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# RESEARCH ON LOAD SPECTRUM OF AERO HYDRAULIC PUMP BASED ON ACCELERATED DEGRADATION TESTING

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## Abstract

*As the power sources of hydraulic systems in aircrafts, gaining reliability information of aero hydraulic pumps tends to be of great significance. However, aero hydraulic pumps with high reliability and long lifetime pose a great challenge to obtaining failure data through traditional life testing or accelerated life testing (ALT). In this paper, accelerated degradation testing (ADT), which is easily accessible to lifetime of pumps without failure data, is proposed. Based on the service conditions and working principle of pumps, the failure mechanism was analyzed. And the ADT load spectrum was designed to reflect the actual working conditions and to ensure a desirable accelerated factor. In addition, by comparing the result of test under service conditions with that of ADT, the aforementioned testing method is proved to be applicable to aero hydraulic pumps and can be further applied to other electro-mechanical products with similar properties.*

## 1 Introduction

Hydraulic pump is the power component of hydraulic transmission and control system of the aircraft. There are mainly gear pumps and piston pumps. Aviation equipment is equipped mostly with piston pumps. Aviation hydraulic pump is a kind of product which is highly-reliable, long-life and expensive. Accelerated life test (ALT) and accelerated degradation test (ADT) are main accelerated testing techniques for the reliability assessment and life estimation of the high-reliability and long-life products. ALT accelerates product failures, shortens test time with the method of increased stress, then chooses appropriate model to estimate life characteristic values of the product under normal stress, Its basic idea is to use lifetime characteristics under high stress levels to extrapolate life characteristics under normal stress. Because of the limitation of test cost and equipment for aviation hydraulic pump which is high-reliability and long-life. Its test generally only lasts for tens of hours or hundreds of hours, the hydraulic pump is far from failure though. We often cannot obtain the failure time data consequently. Therefore, the accelerated life test method can observe only a small amount of failure or even no fault. It is not easy to achieve the reliability and life assessment based on the analysis of failure.[1] In order to get more accurate estimate within acceptable test time, tests need to be performed under higher stress levels with performance degradation data obtained. Then we estimate the reliability or service life of the product under the condition of regular force. Thus the accelerated degradation test (ADT) is proposed. In this test, the stress mode applied is the same as ALT, but ADT needs not to observe fault occurring, just to monitor pre-determined performance degradation parameters.[2,3] In ADT, the "failure" is generally defined that the performance parameters degenerate down to the given engineering index (namely degradation threshold).[4] ADT overcomes defects of ALT such as only recording failure time, ignoring how product fails and the specific failure process and changes of product properties. We can get a better reliability estimation of high-reliability and long-life products through accelerated degradation data processing which makes up the defects for ALT in test data processing of without failure.

To study reliability analysis and life prediction of hydraulic pump, the load spectrum of hydraulic pump needs to be compiled firstly. In this paper, we study a certain aircraft hydraulic pump, and compile accelerated test load spectrum based on the theory and method Russian OCT1 criteria recommended.

## 2 Scheme of Accelerated Degradation Testing

### 2.1 Introduction of aviation hydraulic pump

Research object in this test is a type of constant-pressure and variable-flow aviation piston pump with 9 pistons. The performance index requirements are as shown in Table 1 and structure in Fig. 1.

The working principle of the hydraulic piston pump is as follows:

As shown in Fig. 1, the hydraulic pump shaft is connected with reduction device through transmission shaft, and the hydraulic pump rotates when reducer starts rotating. The plunger rotates with rotor and also does reciprocating motion along the plunger hole of rotor to absorb and discharge oil. There are 9 pistons and corresponding plunger holes. When pump shaft rotates a circle, every pair of the piston and bore completes the process of oil absorption and drainage, so that the continuous process of oil suction and drainage for hydraulic pump is accomplished. The oil supply of hydraulic pump is determined by the speed of pump and the oil discharge per rotation. When the speed is constant, oil supply is adjusted by the inclination of swash-plate.

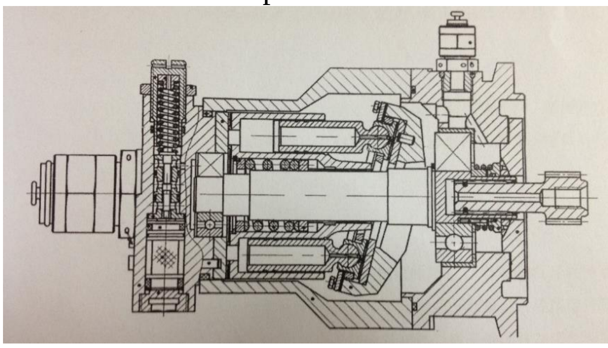

Fig. 1 Hydraulic pump structure

Table 1 Performance index of aero hydraulic pump

| **Rated working pressure** | **Rated speed** | **Rated flow** | **Full flow working pressure** | **oil return volume of shell** | **Rated inlet pressure** |
|---|---|---|---|---|---|
| $21_{0}^{+0.5}$ MPa | 4035 r/min | beginning of life $35_{0}^{+3.5}$ L/min; end of life not less than 34L/min | beginning of life more than 20 MPa; end of life more than 19.5 MPa | beginning of life less than 2L/min; end of life less than 3L/min | 0.1MPa |

### 2.2 Failure Mode and degradation parameters of aviation hydraulic pump

Through analysis of previous failure mode and structure, working principle and performance of aviation hydraulic pump, we draw the main failure mechanism of hydraulic pump is wear, fatigue and aging. Key components and related failure mode of hydraulic piston pump, as is shown in Fig. 2. Pressure, rotational speed and oil temperature hydraulic pump are dynamic and sensitive stress during use. Hydraulic pump failure is mainly marked by decrease of pressure, decrease of outlet flow and increase of oil return volume. Pressure and flow rate are chosen as the performance degradation parameters of hydraulic pump according to the selection principle of degradation parameters. However, the pressure parameter during the experiment is not obvious, while the change of the oil return amount is more obvious from the degradation data of hydraulic pump measured by actual test, which reflects the degradation and failure mechanism of hydraulic pump. So finally we choose oil return volume as performance degradation parameter of hydraulic pump, whose failure threshold as the failure criterion is: oil return volume of shell≥3 L/min.

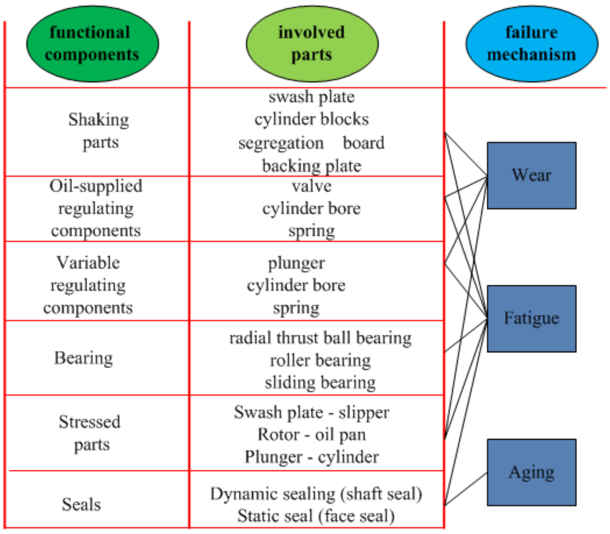


Fig. 2 Failure mode of key components of hydraulic piston pump

## 2.3 Conventional test (long-time test) conditions

Long-time test scheme is based on the Russian and GJB standards, conventional test conditions are as follows: the testing time, a total of 300 hours, is divided into 6 stages including 3 rotational speeds 2700,4035 and 4640 r/min (long-time test spectrum is not given here).

## 2.4 Program of accelerated testing

### *2.4.1 Selection of accelerated stress*

According to the above analysis of failure mode of hydraulic pump, the main failure modes of the test pump are wear, fatigue and aging. Flow and speed affect the wear and fatigue of the pump, and the main factor affecting the aging is temperature. Therefore flow, rotational speed and temperature are chosen as the accelerated stress.

### *2.4.2 Design of accelerated program and Analysis of accelerated model*

Design the accelerated process of six stages respectively with reference to the setting of the above routine test spectrum. Since the test time of stage 3 and 6 is shorter, a very small proportion of total time, acceleration is not implemented any longer in the accelerated test and the original test time is retained. In addition, with reference to Russian test standard, change the cyclical patterns from single cycle in each phase to the mixed cycle if pump test bed allows, each cycle time for 5 s; Accelerated flow levels are set as four levels: 5.5,12,28 and 36.5 L/min(stage 3 and 6 unchanged); Medium temperature is 100 degrees Celsius.

Based on the analysis of performance degradation mechanism of hydraulic pump, the accelerated stress of hydraulic pump is flow, rotate speed and temperature. Therefore, the comprehensive accelerated stress model of aviation hydraulic pump should be chosen as follows:

$$\eta = e^{\alpha_0+\alpha_1\cdot\varphi(q)+\alpha_2\cdot\varphi(n)+\alpha_3\cdot\varphi(T)} \quad (1)$$

where $\eta$ is a characteristic value of degradation, $a_0, \alpha_1, \alpha_2, \alpha_3$ are model parameters. $\phi(q)$ is known function of flow rate $q$, $\varphi(n)$ is known function of rotational speed $n$, and $\phi(T)$ is known function of temperature $T$, where

$$\phi(q) = \ln q \quad (2)$$

$$\phi(n) = \ln n \quad (3)$$

$$\varphi(T) = \frac{1}{T} \quad (4)$$

## 3 Compilation of accelerated test load spectrum

Load spectrum is the premise and basis for reliability analysis. The load spectrum of the hydraulic pump requires to be firstly compiled to study the reliability and life prediction of hydraulic pump.

## 3.1 Calculation of Load spectrum

Because this type of pump is designed based on the prototype of Russian introduced product, accelerated spectrum is compiled on the basis of Russian OCT1 criteria. For variable piston pump, rotation rate, flow and temperature are accelerated stress. The stress level chosen cannot exceed the limit of hydraulic pump, notably the failure mechanism of hydraulic pump should remain unchanged. Then design the acceleration of the 6 stages respectively referring to the settings of conventional spectrum. In stage 3 and 6, acceleration is not implemented and the original test time is retained. Accelerated test time is calculated through corresponding formula in Russian OCT1. Calculate accelerated test time respectively according to different failure mechanism as follows.

(1) Considering wear

According to Russian criteria, as wear forms are abrasive and fatigue wear, in

$$T^y = T^H \frac{n^H h^H}{n^y h^y} \left(\frac{q^H}{q^y}\right)^m \qquad (5)$$

*m*=4. By the accelerated wear formula, considering the effect of temperature, we compare the test time of each accelerated test phase with the time of corresponding normal phase, and the results are shown in Table 2.

Table 2 Accelerated test time considering wear

| **Phase** | **Before acceleration /h** | **After acceleration /h** | |
|---|---|---|---|
| | | piston-cylinder | slipper-swash plate |
| 1-1 | 3.27 | 0.00 | 1.46 |
| 1-2 | 8.17 | 2.24 | 2.80 |
| | 8.17 | 3.17 | 3.63 |
| 2-1 | 55.50 | 5.54 | 41.39 |
| 2-2 | 55.50 | 30.18 | 41.48 |
| 3-1 | 7.50 | 4.40 | 5.02 |
| 3-2 | 7.50 | 4.40 | 5.02 |
| 4-1 | 4.48 | 0.00 | 3.00 |
| | 4.48 | 0.00 | 2.98 |
| 4-2 | 22.42 | 13.00 | 14.90 |
| | 22.42 | 13.00 | 14.90 |
| 5-1 | 49.55 | 4.94 | 36.95 |
| 5-2 | 49.55 | 1.26 | 32.99 |
| 6-1 | 0.25 | 0.25 | 0.25 |
| 6-2 | 1.25 | 0.73 | 0.83 |
| **Total** | **300** | **83.11** | **78** |

(2) Considering fatigue

According to the actual working condition, in the working process of hydraulic pump, the swash plate, bearing are constantly impacted by cyclic load, prone to fatigue causing hydraulic pump failure. Computing accelerated test time of swash plate, ball bearing and needle bearing considering fatigue, then compare with normal test time, results are shown in Table 3.

Table 3 Accelerated test time considering fatigue

| **Phase** | **Before acceleration /h** | **After acceleration /h** | | |
|---|---|---|---|---|
| | | swash plate | ball bearing | needle bearing |
| 1-1 | 3.27 | 0.00 | 1.47 | 0.04 |
| 1-2 | 8.17 | 1.43 | 4.49 | 3.66 |
| | 8.17 | 2.41 | 4.49 | 3.66 |
| 2-1 | 55.50 | 3.13 | 30.43 | 11.61 |
| 2-2 | 55.50 | 23.83 | 42.79 | 32.43 |
| 3-1 | 7.50 | 3.37 | 6.55 | 5.03 |
| 3-2 | 7.50 | 3.37 | 6.19 | 5.02 |
| 4-1 | 4.48 | 0.00 | 2.97 | 0.06 |
| | 4.48 | 0.00 | 1.97 | 0.01 |
| 4-2 | 22.42 | 9.90 | 18.43 | 15.00 |
| | 22.42 | 9.90 | 18.43 | 15.00 |
| 5-1 | 49.55 | 2.79 | 27.17 | 10.37 |
| 5-2 | 49.55 | 0.52 | 30.83 | 5.02 |
| 6-1 | 0.25 | 0.25 | 0.00 | 0.17 |
| 6-2 | 1.25 | 0.55 | 0.00 | 0.84 |
| **Total** | **300** | **61.45** | **196.21** | **107.92** |

(3) Considering aging

Thermal aging is mainly related to seals, for this test pump, seals resulting in aging fault of all are static seal, sealing parts have no temperature rise caused by throttling, seal temperature is related to medium temperature and ambient temperature. The calculation results are shown in table 5(next page).

As can be seen from table 2, 3, 4, it can be relatively easy to realize the acceleration of 2:1 considering the wear, fatigue and aging conditions.

## 3.2 Compilation of Load spectrum

According to the above analysis and calculation, on the basis of routine test spectrum, referring to Russian standard and weigh the bearing capacity of test-bed, we draw up the accelerated test load spectrum, as is shown in Fig. 3.

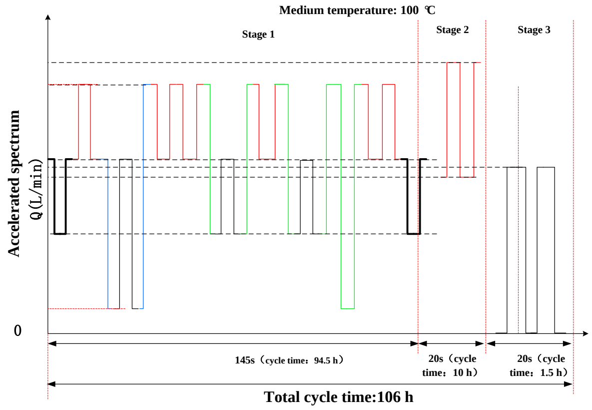


Fig. 3 Load spectrum of accelerated degradation test

As can be seen from the above image, (1)The test spectrum is divided into three periods, the first cycle has four different flow levels, corresponding to accelerated stage 1, 2, 4, 5 in Table2; (2) There are separately two different flow stress levels in the second and third cycle; (3) Rotation speed of the motor in each cycle is constant, but different between different cycles; (4) The medium temperature of the accelerated test remains 100 degrees Celsius; (5) The whole test process is divided into 33 stages cycling and the whole cycle includes 3 periods. The first lasts 94.5 hours, the second lasts 10 hours and the third lasts for 1.5 hours. (6) The whole cycle takes 106 hours, corresponding to the original long-test cycle time of 300 hours.

Table 4 Accelerated test time considering aging

| | Duration | Ambient temperature | Working fluid temperature | Temperature load coefficient | Additional temperature rise of seal | Seal temperature |
|---|---|---|---|---|---|---|
| **Before acceleration** | 300 | 25 | 80 | 0.1 | -6 | 74 |
| **After acceleration** | 105 | 25 | 100 | 0.1 | -8 | 92 |
| **Acceleration coefficient** | $\prod_{i=1}^{n_{10}} X_i = 1.84^{0.6} \times 1.79 \times 1.69^{0.2} = 2.87$ | | | | | |

## 3.3 Results and discussion

According to the comparison and analysis of test data before and after the accelerated test, then we evaluate accelerated test protocol proposed. The accelerated test scheme is designed on the basis of conventional test of this pump, and the speedup rate is required to reach 2:1. By comparing the main performance indexes of hydraulic pump between the long-time test and the accelerated test including rated flow, oil return volume, efficiency and so on, evaluate the validity of the scheme. The contrast curves before and after the testing are shown in Fig. 4- Fig. 7.

Fig. 4, 5, 6 are contrast curves respectively of rated flow, full flux oil circulation, zero flow oil return between conventional and acceleration test. As can be seen by comparing the horizontal axis, the time of test points on the conventional test is almost 3 times of the corresponding points on the accelerated test curve, and the two curves are remarkably similar, meeting the design requirements, thus confirmed this design of the proposed scheme is rational and feasible. Fig. 7 shows the contrast curve of overall efficiency between conventional and acceleration testing, and the two overall efficiency curves are roughly identical as a whole, thus verifying the validity of design of test scheme again.

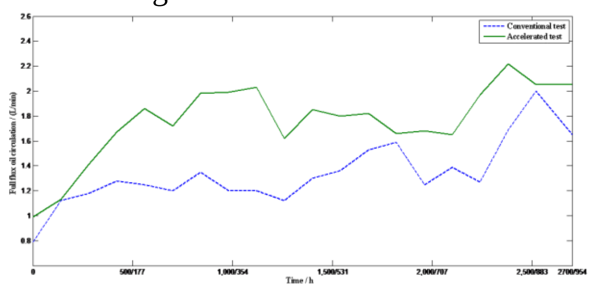


Fig. 4 Rated flow contrast between long-time and accelerated test

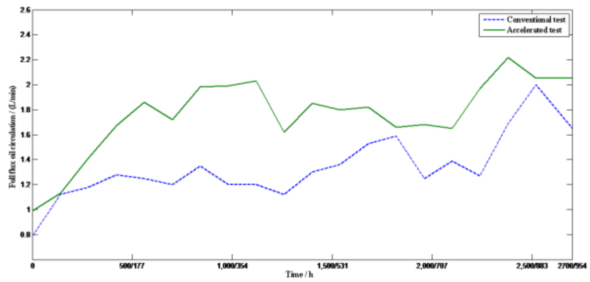


Fig. 5 Full flux oil circulation contrast

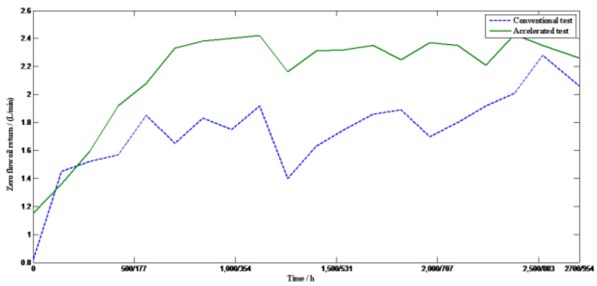


Fig. 6 Zero flow oil return contrast

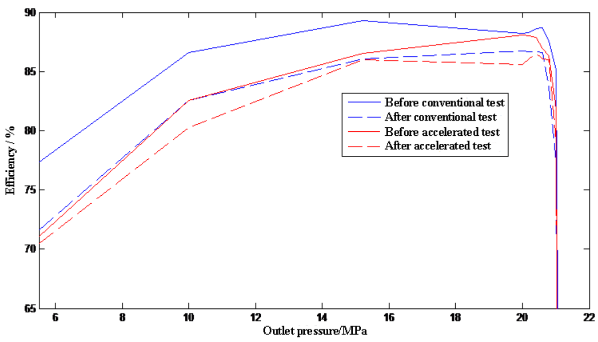


Fig. 7 Total efficiency contrast

## 4 Conclusions and Outlook

This paper has studied on a certain type of aircraft hydraulic pump, compiled aircraft hydraulic pump load spectrum based on accelerated performance degradation testing, and verified the validity of the acceleration program by comparing key performance indicators of hydraulic pump of conventional test with accelerated test. In this accelerated test, temperature stress always remains constant and the speed at each stage is also constant, which is different from actual working conditions of aircraft, so it is of great significance to study the accelerated load spectrum of hydraulic pump closer to the actual working conditions, which is also the research orientations in the future of ADT. ADT has important research and application value in life prediction of high-reliability products, which has a broad prospect in application.

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