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Life prediction and test period optimization research based on small sample reliability test of hydraulic pumps①

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Abstract

Hydraulic pumps belong to reliable long-life hydraulic components. The reliability evaluation includes characters such as long test period, high cost, and high power loss and so on. Based on the principle of energy-saving and power recovery, a small sample hydraulic pump reliability test rig is built, and the service life of hydraulic pump is predicted, and then the sampling period of reliability test is optimized. On the basis of considering the performance degradation mechanism of hydraulic pump, the feature information of degradation distribution of hydraulic pump volumetric efficiency during the test is collected, so an optimal degradation path model of feature information is selected from the aspect of fitting accuracy, and pseudo life data are obtained. Then a small sample reliability test of period constrained optimization search strategy for hydraulic pump is constructed to solve the optimization problem of the test sampling period and tightening end threshold, and it is verified that the accuracy of the minimum sampling period by the non-parametric hypothes is tested. Simulation result shows it could possess instructional significance and referenced value for hydraulic pump reliability life evaluation and the test's research and design.

Key words: hydraulic pump, small sample test, volumetric efficiency, degradation path model, life span, period optimal

0 Introduction

Hydraulic pump with characteristics of high reliability and long-life is the key hydraulic component in the hydraulic system and as "Three Basic" mechanical basis belonging to the mechanical field. Its level directly determines many major equipment and the host of product performance, quality and reliability. However, there are many problems, such as large power, long test period, high costly testing, closed-end transmission of power, poor measurability of parameters, and diversity of failure mechanism. The situation of zero-failure data may occur in the conventional or accelerated reliability life test of hydraulic pump. Therefore, Reliability assessment and growth of the key fundamental parts and components with high reliability and long-life, represented by hydraulic pump, has become one of the key techniques to be solved urgently in engineering field[1,2].

At present, the test of reliability life usually takes a long life test in developed countries, and there is a big disparity with the situation of our country. In the United States, the hydraulic pump life test standards has been developed from MIL-P-19692D, MIL-P-19692E, MIL-P-19692C to SAE-ASI19292A, which marks the important development of the relevant standards[3]. Hydraulic transmission laboratory of Sundstron Company was equipped with hydraulic pump test system, and began the full-life-test of hydraulic pumps as early as in 1964. Since the introduction of the microcomputer in 1974, At present, the test of reliability life usually takes a long life test in developed countries, and there is a big disparity with the situation of our country. UK National Laboratory developed ISO standard hydraulic pump test rig, and then studied the relia-

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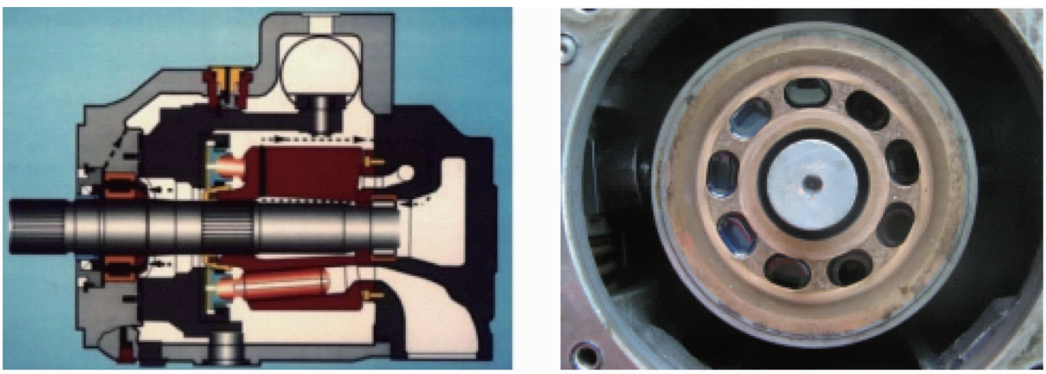
bility of the hydraulic pump. The Institute of Metallurgical Machinery in Korea developed the reliability test and data processing system of the hydraulic pump. The Research Center of Mechanical Industry (ETIT) in France developed the experimental platform of hydraulic pump[4-8]. In recent years, a lot of life experiment researches have been conducted in China, and have achieved periodic achievement. Sanyi Heavy Industry and Xuzhou Construction Machinery Group carried out the on-board test for their own matching pump. Harbin Industrial University conducted a study of the test method of life and reliability for hydraulic components[9,10]. Shanghai Jiaotong University evaluated the life characteristics of 25CY14-1B type axial piston pump[11]. Huazhong University of Science and Technology developed a reliability test for ceramic plunger of water hydraulic pump[12]. Zhejiang Ocean University focused on the research of 32 hydraulic pumps and got the comprehensive estimation of the hydraulic pump reliability without failure data after the introduction of the failure information[13]. Extensive reliability test studies were conducted for the factors effecting the reliability of the hydraulic devices of multi-industries and multi-fields[14,15], Yanshan University has published the "reliability engineering of the hydraulic system"[16]. Those studies involved the acquisition of the failure information under conventional test and accelerated test and the reliability assessment based on small sample and performance degradation, but the related researches, which makes use of the principles of performance degradation to predict the reliability life and optimize the test period, are still lacking.

By introducing the performance degradation theory of hydraulic pump, the reliability test of small sample size is designed. Through the screening of degradation model, the reliability of hydraulic pump is predicted. Test period optimization of hydraulic pump small sample reliability test is achieved. It has great value in academic and engineering area to research reliability assessment of hydraulic pump. The structure and principle of A4V series hydraulic pump and the main failure modes after testing are shown in Fig. 1.



(a) The structure and principle of A4V series hydraulic pump (b) The main failure modes of A4V series hydraulic pump

Fig. 1 The principle of the axial piston pump reliability test rig operation

1 Degradation model selection and life prediction based on performance degradation theory

1.1 Performance degradation data structure and model

The population is sampled for the degradation test, and the random simple size is n. The degradation test was carried out at given k time points, $t_1 < t_2 \cdots < t_k$, monitoring one of the performance degradation parameters. The n groups' degradation test data are obtained. Y_{ij} would be seen as the measured value of the sample No. i at the time t_j. Degenerate data and time are described as

$$y_{ij} = \phi(t_{ij}, w_{1i}, w_{2i}, w_{mi}) + \varepsilon_{ij} \quad (1)$$

where $i = 1, 2, \cdots, n$; $j = 1, 2, \cdots, \phi(t_{ij}, w_{1i}, w_{2i}, w_{mi})$ is the degradation path of the No. i sample at time t_j, $\varepsilon_{ij} \sim N(0, \sigma^2)$ is error measurement.

In the range of the errors permitted, product performance degradation parameters and time series vector can be fitted effectively by adopting the following five kinds of models, which can be considered as the actual degradation of product performance parameters.

Liner: $y_i = \alpha_i t + \beta_i$ (2)

Exponential: $y_i = \alpha_i e^{\beta_i t}$ (3)

Power: $y_i = \alpha_i t^{\beta_i}$ (4)

Logarithmic: $y_i = \alpha_i \ln(t) + \beta_i$ (5)

Gampertz: $y_i = \alpha_i - \dfrac{\beta_i}{t}$ (6)

where α_i, β_i are unknown parameters in the degradation model, y_i is the target value, i is the number of samples under a certain stress level, and t is test time.

1.2 Degradation path fitting method

The nonlinear degenerate models as Eqs(2) ~ (6) would be expressed as $\boldsymbol{y} = \boldsymbol{F}(\boldsymbol{X}, \boldsymbol{\alpha}) + \boldsymbol{\varepsilon}$, where $\boldsymbol{\alpha}$ is the model coefficient vector, $\boldsymbol{X}$ is a matrix of model design, $\boldsymbol{F}$ is a function of $\boldsymbol{\alpha}$ and $\boldsymbol{X}$, $\boldsymbol{\varepsilon}$ is the error vector, and $\boldsymbol{y}$ is response vector data. Solution of the nonlinear regression models can be fitted by a nonlinear least square method.

$$\min_x \frac{1}{2} \| \boldsymbol{F}(\boldsymbol{x}, \boldsymbol{xdata}) - \boldsymbol{ydata} \|_2^2 - \frac{1}{2} \sum_i (\boldsymbol{F}(\boldsymbol{x}, \boldsymbol{xdata}_i) - \boldsymbol{ydata}_i)^2 \quad (7)$$

where $\boldsymbol{F}(\boldsymbol{x}, x\text{data})$ is the vector valued function, $xdata$ is the independent variable vector, $xdata = [t_1, t_2, \cdots, t_m]$, $ydata$ is dependent variable vector, $ydata = [y_{i1}, y_{i2}, \cdots, y_{im}] (i = 1, 2, \cdots, n)$.

1.3 Optimal degradation path search strategy

1.3.1 Degradation path search decision matrix

Suppose n degenerate path equations can be achieved by the fitting of the degradation data, m impact properties of search scheme need to be considered. $\boldsymbol{X} = [X_1, X_2, \cdots, X_n]$ is a set of n alternative degradation paths. $\boldsymbol{Y} = [Y_{i1}, Y_{i2}, \cdots, Y_{im}]$ is a set of No. i path and No. $j (j = 1, 2, \cdots, m)$ property. Attribute Y_{ij} is expressed by objective function

$$Y_{ij} = f_i(X_i) \quad (8)$$

The attribute values of each path scheme can be expressed as the search decision matrix $\boldsymbol{A}$.

$$\boldsymbol{A} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1m} \\ Y_{21} & Y_{22} & \cdots & Y_{2m} \\ \vdots & \vdots & & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nm} \end{bmatrix} \quad (9)$$

The weighted normalized decision matrix is got by the weight of the search decision matrix.

$$\boldsymbol{B}_{ij} = \lambda_j \cdot Y_{ij} / \sqrt{\sum_{i=1}^{n} Y_{ij}^2} \quad (10)$$

where λ_j is the weight coefficient, $i = 1, 2, \cdots, n$, $j = 1, 2, \cdots, m$.

2.3.2 Algorithm for solving the optimal degradation path

According to the TOPSIS theory that the method of evaluating the similarity degree of the object and the ideal target, an optimal solution and the worst solution are firstly determined, the scheme that the best solution to the nearest and farthest from the best solution would be selected as ideal optimization scheme.

The optimal solution of $\boldsymbol{X}^+$ and the worst solution $\boldsymbol{X}^-$ are defined as

$$\begin{cases} \boldsymbol{X}^+ = \{ (\max_i X_{ij} \mid j \in J), (\min_i X_{ij} \mid j \in J') \mid i = 1, 2, \cdots, n \} = \{ X_1^+, X_2^+, \cdots, X_m^+ \} \\ \boldsymbol{X}^- = \{ (\min_i X_{ij} \mid j \in J), (\max_i X_{ij} \mid j \in J') \mid i = 1, 2, \cdots, n \} = \{ X_1^-, X_2^-, \cdots, X_m^- \} \end{cases} \quad (11)$$

where J is a set of benefit type attribute, J' is a set of cost attribute.

The distance of each solution to the optimal solution is

$$\boldsymbol{L}_i^+ = \sqrt{\sum_{j=1}^{m} (X_{ij} - X_j^+)^2}, \; i = 1, 2, \cdots, n \quad (12)$$

The distance of each solution to the worst solution is

$$\boldsymbol{L}_i^- = \sqrt{\sum_{j=1}^{m} (X_{ij} - X_j^-)^2}, \; i = 1, 2, \cdots, n \quad (13)$$

In order to judge the solution, the relative similarity degree is introduced to measure the distance between two kinds of distance. The relative similarity degree to the optimal solution is defined.

$$\boldsymbol{T}_i^+ = \frac{\boldsymbol{L}_i^-}{\boldsymbol{L}_i^- + \boldsymbol{L}_i^+}, \; 0 \leqslant \boldsymbol{T}_i^+ \leqslant 1, \; i = 1, 2, \cdots, n \quad (14)$$

The value of $\boldsymbol{T}_i^+$ is close to 1 (or more), which indicates that the corresponding model is more consistent with the deterioration law of actual data.

1.4 Test period optimization search strategy

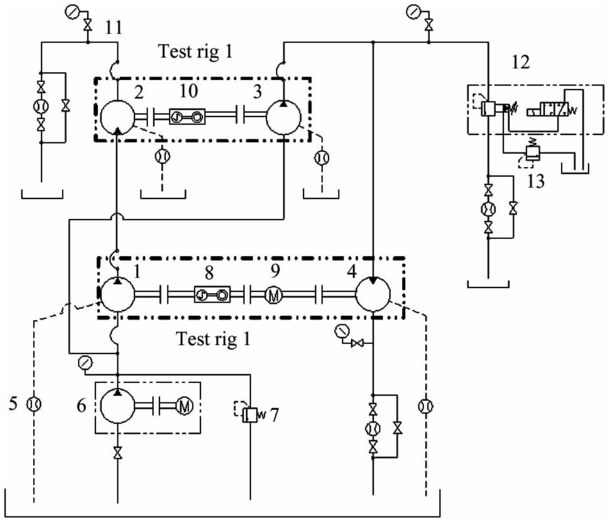
According to the search strategy of the optimal degradation model and the fitting results from section 2.3, comparatively accurate hydraulic pump volumetric efficiency test data degradation model would be got. According to the programme, the mean error square and fitting goodness index matrix of the actual degradation data and optimal degradation trajectory in specific timing interval can be acquired. And that is selected to construct test period constrained optimization search strategy of the hydraulic pump reliability short-time test for search index fitting goodness. According to the algorithm introduced in the Section 1.3, the fitting search for the twice time is carried, and then the optimal truncated threshold of the minimum sampling period and the performance degradation would be acquired.

2 Small sample reliability test of hydraulic pump

2.1 The design of test system and program

In the laboratory the existing condition's foundation, the small sample reliability test rig of hydraulic pump based on the energy saving and power recovery principle is designed.

Test hydraulic system and test rig are shown in Fig. 2 and Fig. 3.



1、3- Test subjects of axial plunger pump; 2、4- Test subjects of axial piston motor; 5-Flowmeter; 6-Screw pump oil compensator; 7、13-Overflow valve; 8、10- Torque Tachometer; 9- Biaxial stretch Motor; 11- Pressure gauge; 12-Electromagnetic relief valve;

Fig. 2 The principle of the axial piston pump reliability test rig operation

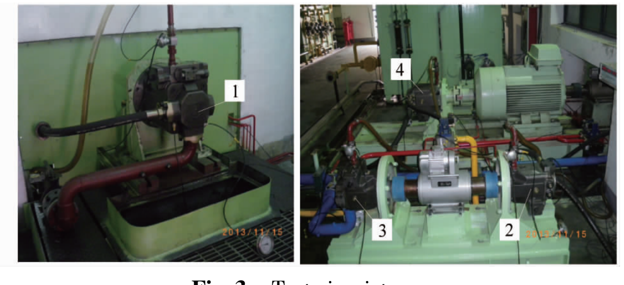


Fig. 3 Test rig pictures

The reliability test subjects are A4VS series axial piston pumps that were produced by a domestic enterprise. The nominal rated pressure of A4VS series productions is 35MPa, and the peak pressure is 40MPa. The four samples selected include open circuit hydraulic pump whose displacement is 250ml/r, closed loop hydraulic pump whose displacement is 250ml/r, open circuit hydraulic pump whose displacement is 125ml/r, and closed loop hydraulic pump whose displacement is 125ml/r.

2.2 Failure detection and judgment

The volumetric efficiency is selected as the main performance appraisal parameter, in addition, dynamical sealing capacity, outlet pressure oscillation and sealing property are detected during the test. And failure judgment criteria are shown in Table 1.

Table 1 The failure judgment criteria of hydraulic pump

No.	Performance parameters	Failure judgment criteria
1	Volumetric efficiency	Decrease more than 5% than the predetermined value ,that is 87% or less
2	Dynamical sealing capacity	No leakage at rest. When running, the oil spill is not more than 1 drop per 5min
3	Sealing performance	All static seal without penetration

2.3 Experimental data processing

2.3.1 The analysis of experiment result

The working condition of the hydraulic pump is tested in real time. The life time and failure mode of hydraulic pump are recorded when the performance parameter monitored is below the predetermined index value. The fulfillment of test is shown in Table 2.

Table 2 The fulfillment of the reliability accelerated life test of hydraulic pump

	Test subjects	Test pressure (MPa)	Speed(rpm)	Volumetric efficiency	Time to failure
First test stage (1030h)	1#pump (HLA4VSO250)	35	1500	93.5%	No failure
	2#pump (HLA4VSG125)	35	1685 ~ 1850	92%	No failure
	3# pump (HLA4VSO125)	35	1685 ~ 1850	86.7%	1030
	4# pump(HLA4VSG250)	35	1500	93%	No failure
Second test stage 850h	1# pump (HLA4VSO250)	41	1500	85% ~ 86%	656.3
	2#pump (HLA4VSG125)	41	1540 ~ 1600	85% ~ 86%	358
	3#pump (HLA4VSO125)	41	1540 ~ 1600	90%	No failure
	4#pump (HLA4VSG250)	41	1500	86%	846.4

2.3.2 The determination of volumetric efficiency degradation path

The four samples volumetric efficiency degradation data are fitted by using nonlinear least squares, the sum square error of them is selected as the evaluation result. Based on the search strategy in Section 2.3, according to the search strategy in Section 2.3, the original search decision matrix $\boldsymbol{A}$ is established according to Eq. (9), the effects of their weighting assignment could be ignored, which means that $\lambda_j = 1$. So normalized matrix $\boldsymbol{B}$ would be got according to Eq. (10).

$$\boldsymbol{A} = \begin{bmatrix} 0.0049 & 0.0188 & 0.0792 & 0.0136 \\ 0.0056 & 0.0175 & 0.0808 & 0.0147 \\ 0.0074 & 0.0267 & 0.1622 & 0.018 \\ 0.0073 & 0.0266 & 0.2597 & 0.0189 \\ 0.0085 & 0.0319 & 0.2699 & 0.0280 \end{bmatrix} \quad (15)$$

$$\boldsymbol{B} = \begin{bmatrix} 0.5786 & 0.5348 & 0.6484 & 0.5607 \\ 0.5063 & 0.5745 & 0.6356 & 0.5188 \\ 0.3831 & 0.3765 & 0.3166 & 0.4237 \\ 0.3884 & 0.3780 & 0.1978 & 0.4035 \\ 0.3336 & 0.3152 & 0.1903 & 0.2724 \end{bmatrix} \quad (16)$$

According to Eqs(11) ~ (14), the optimal solution is $\boldsymbol{D}^+ = [0.5786 \quad 0.5745 \quad 0.6484 \quad 0.5607]$, and the worst solution is $\boldsymbol{D}^- = [0.3336 \quad 0.3152 \quad 0.1903 \quad 0.2724]$. The distance of the solution to the optimal solution is $\boldsymbol{L}_i^+ = [0.0397 \quad 0.1271 \quad 0.8623 \quad 0.9947 \quad 1.2509]^T$, and the distance of the solution to the worst solution is $\boldsymbol{L}_i^- = [1.2112 \quad 1.1238 \quad 0.3886 \quad 0.2562 \quad 0]^T$. The relative similarity degree matrix of the solution to the optimal solution is

$$\boldsymbol{T}_i^+ = [0.9682 \quad 0.8984 \quad 0.3107 \quad 0.2048 \quad 0]^T \quad (17)$$

According to the relative similarity degree matrix, a conclusion is drawn that the fitting of the performance degradation data and the linear degradation model $y_i = \alpha_i t + \beta_i$ is the best, whose solution most accurately describes the optimal solution, the relative similarity degree is 0.9682. As a result, the linear model is used as the degradation path of hydraulic pump volumetric efficiency, and the model parameters can be obtained by the nonlinear least square method. The model parameters can be obtained from 4 samples.

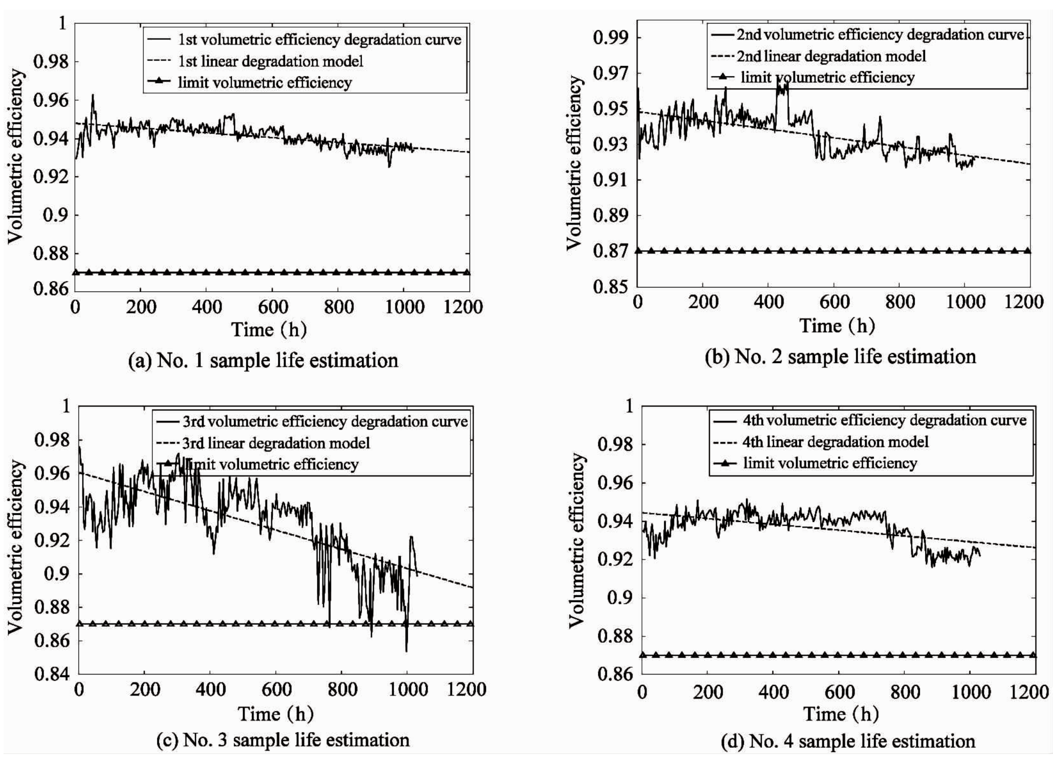
$$y_1 = -1.255 \times 10^{-5} t + 0.9481 \quad (18)$$

$$y_2 = -2.4464 \times 10^{-5} t + 0.9484 \quad (19)$$

$$y_3 = -5.7492 \times 10^{-5} t + 0.9607 \quad (20)$$

$$y_4 = -1.5222 \times 10^{-5} t + 0.9445 \quad (21)$$

Such regulation is formulated that the corresponding test time is the life of the hydraulic pump when the volumetric efficiency of the test sample is reduced to the limit of 87% in the condition of 35MPa. In Fig. 4,



(a) No. 1 sample life estimation
(b) No. 2 sample life estimation
(c) No. 3 sample life estimation
(d) No. 4 sample life estimation

Fig. 4 Test sample life estimation

the horizontal line is the limit value, and the dotted line is the curve of the volumetric efficiency. It is conclued that the volumetric efficiency of hydraulic pump shows a downward trend over time as a whole. The corresponding time of intersection of the degradation path curve and the horizontal line is the life prediction of the hydraulic pump. It is shown in Table 3 that the predicted life of the hydraulic pump, which is the degradation rate of the volumetric efficiency is fitted.

Table 3 Test sample forecast life data

Sample number	1	2	3	4
Fitting degradation rate	-1.255×10^{-5}	-2.4464×10^{-5}	-5.7492×10^{-5}	-1.5222×10^{-5}
Life(h)	6216	3204	1578	4895

3 Hydraulic pump small sample reliability test period optimization

3.1 Test period optimization search decision matrix

According to the search strategy of the optimal degradation model and the fitting results, the mean error square and fitting goodness index matrix of the actual degradation data and optimal degradation trajectory in specific timing interval can be acquired, as shown in Table 4.

Table 4 The minimum sampling period search index

Time \ Sample	1($\overline{SSE}\times10^{-3}$)	2($\overline{SSE}\times10^{-3}$)	3($\overline{SSE}\times10^{-3}$)	4($\overline{SSE}\times10^{-3}$)
300	0.0314	0.0986	0.1778	0.0615
400	0.0266	0.0834	0.1943	0.0490
500	0.0247	0.1209	0.1913	0.0481
600	0.0232	0.1112	0.1798	0.0526
700	0.0201	0.1048	0.1711	0.0515
800	0.0181	0.0938	0.1596	0.0477
900	0.0169	0.0872	0.1639	0.0462
1000	0.0159	0.0807	0.1800	0.0456
1100	0.0154	0.0778	0.1790	0.0430
1200	0.0150	0.0758	0.1783	0.0415
1300	0.0152	0.0732	0.1710	0.0440
1400	0.0147	0.0717	0.1733	0.0451

According to Table 4, the test period constrained optimization search matrix $\boldsymbol{A}$ of the hydraulic pump reliability short-term experiments is established, the effects of their weighting assignment could be ignored, which means that the $\lambda_j = 1$. So the normalized matrix $\boldsymbol{B}$ would be got.

3.2 The minimum sampling period algorithm

According to the TOPSIS theory and the Eqs(11) ~ (14), the optimal solution is $\boldsymbol{D}^+ = [0.3559\ 0.3480\ 0.3181\ 0.3288]$, and the worst solution is $\boldsymbol{D}^- = [0.1666\ 0.2064\ 0.2613\ 0.2219]$. The distance of the solution to the optimal solution is $\boldsymbol{L}_i^+ = [0.2395\ 0.1830\ 0.2136\ 0.1959\ 0.1605\ 0.1141\ 0.0846\ 0.0663\ 0.0482\ 0.0390\ 0.0314\ 0.0363]^{\mathrm{T}}$, the distance of the solution to the worst solution is $\boldsymbol{L}_i^- = [0.0526\ 0.1128\ 0.0767\ 0.0751\ 0.1135\ 0.1609\ 0.1859\ 0.2083\ 0.2295\ 0.2455\ 0.2422\ 0.2518]^{\mathrm{T}}$. The relative similarity degree matrix of the solution to the optimal solution is $T_i^+ = [0.1801\ 0.3813\ 0.2642\ 0.2772\ 0.4143\ 0.5851\ 0.6871\ 0.7984\ 0.8558\ 0.8630\ 0.8852\ 0.8739]^{\mathrm{T}}$.

According to matrix of relative degree of approximation, it could be found that fitting precision would be 85.85% when the sampling period reaches 1100 hours, which could meet the requirement of engineering practice. So the minimum sampling period of hydraulic pump reliability short time test as 1100 hours is preliminarily determined.

The optimal truncated threshold of the performance degradation would be acquired just as shown in Table 5.

Table 5 The optimal truncation threshold of performance degradation of hydraulic pump reliability short time test

Sample	1	2	3	4
The optimal truncation threshold	0.9339	0.9227	0.8970	0.9245

3.3 Nonparametric tests of the minimum sampling period

The minimum sampling period is T = 1100h by the above calculation. As to the life data from the minimum sampling period method or the complete life test data from the reliability test, its reliability is to be verified by using nonparametric *K-S* test model. That would assess the accuracy of the minimum sampling period.

The linear degradation model of four hydraulic pumps Eqs(22) ~ (25) can be obtained by the data from the former 1100h. Pseudo failure life time of four hydraulic pumps can be calculated by Matlab, just as shown in Table 6.

$$y = -1.069 \times 10^{-5}x + 0.9454 \quad (22)$$

$$y = -2.491 \times 10^{-5}x + 0.9495 \quad (23)$$

$$y = -5.116 \times 10^{-5}x + 0.9597 \quad (24)$$

$$y = -1.182 \times 10^{-5}x + 0.9428 \quad (25)$$

According to *K-S* two-sample test method, suppose the small sample life reliability test data acquired is seen as the complete life test data, so distribution function is got, called $F(x)$. And life distribution function that is got by fitting with volumetric efficiency degradation trajectory is called $G(x)$. The null hypothesis is put forward:

$$H_0: \quad F(x) = G(x) \quad (26)$$

And corresponding alternative hypothesis:

$$H_1: \quad F(x) \neq G(x) \quad (27)$$

$G(x) = 1 - e^{-(\frac{t}{4543.8})^{2.18}}$ can be calculated according to inverse moment estimation in Table 6. After the quick and accurate analysis with software programming, the results are shown in Table 7, $h = 0$ and $p -> \alpha$, indicating that the null hypothesis could not be rejected, and it shows that the life data from the minimum sampling period method and the complete life test data from the hydraulic pump reliability test method are reliable, in other words, the minimum sampling period from the above calculation process is real and reliable.

Table 6 Pseudo failure lifetime of four hydraulic pumps

Test methods	Significance level	Test results	p-value	Statistics
K-S Test	0.05	0	0.9969	0.25

Table 7 Analysis of test results

Sample	1	2	3	4
Pseudo failure lifetime (h)	7053	3191	1753	4017

4 Conclusion

Hydraulic pump with characteristics of high reliability and long-life is taken as research objects. For hydraulic pump life prediction and reliability test period optimization, the small sample reliability test of the hydraulic pump was carried out, which selected the volumetric efficiency as the main performance appraisal parameter.

(1) The test period optimize method of the hydraulic pump reliability test is put forward, and test period optimization search strategy for reliability test is built. The optimal truncated threshold of the minimum sampling period and the performance degradation is acquired. Then non-parametric hypothesis test proves that the minimum sampling period is right.

(2) Through building the model of feature information degradation path sequence, the optimization of degradation path of the hydraulic pump small sample reliability test is determined, and hydraulic pump life is predicted. The results show that performance of hydraulic pump nearly has reached the same level as that abroad.

(3) The small sample hydraulic pump reliability test rigs based on the energy-saving and power recovery principle are designed and built. And according to the experimental program, two-stage step stress accelerated life test is completed, so a full life test data is got.

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