RELIABILITY RESEARCH ON HYDRAULIC AXIAL PISTON PUMP

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ABSTRACT

This paper describes the reliability of 25 SCY hydraulic axial piston pumps. On the basis of investigations, experiments and theoretical analyses, the pump failure mode and failure mechanism were found. The statistical study of test data was done, the failure distribution function and the distribution parameters were determined, and the pump life was estimated.

In order to save testing time and money, an accelerated life test has been conducted. The acceleration equation has been formulated successfully. After making an improved design, the pump life has been prolonged greatly. At the end of this paper, a life acceptance testing plan of censored small samples is put forward.

KEY WORDS

Reliability, Failure distribution, Accelerated testing,

NOMENCLATURE

A -- coefficient
B -- coefficient
C -- coefficient
Ce -- kurtosis coefficient
Cs -- skewness coefficient
M3 -- third order central moment of samples
M4 -- fourth order central moment of samples
m -- shape parameter of Weibull distribution
N -- rotational speed
n -- sample size
p -- rated pressure
P -- confidence level
Q -- pump displacement
S -- stress level
t -- test time

t0.5 -- median life
Γ -- gamma function
ξ -- characteristic life
λ -- failure rate
μ -- average life (mean time to failure)
σ -- life acceleration factor
σ -- standard deviation

Subscript:
0 -- for the pressure of 32 MPa
1 -- for the pressure of 35 MPa
2 -- for the pressure of 40 MPa

INTRODUCTION

Reliability of hydraulic systems occupies an increasingly important place in engineering practice. Recently it is strongly desired to improve the reliability of hydraulic components. In order to raise the life of the 25 SCY axial piston pump which is widely used in China, a special research program has been finished.

The objectives of this research were
1. to find out the weakest point of the pump failure and the failure mechanism,
2. to determine the failure distribution function and distribution parameters,
3. to estimate the life of the pump,
4. to conduct an accelerated life test which could shorten the test time and study the relationship between the load pressure and the pump life,
5. to offer effective measures to prolong the pump life,
6. to propose a life testing plan to pump manufacturers and users for life estimating.

After a series of investigations, a total of 270 failure pumps provided by more than 20 users have been analyzed in detail. It is shown that the failure forms of 25 SCY pumps mainly are excessive wear on pistons and porting plate, bearing failure, malfunctions of slide shoes and the fatigue crack at the piston neck.

Even though much information can be
derived from field data, there is a difficulty in reaching the certainty because the field data usually come from unidentified environmental and operational conditions. Therefore, laboratory test is necessary. Laboratory data can provide more information per sample unit, both in the precise time to failure and in the mechanism by which the failures occur.

Twelve pumps of an identical model from the same manufacturer have been tested on a special energy saving test rig. The criterion used to judge the pump failure is either the 5 percentage point drop in volumetric efficiency or any part failing to work. As a result of the testing, the failure mode or the failure mechanism at different load stress levels has been found to be a fatigue rupture. The weakest point is the fatigue crack at the piston neck. The failure test data can be normally evaluated by the two-parameter Weibull distribution.

According to the accelerated test data the acceleration equation has been formulated and the acceleration factor, which is equal to 4.73, has been obtained. The value of the acceleration factor is most significant for the reliability and life verification.

In order to strengthen the piston neck, an improved design of the axial piston pump has been made. The tests on two pump specimens show that the life of the improved pump is 2.6 times that of the old one. The manufacturer has obviously got the economic and social benefits from the reliability research.

TEST CONDITIONS

Test conditions are important considerations which require a understanding both of the loading to which the pump is subjected and of the environment within which it operates.

The specifications of the 25 SCY pump are as follows:

- Max. displacement Q = 25 ml/rev.
- Rated pressure p = 32 MPa
- Rotational speed N = 1500 rpm

Test was conducted at the fluid temperature of 50±15°C and the contamination level of the testing system was controlled to meet the class 9 of NAS 1638 standard, U.S.A.

It is well known that pumps are normally used in continuous operation and failures are caused by deterioration. In such situations advanced stress testing can be employed to accelerated failures. Generally speaking, advanced stress will make the pump failure rate increase. Thus, a decrease in reliability can be related to an increase in stress level. And for this reason, the life tests can be performed at high stress levels, and the reliability at normal stress level can finally be inferred. The "stress" here is in broad sense. All these such as load pressure, temperature, rotational speed and contaminant can be referred to as "stress".

Considering the significant effects of the load pressure on the failure of the pumps, we prefer choosing the load pressure as an acceleration stress. In conducting an accelerated test, it is essential that the failure mode under the accelerated condition be the same as under the normal operating condition. On the ground of the identity of failure modes and the limitation of the lives of other components in testing system, the accelerated life tests of 25 SCY pumps were operated under the load pressure of 40 MPa and of 35 MPa.

Twelve pumps which were picked at random from the same manufacturer were tested on a special energy-saving test rig. The hydraulic circuit of the test rig is shown in Fig 1.

TEST CONDITIONS

In our test, censoring method was used. That means the test time was fixed. The results of the test are given in Table 1.

It can be seen that among the twelve samples nine pumps failed to work. After disassembling and inspecting each failure pump, it was found that all these failures were resulted from ruptures at the piston necks, and the failure modes of nine pump were same, that is, their modes were identical with each other no matter what the stress level was. While the ruptures took place, the decrease of pump volumetric efficiency was less than 3 percentage. That indicates the wear on pump components was not serious.

Metallographic examination and mechanics analysis have been done carefully. It has been indicated that the failure mechanism of 25 SCY pumps is not the wear, but the fatigue breakdown, if the system contamination is normally controlled. The fatigue ruptures at the piston neck are due to the improper design, technology and surface treatment of the piston. It gives us a useful guidance to improve the reliability of 25 SCY pumps.
Table 1. Test Data

<table>
<thead>
<tr>
<th>Stress Level (MPa)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
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</tr>
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<td>76</td>
<td>122</td>
<td>53</td>
<td>45</td>
<td>56</td>
</tr>
</tbody>
</table>

[¹] Suspended Item

STATISTICAL STUDY OF TESTING DATA

Statistical method can be used more effectively in making quantitative estimates of reliability. Firstly, the testing data were examined by Dixon method to determine whether one or more observations should be rejected as being faulty. The results have confirmed that among the testing data there are no observations which should be rejected. That is, all of these data are realiable and meaningful.

In order to determine the type of failure distribution, the skewness coefficient and kurtosis coefficient have been calculated:

- Skewness coefficient \( C_s = \frac{M_3}{\sigma^3} \)
- Kurtosis coefficient \( C_e = \frac{M_4}{\sigma^4} \)

By computing these formulas, we have:

For \( S_1 = 35 \text{MPa} \): \( C_s = 1.18, \ C_e = 1.39 \)
For \( S_2 = 40 \text{MPa} \): \( C_s = 1.20, \ C_e = 1.50 \)

From the theory of distribution functions we have already known in the case of normal distribution \( C_s \) equals 0 and \( C_e \) equals 3, in the case of exponential distribution, \( C_s = 2, \ C_e = 9 \). It is obvious that the pump failure distribution is neither normal distribution nor exponential distribution.

Graphical method is a simple method which allows us to evaluate the goodness of fit visually without using advanced mathematics, and at the same time to estimate the parameters that define the distribution.

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In order to estimate the parameters of this distribution, the graphical method, the least square method and the best linear unbiased estimation were used separately. The results are shown in Table 2, and the regression equations are as follows:

For \( S_1 = 35 \text{MPa} \), \( Y = 0.592X - 3.957 \)
For \( S_2 = 40 \text{MPa} \), \( Y = 0.659X - 3.791 \)

ACCELERATION EQUATION AND FAILURE DISTRIBUTION FUNCTION

According to material science there is a relationship between stress and life. This relationship can be represented by the following equation:

\[ \eta = A e^{-B} \]

This shows that life decreases as the intensity of stress increases.

Taking the logarithm expression,

\[ \ln \eta = C - B \ln \sigma \]

Substituting the testing values into the above equation,

\[ \ln 800 = C - B \ln 35 \]
\[ \ln 315 = C - B \ln 40 \]

Solving these equations, gives

\( C = 31.4, \ B = 6.96 \)
Then we obtain

\[ \ln n = 31.4 - 6.96 \ln S \]

This equation is called the acceleration equation of 25 SCY pumps.

Using the acceleration equation and taking the average of \( m_1 \) and \( m_2 \) we can get:

For the rated stress level (\( S_0 = 32 \text{MPa} \))

the shape parameter \( m_0 = 0.625 \)

the characteristic life = 1451 hours

Hence, the failure cumulative distribution function is

\[ F(t) = 1 - e^{-\left(\frac{t}{1451}\right)^{0.625}} \]

the failure probability density function is

\[ f(t) = 6.6 \times 10^{-3} t^{-0.375} e^{-\left(\frac{t}{1451}\right)^{0.625}} \]

the failure rate is

\( \lambda(t) = 6.6 \times 10^{-3} t^{-0.375} \)

Then, the life of the 25 SCY pump can be estimated:

\( \eta = 1451 \) h

\( \mu = 7 \lambda \left(1 + \frac{1}{m}\right) = 2074 \) h

\( t_{0.5} = \eta \left(-1n0.5\right)^{1/m} = 807 \) h

**IMPROVED DESIGN**

It is obvious that the pump life is too low to meet the customers' requirements. There is a need to increase the pump reliability and prolong the pump life.

Two specimens of the improved pump in which the piston neck was redesigned were tested for 1000 h at the pressure of 40 MPa without failure.

From acceleration equation:

Life acceleration factor \( \tau_{S_2-S_0} = \frac{t_0}{t_2} \)

\[ = \left(\frac{S_2}{S_0}\right)^{8} \]

substituting \( S_2 (40 \text{MPa}), S_0 (32 \text{MPa}), B (6.96) \) and \( t_2 (1000 \text{h}) \) into this expression, we have

\[ \tau_{40-32} = 4.73 \]

\( t_0 = 4730 \) h

Therefore, the accelerated test running of 1000 h at the pressure of 40 MPa is equivalent to the normal test running of 4730 h at the pressure of 32 MPa.

According to the statistical formula:

\[ P = 1 - \exp \left[-n \left(\frac{\tau_0}{\tau}\right)^m\right] \]

With 90 percent confidence level, the new pump possesses:

\( \eta_0 = 3776 \) h

\( \mu_0 = 5398 \) h

\( t_{0.5} = 2101 \) h

**CONCLUSIONS**

1. Under the normal control of the hydraulic system, the failure mode of 25 SCY axial piston pumps is the fatigue rupture at the piston neck. The failure distribution belongs to two-parameter Weibull distribution with shape parameter \( m = 0.625 \) and characteristic life = 1451.

2. Using load pressure as an advanced stress is most effective in the accelerated test of pumps. The acceleration factor \( \tau_{40-32} \) of the 25 SCY pump is equal to 4.73, which is valuable for life tests.

3. Through redesign the early failure of the 25 SCY pump has been eliminated. It has been proved with 90 percent confidence the new pump has at least 5394 h mean time to failure, which is 2.6 times that of the old one.

4. Based on the research results, a life acceptance testing plan is put forward. This plan is offered to ensure that the MTTF of 25 SCY pumps is not smaller than 1000 h with a confidence 0.90. Conducting an accelerated test with the load pressure, the sample size and the test time selected from Table 3, if none of these test samples fails to work this means the pump life goal of 1000 h has been achieved.

5. The pump failure mode under cyclic pulse load may be different from that under static pressure load. A research work on the reliability of 25 SCY pump has been finished recently. The research results were represented in another paper (1).

**Table 3. Life Acceptance Testing Plan**

<table>
<thead>
<tr>
<th>Stress level (MPa)</th>
<th>Sample size</th>
<th>Test time (h)</th>
</tr>
</thead>
<tbody>
<tr>
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</table>

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REFERENCES

