$, $\hat{\eta}^*=e^{\hat{\mu}^*}$

The reliability point estimate is $\hat{R}^*(t_0)=1-\hat{F}^*(t_0)$ at a given time is t_0. In the case of a large number of multiple samplings, the reliability point estimates obtained by the Bootstrap method fluctuate up and down. Although there are differences, it can effectively reflect the data characteristics of the sample size, to obtain a confidence α interval under a certain confidence level and evaluate the estimation accuracy of reliability. The steps are as follows: (1) According to the distribution function $\hat{F}(t)$, use The Bootstrap method extracts autonomous samples with the same sample size, establishes the distribution function under the new sample $\hat{F}^*(t^*)$, and brings in t_0 the reliability point estimate under $\hat{R}^*(t_0)$ time t_0; (2) Repeat step (1) to obtain B the reliability of each sample under the Bootstrap method. Is estimated as $\hat{R}_1^*(t_0)$, $\hat{R}_2^*(t_0)$, … $\hat{R}_B^*(t_0)$, then the reliability estimation expectation is:

$$\bar{\hat{R}}^*(t_0)=\sum_{i=1}^{B}\frac{\hat{R}_i^*(t_0)}{B} \tag{27}$$

After converting the above steps into Matlab programming, the upper and lower limits of the reliability interval estimation of the motorized spindle under the Bootstrap method can be obtained as:

$$\begin{cases}\hat{R}_{up}(t,\hat{\beta},\hat{\eta})=e^{-(\frac{t}{2107.78})^{1.891}}\\ \hat{R}_{low}(t,\hat{\beta},\hat{\eta})=e^{-(\frac{t}{1704.65})^{1.642}}\end{cases} \tag{28}$$

In order to observe the data results more clearly, the upper and lower bounds of the obtained interval estimates and the reliability point estimates based on E-Bayes are plotted in Figure 2 .

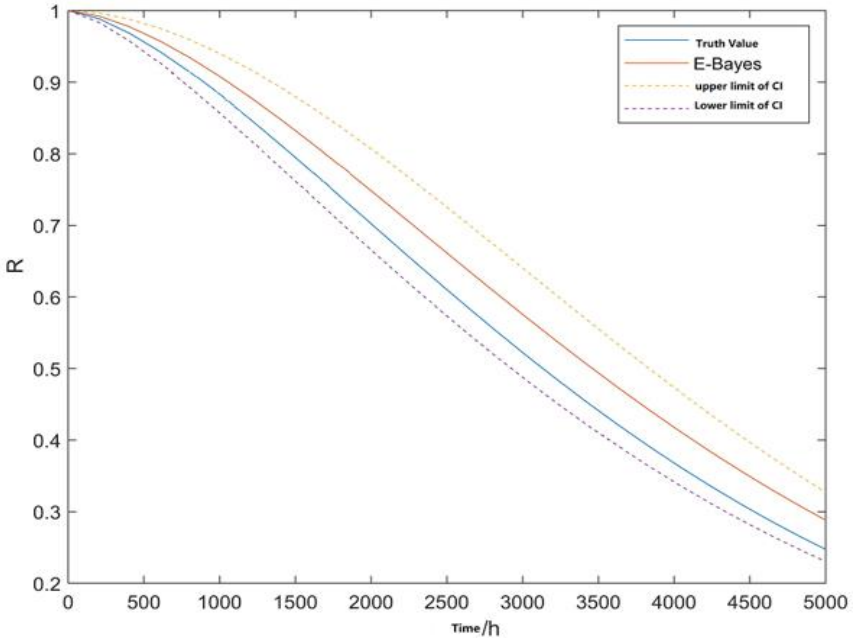


Figure 2. Variation curve of reliability of electric spindle with working time.

Correspondingly, it can be seen from Fig.3 that the reliability of the electric spindle decreases with the increase of working time. When the working time is short, the reliability calculated by using the point estimate under the E-Bayes estimation It is very close to the true value of the reliability of the electro spindle, at the same time, the interval estimate obtained using Bootstrap random sampling method also contains the true value and the interval width is small.

In this way, the new model can show that the reliability estimation of the electro-spindle is very good when the working time of the electro-spindle is short. When the working time exceeds 500 hours to 1000 hours, the point estimates under the E- Bayes estimate are higher than the true value, and the width of the interval estimates obtained by the Bootstrap random sampling method begins to tend to be constant and contains actual value. The interval estimate of reliability can still contain the true value after the operating time exceeds 1500 hours. It can be seen that the reliability assessment under the new model fully meets the analysis requirements.

3. Conclusion

In the content of this paper, a new model is proposed to evaluate the reliability of the motorized spindle with no failure data. After generating random numbers according to the Monte Carlo method, the failure probabilities of the electro - spindle at different truncation times were calculated by using the E - Bayes and multi-layer Bayes methods and compared and analyzed. According to the distribution curve method the cumulative fault distribution curve of the electro-spindle is obtained to obtain the point estimation of reliability. The cumulative fault distribution curve is repeatedly sampled by Bootstrap method, and the confidence interval estimation of the reliability of the electro spindle is obtained according to the new sample. Compared with the parameter interval estimation method of the confidence limit method, it can be seen that the model can effectively ensure the reliability of the results, and this new model can obtain the reliability point estimation and interval estimation of the electric spindle at the same time, which meets the reliability of the electric spindle. Assessment requirements.

According to the collected experimental data, a reliability evaluation model that does not reduce the credibility of the evaluation results is proposed for the case where there is no failure data in the accelerated degradation test of the electric spindle. The new motor-spindle reliability evaluation model can obtain the point estimation and interval estimation of the reliability of the motor-spindle at the same time. The E-Bayes method is used to calculate the failure probability estimates of the electric spindle at different truncation times. At the same time, the distribution curve of the electric spindle is fitted to obtain the cumulative fault distribution curve of the electric spindle, and the reliability point estimate of the electric spindle system is obtained. Then, the idea of Bootstrap sample self-help method is used to extract samples from the accumulated fault distribution curve that has been obtained, and the confidence interval estimation of the reliability of this model of motorized spindle is obtained by estimating the new samples obtained. It provides a new idea for the follow-up reliability evaluation of the electro-spindle.

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