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Reliability evaluation of bladder accumulator with no failure data①

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Abstract

As a bladder accumulator is a high reliable and long life component in a hydraulic system, its cost is high and it takes a lot of time to test its reliability, therefore, a reliability test with small sample is performed, and no failure data is obtained using the method of fixed time truncation. In the case of Weibull distribution, a life reliability model of bladder energy storage is established by Bayesian method using the optimal confidence intervals method, a model of one-sided lower confidence intervals of the reliability and one-sided lower confidence intervals model of the reliability life are established. Results of experiments show that the evaluation method of no failure data under Weibull distribution is a good way to evaluate the reliability of the accumulator, which is convenient for engineering application, and the reliability of the accumulator has theoretical and practical significance.

Key words: bladder accumulator, Weibull distribution, fixed time truncation, no failure data, reliability assessment

0 Introduction

A bladder accumulator is mainly comprosed of shell, capsule, inflatable valve, oil valve, bacteria valve, etc., where the capsule is filled with nitrogen, the chamber is composed of shell and capsule is filled with hydraulic oil. In the hydraulic system it is used mostly for energy storage stable pressure, reducing the hydraulic pump power, compensation for leakage, absorption pressure and pulsating pressure and other effects, and easy maintenance, less ancillary equipment and easy installation.

In the reliability evaluation of hydraulic components, because of the high cost and long test period, the number of samples is limited by cost and time, so a method of small sample data analysis is adopted. Therefore, it is very important to choose the appropriate reliability test data analysis and processing methods, mainly using the classical statistical small sample evaluation method and numerical simulation method. Especially in the small sample of high reliability problems, the failure data is unavailable, the results are no failure data. To resolve this problem, the use of data for research failure is unfeasible, and the only method is failure-free date reliability study. The reliability evaluation methods of failure-free data include Bayesian method, multi-layer Bayesian method, maximum likelihood function method, distribution curve method, least squares method and statistical analysis of degenerate failure model. The earliest reliability of no-failure data are proposed by Martz and Waller[1]. Guo[2], et al. studied it based on the information of the deterioration and distribution of hydraulic pump volume efficiency and a small sample reliability test of hydraulic pump cycle constrained optimization search strategy was constructed, which has the reference value for hydraulic pump reliability life evaluation and experimental research and design. In the Weibull distribution, Jia[3], et al. analyzed all aspects of the distribution curve method in detail and improved it. Han[4], et al. proposed a sample verification method of product reliability parameters with life expectancy exponential distribution, which was obtained by classical method and Bayesian method, and it is demonstrated that the Bayesian method can use the prior information in this method. Xu[5], et al. used Weibull distribution model to study the life distribution of high voltage cable, and proposed a modified maximum likelihood function

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method to provide a new parameter estimation method for zero failure data. Based on the fault data, Zhao[6], et al. tested the correlation of Weibull distribution function, and verified that the fault interval distribution of the equipment obeyed Weibull distribution, and obtained the reliability evaluation indexes of the equipment. Based on the equation of the optimal lower confidence intervals in the case of failure-free data, Chen[7], et al. obtained the optimal lower confidence intervals of the reliability and the reliable life of the product with exponential distribution, lognormal distribution and Weibull distribution. Based on the analysis of the components, a prediction model of the reliability and availability of the system was derived using the Markov chain and the semi-Markov chain and the formula of the probability distribution in the state of stay, an example showed that the resulting model was effective[8]. Combining the exponential distribution and Weibull distribution, Wang[9], et al. gave the average life expectancy of the modified maximum likelihood estimation (MMLE) and reliability estimates.

Based on the distribution curve method and the modified likelihood function method, Xiao[10], et al. put forward the reliability estimation of the estimated value and the given time using the no-failure data of a certain mechanical seal. Using the zero failure data, Zhou[11], et al. studied the parameter estimation method and the estimation method of the failure probability in small samples. Han[12] proposed a new reliability parameter estimation method——E-Bayes estimation method. In the Weibull distribution, Liu[13], et al. gave the relationship between the failure probability at different test times by the concavity method. Then, from the perspective of practical application, Bayesian estimation of failure probability at different moments is obtained by prior information. Based on the multi-layer Bayes method, Gao[14], et al. studied the experimental grouping problem in the no-failure reliability test.

The theory of performance degradation of accumulator is introduced, and the reliability test under small sample size is designed. The life of the accumulator is predicted by the screening of the degradation model, and the cycle optimization and verification of the small sample reliability test are completed. Accumulator reliability assessment has theoretical and engineering significance.

1 Bayes and confidence intervals in Weibull distribution

In the reliability life test of mechanical products, Weibull distribution is the most widely used. Many products with a partial failure or malfunction can lead to failure of the overall function, the life of these products can be seen as obedient to Weibull distribution. The capsule type accumulator consists of a variety of components. Typical failure modes include skin rupture, inflatable valve loosening, fatigue failure of spring components, etc. Therefore, the life of the capsule accumulator is actually dependent on the composition of the components of the weakest link, the life of the accumulator as obedience Weibull distribution is reasonable. According to the theoretical research and empirical analysis, the life of the accumulator obeys the two-parameter Weibull distribution, that is, the position parameter γ is zero.

The test can not be repeated a large number of tests to obtain a large number of observations, can only get a small amount of observations, a small sample of the situation. Therefore, the application of small sample in the case of excellent estimation method: Weibull distribution Bayesian method and the optimal confidence intervals method.

The life analysis is attributed to the reliability estimate of the failure-free data in the case of a known life profile and a time-truncated test.

1.1 Bayes in Weibull distribution

Assuming that product lifetime T obeys the Weibull distribution, the distribution function is

$$F(T) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^m\right] \quad m > 0,\ \eta > 0 \tag{1}$$

The product is subjected to a k-time cut-off life test with censoring time $t_1 < t_2 < \cdots < t_k$. The corresponding numbers of test samples are $n_1, n_2, \cdots, n_k$ without a failure, where $n_1 = n_2 = \cdots = n_k = 1$, and $n_1 + n_2 + \cdots + n_k = 6$, $(i = 1, 2, \cdots, k)$.

Bayesian method is used to estimate the no-failure data of the accumulator under the Weibull distribution. According to the Bayesian analysis framework proposed by Mao Shisong: 1) First, the Bayesian estimate $\hat{p}_i$ of the probability of failure p_i is obtained at point $t_i (i = 1, 2, \cdots, k)$. 2) Configure a Weibull distribution curve through each point $(t_i, \hat{p}_i)$. In the Weibull distribution curve family, a curve is chosen according to the weighted least squares method closest to the point $(t_i, \hat{p}_i)$. 3) Through this distribution curve, the estimation of different reliability indexes is carried out.

According to the Bayesian assumption, uniform distribution p on A is taken as the prior distribution, which is

$$\pi_k(p_k) = \begin{cases} \dfrac{1}{\lambda_k} & 0 < p_k < \lambda_k \\ 0 & \text{else} \end{cases} \tag{2}$$

Under the prior distribution of Eq. (2), the Bayesian theory is used to obtain the prior distribution of p_i:

$$\pi_i(p_i) = \pi_k(p_k)\frac{\mathrm{d}p_k}{\mathrm{d}p_i} = \frac{t_k}{\lambda_k t_i}(1 - p_i)^{\frac{t_k}{t_i}-1} \quad 0 < p_i < \lambda_i \tag{3}$$

where, $\lambda_i = 1 - (1 - \lambda_k)^{\frac{t_i}{t_k}}$, $i = 1, 2, \cdots, k$.

When the time comes to t_i, s_i products are not invalid. Therefore, the likelihood function of the entire test data at time t_i is

$$L(p_i) = (1 - p_i)^{s_i} \tag{4}$$

Let $r_i = s_i + \dfrac{t_k}{t_i} - 1$, according to the prior distribution of Eq. (3), the posterior distribution of p_i can be obtained:

$$\pi_i(p_i \mid s_i) = \frac{(1 - p_i)^{r_i}}{\int_0^{\lambda_i}(1 - p_i)^{r_i}\mathrm{d}p_i} \quad 0 < p_i < \lambda_i \tag{5}$$

So under the square loss function, the Bayesian estimate of p_i is:

$$\hat{p}_i = \int_0^{\lambda_i} p_i \, \pi_i(p_i \mid s_i)\,\mathrm{d}p_i$$

$$\frac{\dfrac{1}{r_i + 2}[1 - (1 - \lambda_i)^{r_i+2}] - \lambda_i(1 - \lambda_i)^{r_i+1}}{1 - (1 - \lambda_i)^{r_i+1}} \tag{6}$$

After the Bayesian estimation of p_i is obtained, the Weibull distribution curve is fitted using the weighted least squares method according to each point $(t_i, \hat{p}_i)$, and the relevant reliability index of the product can be obtained. According to the Weibull distribution function (Eq. (1)), and according to the weighted least squares method, let the mean $\mu = \ln\eta$, the variance $\sigma = \dfrac{1}{m}$.

The error caused by replacing p_i with $\hat{p}_i$ is denoted as e_i, $y_i = \mu + \sigma x_i + e_i$, among $x_i = \ln\ln\left(\dfrac{1}{1 - \hat{p}_i}\right)$, $y_i = \ln t_i$. According to the weighted least squares method, the estimates of μ and σ can be obtained:

$$\hat{\mu} = \frac{BC - AD}{B - A^2} \tag{7}$$

$$\hat{\sigma} = \frac{D - AC}{B - A^2} \tag{8}$$

where $A = \sum_{i=1}^{k} w_i x_i$, $B = \sum_{i=1}^{k} w_i x_i^2$, $C = \sum_{i=1}^{k} w_i y_i$, $D = \sum_{i=1}^{k} w_i x_i y_i$ and $w_i = \dfrac{n_i t_i}{\sum_{i=1}^{k} n_i t_i}$ are the weight coefficients.

Through the above process the following can be got:

$$m = \hat{\sigma}^{-1} \tag{9}$$

$$\eta = e^{\hat{\mu}} \tag{10}$$

Finally, the reliability of the distribution function is

$$R(t) = e^{-(\frac{t}{\eta})^m} \tag{11}$$

1.2 Confidence intervals in Weibull distribution

Let product lifetime T obey the Weibull distribution, then the distribution function is expressed as

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^m\right], \; m > 0, \; \eta > 0 \tag{12}$$

Extracting n products from a batch of products randomly, the nature of the test is a regular censoring test. The test is carried out until the specified time without product failure, and the working time is $t_1 < t_2 < \cdots < t_n$.

According to the reliability of the reliability life t_R in the exponential distribution, when reliability R and confidence degree r have been given, the lower limit of the unilateral confidence of the reliable life t_R is

$$t_{RL} = \left[\frac{\ln R}{\ln(1 - r)}\sum_{i=1}^{n} t_i^m\right]^{\frac{1}{m}} \tag{13}$$

When only lower limit m_0 of the shape parameter m is known, that is, $m \geqslant m_0$, and for a given reliability R, if the following condition is met, that is

$$R \geqslant \exp\left[\ln(1 - r)\exp\left(\frac{\sum_{i=1}^{n} t_i^{m_0}\ln t_i^{m_0}}{\sum_{i=1}^{n} t_i^{m_0}} - \ln\sum_{i=1}^{n} t_i^{m_0}\right)\right] \tag{14}$$

then the confidence level of reliable life t_R is at least r, the lower limit of unilateral confidence is

$$t_{RL_0} = \left[\frac{\ln R}{\ln(1 - r)}\sum_{i=1}^{n} t_i^{m_0}\right]^{\frac{1}{m_0}} \tag{15}$$

which is

$$P(t_R \geqslant t_{RL_0}) \geqslant r \tag{16}$$

2 Accumulator test

The reliability test of accumulator is a test of fatigue life, which is an important content of accumulator type test. Test accumulator is a capsule, belonging to the category of isolated accumulators. In the industry standard, the mechanical industry standard accounted for the majority, mainly including national standards such as JB _ T 7037-2006 hydraulic isolation type accumulator test method and JB _ T 7034-2006 hydraulic diaphragm type and size, have designed a kind of energy saving, an efficient accumulator fatigue test system to carry out the accumulator reliability test.

2. 1 Test system and program design

The accumulator reliability test system assembly is shown in Fig. 1. The test bed mainly includes three parts: a physical test mechanism part of the accumulator reliability test bed, namely a hydraulic main system; data acquisition and transmission of the test bed, a control part, namely the control system; a real-time monitoring of the performance parameters of the accumulator, data display and fault diagnostic part, namely a state monitoring system.

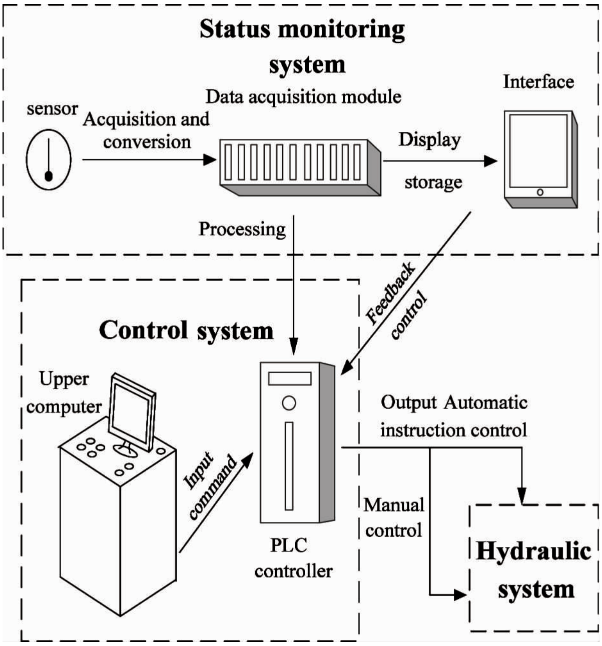
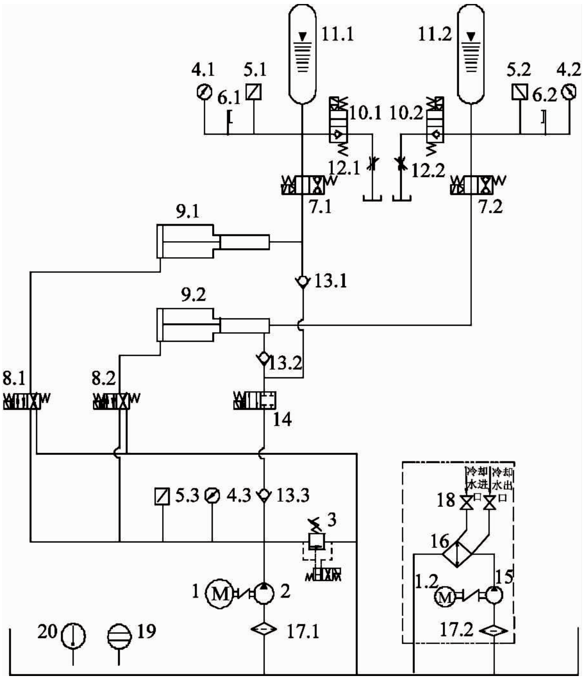


Fig. 1 Test system assembly

The accumulator reliability test bed is a fatigue life test bed capable of repeatedly filling and discharging the hydraulic accumulator. The main characteristic is that it can test two accumulators at the same time. In the hydraulic system circuit, the pressurized cylinder is used to pressurize the liquid filling process, which reduces the working load of the hydraulic pump, and through repeated differential of the pressurized cylinder, the accumulator is charged and discharged repeatedly, while also saving test time.

The schematic diagram of the hydraulic main system of the test bench is shown in Fig. 2.



1. 1 ,1. 2-Motor 2-Hydraulic pump3-Electromagnetic overflow valve4. 1 ,4. 2 ,4. 3- Pressure gauge5. 1 ,5. 2 ,5. 3- Pressure sensor 6. 1 ,6. 2-Temperature sensor 7. 1 ,7. 2-Electromagnetic ball valve (two - way seal)8. 1 ,8. 2-Solenoid directional valve9. 1 ,9. 2-Pressurized cylinder10. 1 ,10. 2-Electromagnetic ball valve (one-way seal)11. 1 ,11. 2-Subject accumulator 12. 1 ,12. 2-Throttle valve13. 1 ,13. 2 ,13. 3-Check valve 14-Electrohydraulic valve15-water pump16-Plate heat exchanger 17. 1 ,17. 2-filter18-Butterfly valve19-Level gauge20-Liquid temperature meter

Fig. 2 Schematic diagram of hydraulic system

The scene picture of reliability test bed is shown in Fig. 3.

Fig. 3 Reliability test stand site

2. 2 Subject sample and its pressure volume match

The sample of this test is NXQ A-31. 5/20-L-Y accumulator, as shown in Fig. 4.

Due to the inside of the accumulator, the internal gas will produce compression and expansion. Using Boyle's law on Eq. (17) for the state change in the ideal gas, the 'pressure-volume' relationship is shown in Fig. 5.

Fig. 4 Accumulator sample

$$P_0 \times V_0^n = p_1 \times V_1^n = p_2 \times V_2^n \tag{17}$$

In the formula:

V_0 ——the pre-filled nitrogen volume when the pressure is p_0 (L),

V_1 ——the pre-filled nitrogen volume when the pressure is p_1 (L),

V_2 ——the pre-filled nitrogen volume when the pressure is p_2 (L),

p_0 ——pre-filled nitrogen gas pressure (MPa),

p_1 ——minimum working pressure (MPa),

p_2 ——maximum working pressure (MPa),

n ——variable index.

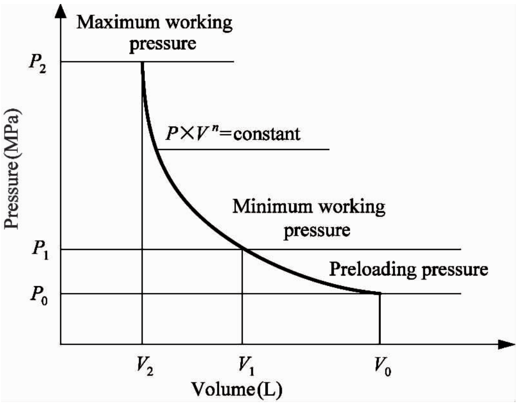


Fig. 5 Accumulator PV chart

2.3 Test program selection

This test uses a timed cut-off mode, in which the life analysis is attributed to the reliability estimate of the no-failure data in the case of a known life profile and a time-truncated test. Charge and discharge times of the accumulator are set as ‘time’. Reference to the repeated charge and discharge action test of mechanical industry standard JB/T7037-2006 hydraulic isolation accumulator test method of the charge and discharge times are set as 20000 times. This is not sufficient for the reliability test to be analyzed, so according to experience and cost selection of 600000 to 750000 times for the cut-off time, the frequency of the test is 6 times per minute, and 24 hours per day. Then 600 thousand takes about 70 days.

2.4 Failure detection and diagnostics and data acquisition

This data is of laboratory test, each of the two test samples for a series of tests, according to 7 days a week to do the test. During the test, the apparatus was running continuously 24 hours a day, and checked daily to observe. But no failure occurred during the test, and the time of the capsule accumulator cut-off time is as shown in Table 1.

Table 1 no failure test data of bladder accumulator

Serial number	Charge and discharge times t_i	Number of samples n_i
1	600158	1
2	600420	1
3	625100	1
4	672216	1
5	729800	1
6	741532	1

3 Reliability parameter estimation of no failure data in Weibull distribution

Six of the same batch were tested for reliability life test. According to the Bayesian method mentioned above, the optimal confidence intervals method were used to estimate the reliability parameters.

3.1 Reliability parameter estimation of no failure data based on the Bayes method

According to the Bayesian method, the first failure-free data is collated and then calculated, and the data is shown in Table 2.

Table 2 Timing no failure life test data of bladder accumulator

Serial number	t_i	n_i	s_i
1	600158	1	6
2	600420	1	5
3	625100	1	4
4	672216	1	3
5	729800	1	2
6	741532	1	1

It is seen from Eq. (3) and Eq. (6), the λ_k selection is very important. General λ_k is chosen according to the maximum principle of correlation coefficient[15]. If the product is in the development of research and development stage, only a small batch of production, this time the product reliability will not be high, then usually taking $\lambda_k = 0.382$. If the product is in a stable production stage to carry out large quantities of production, then the reliability of the product will be improved, usually taking $\lambda_k = 0.5$. If the product is in the stage of being optimized, the product enters the automated production stage of the pipeline, and the reliability will be further improved, then $A = 0.618$ is usually taken. Although the cage type accumulator can stabilize mass production, its reliability does not necessarily reach a relatively high level, and also has a larger room for improvement, so this article selects $\lambda_k = 0.5$.

The data obtained by the preceding narrative process are shown in Table 3.

Table 3 Bayes method related data

t_i	n_i	s_i	$\hat{p}_i$	w_i	x_i	y_i
600158	1	6	0.1148	0.1512	−2.1042	13.3049
600420	1	5	0.1267	0.1513	−1.9991	13.3054
625100	1	4	0.1428	0.1575	−1.8701	13.3457
672216	1	3	0.1651	0.1694	−1.7120	13.4183
729800	1	2	0.1946	0.1839	−1.5306	13.5005
741532	1	1	0.2222	0.1868	−1.3811	13.5165

Binding data in Table 3, and Eq. (7), Eq. (8) can be obtained: $\hat{\mu} = 13.9914$, $\hat{\sigma} = 0.3355$, therefore, $m = \hat{\sigma}^{-1} = 2.9804$, $\eta = e^{\hat{\mu}} = 1.1923 \times 10^6$。

The life reliability model of the bladder accumulator is calculated according to the Bayesian method by the two-parameter Weibull reliability model of Eq. (11):

$$R(t) = e^{-(\frac{t}{\eta})^m} = e^{-(\frac{t}{1.1923\times10^6})^{2.9804}} \tag{18}$$

The resulting reliability function is shown in Fig. 6.

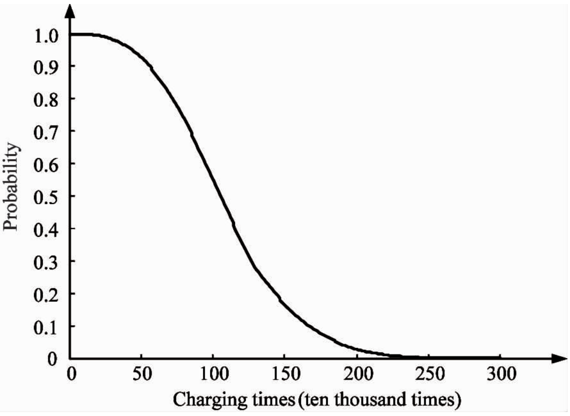


Fig. 6 Reliability function

According to Eq. (1), the distribution function is shown as Fig. 7.

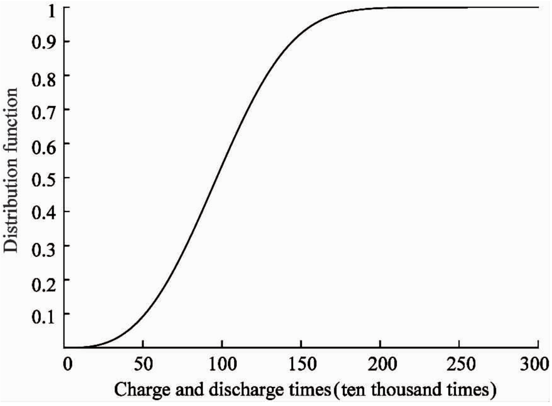


Fig. 7 Distribution function

According to Eq. (19), the failure probability density function is shown as Fig. 8.

$$f(t) = \frac{m}{\eta}(\frac{t}{\eta})^{m-1}e^{-(\frac{t}{\eta})^m} \tag{19}$$

According to the Eq. (20), the failure rate function is shown as Fig. 9.

$$\lambda(t) = = \frac{m}{\eta}(\frac{t}{\eta})^{m-1} \tag{20}$$

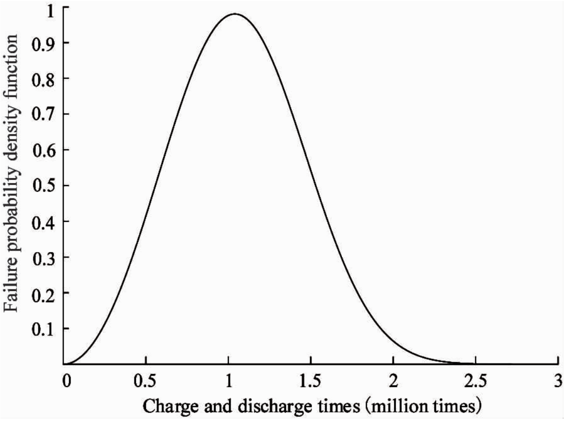


Fig. 8 Failure probability density function

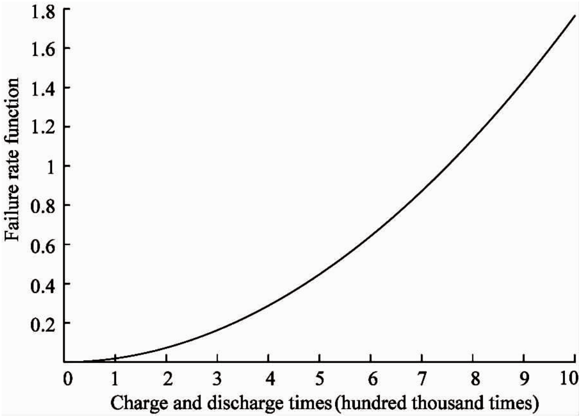


Fig. 9 Failure rate function

3.2 Reliability parameter estimation of no failure data based on the optimal confidence intervals method

According to the optimal confidence intervals method, failure-free data is sorted first, as shown in Table 4.

Table 4 Timing no failure life test data of bladder accumulator

Serial number	Number of stops (ten thousand times)
1	>60
2	>60
3	>60
4	>60
5	>60
6	>60

Eq. (14) is reduced to

$$R \geqslant (1-r)^{\frac{1}{n+1}} \tag{21}$$

Eq. (15) can be simplified as

$$t_{RL_0} = t_0\left[(n+1)\frac{\ln R}{\ln(1-r)}\right]^{\frac{1}{m_0}} \tag{22}$$

$$t \leqslant t_0 \tag{23}$$

$$R_{L_0} = \exp\left[\frac{\ln(1-r)}{n+1}\left(\frac{t}{t_0}\right)^{m_0}\right] \tag{24}$$

It is now required that the confidence level of the capsule type accumulator is $r = 0.9$, corresponding to the confidence intervals of charge and discharge times $t = 200{,}000$ times. For the lower limit m_0 of the Weibull distribution shape parameter m, it can be roughly analyzed by referring to the relevant data: the lower limit of the shape parameter of the aluminum alloy structure m_0 is generally 3.9, and the steel structure is generally 2.2, of course, the lower limit of the shape parameter will also be biased. Here, the capsule type accumulator shape parameter lower limit value m_0 is taken as 2.2.

Therefore, according to Eq. (24), it is possible to obtain the lower confidence intervals for reliability when the charge level corresponding to the capsule type accumulator is 200,000 times and the confidence level is 0.9.

$$R_{L_0} = \exp\left[\frac{\ln(1-0.9)}{6+1}\left(\frac{20}{60}\right)^{2.2}\right] = 0.97$$

For a given reliability $R = 0.99$, the confidence level $r = 0.9$, satisfies the Eq. (21) condition:

$$R = 0.99 \geqslant (1-r)^{\frac{1}{n+1}} = (1-0.97)^{\frac{1}{6+1}} = 0.61$$

Therefore, according to Eq. (22) it can be obtained that when the capsule type accumulator corresponds to the reliability $R = 0.99$, the confidence level is 0.9 the reliability of life confidence intervals:

$$t_{RL_0} = 60\left[(6+1)\frac{\ln 0.99}{\ln(1-0.9)}\right]^{\frac{1}{2.2}} = 12.3$$

(ten thousand times)

In summary, according to the equation:

$$R_{L_0} = \exp\left[\frac{\ln(1-r)}{n+1}\left(\frac{t}{t_0}\right)^{m_0}\right],$$

for the given accumulator lifetime t (charge and discharge times) and confidence level 0.9, the corresponding confidence intervals can be obtained, and the final calculation results are shown in Table 5 and Fig. 10.

Table 5 Reliability of bladder accumulator

Charge and discharge times (ten thousand times)	Reliability R_{L0}
5	0.999
10	0.994
20	0.97
30	0.93
40	0.87
50	0.80
60	0.72

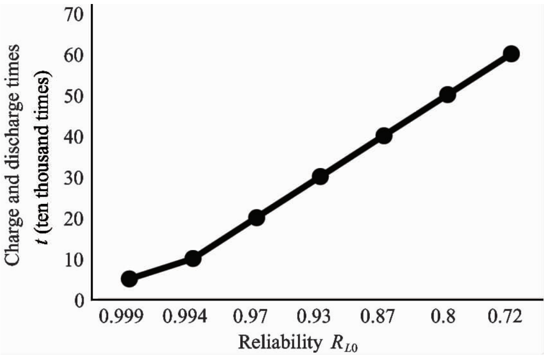


Fig. 10 Reliability chart of bladder accumulator

It can be seen from Table 5 that when the same confidence level is used, the reliability decreases gradually as the number of charge and discharge of the accumulator increases.

For the given confidence level is 0.9, when the reliability condition is satisfied:

$$R \geqslant (1-r)^{\frac{1}{n+1}} = (1-0.1)^{1/7} = 0.7197,$$

according to Eq. (22), for a given accumulator reliability R and confidence level of 0.9, the reliable life confidence intervals (charge and discharge times) can be drawn, the final calculation results are shown in Table 6 and Fig. 11.

Table 6 Reliable life of bladder accumulator

Reliability R	Charge and discharge times t (Ten thousand times)
0.99	12.3
0.95	25.8
0.90	35.8
0.85	43.5
0.80	50.3
0.75	56.5
0.7197	60

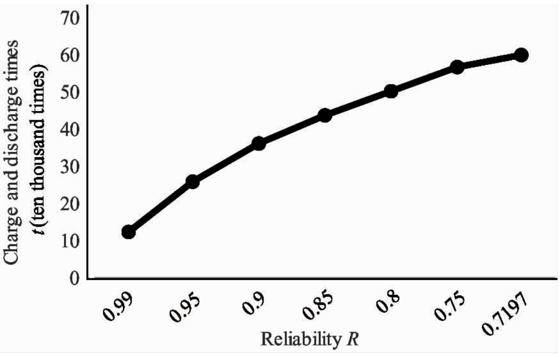


Fig. 11 Reliability chart of bladder accumulator

It can be seen from Table 6 that when the same confidence level is reached, the number of reliable lifespan is gradually increased as the reliability decreases.

4 Conclusion

Based on the study of the theory of accumulator and the current situation of hydraulic reliability test, the reliability test device of the accumulator is designed and the reliability test is carried out and no failure data is obtained. Based on the Bayesian estimation method, the life reliability model of the bladder accumulator is obtained based on the failure-free data of the accumulator reliability test. For the lifetime of the Weibull distribution, and the lower limit of the shape parameter is known, the unilateral confidence intervals of reliability are obtained when the reliable life is t_R and the confidence is at least r, using the established reliability unilateral confidence lower limit estimation model. The unilateral confidence intervals of reliable life are obtained when the reliability is R and the confidence is at least r, using the established reliability estimation model of reliable life unilateral confidence.

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