Research on Life Distribution of Hydraulic Seal O-ring Based on Covariate

Xincheng SONG\textsuperscript{1,a}, YANG Jie\textsuperscript{1,b}, WANG Wei\textsuperscript{1,c}, Jiawei LI\textsuperscript{2,d}, WANG Hao\textsuperscript{3,e}, Shaoqiang YI\textsuperscript{4,f}

\textsuperscript{1}Air Defense and Antimissile Institute, Air Force Engineering University, Xi’an, shaanxi, China
\textsuperscript{2}Unit 94011 of PLA
\textsuperscript{3}Unit 93285 of PLA
\textsuperscript{4}Unit 91315 of PLA
\textsuperscript{a}email: 361388343@qq.com, \textsuperscript{b}yyjjj930@126.com, \textsuperscript{c}email: admin@kgd.mtn
\textsuperscript{d}email: 473803332@qq.com, \textsuperscript{e}email: 604252794@qq.com, \textsuperscript{f}email: ysqlychee@163.com

Abstract. Due to the lack of reliable big data, data-driven methods cannot be used to study the life distribution of hydraulic components. Facing the leakage failure of the hydraulic component is caused by the failure of the O-ring wear in hydraulic contact seal, According to the O-ring adhesive wear principle and Archard model, a method of fusing the internal leakage life test of hydraulic components with the simulation experiment based on the equivalent cross-sectional diameter of the O-ring is proposed. The leakage life test and simulation scheme of hydraulic cylinder designed by this method are used to solve the life distribution of piston hydraulic seal O-ring based on covariate. Finally, the life distribution response surface is established. It is proved that the method is feasible. The method provides a data channel for studying the reliability related problems of hydraulic components.

1. Introduction
Performance degradation failure of hydraulic system is caused by one or more factors, which are generally called covariates, such as temperature, material fatigue characteristics, equipment running speed, load [1]. As an actuator, hydraulic cylinder often has internal leakage fault due to the wear and failure of O-ring of piston hydraulic dynamic seal. Lou Weitao et al. [2] studied the degradation of NBR O-rings exposed to hydraulic oil and air by accelerated aging test. Pan j et al. [3] developed a reliability model to estimate the life of NBR O-rings under storage conditions, considering the two performance characteristics of compression deformation and compression stress relaxation.

In the study of O-ring, most scholars only focus on the relationship between sealing performance and covariates. This paper establishes the response surface of O-ring life distribution under different working conditions by combining life test and simulation experiment, which provides data support for using data-driven method to evaluate the health status of hydraulic components and predict the remaining service life of hydraulic components.
2. Fusion method of life test and simulation

According to the principle of adhesive wear, the wear of O-ring can be described by Archard model [4]:

\[ t = \frac{\Delta V}{K_f P(t)} \]  

\( \Delta V \) - wear volume; \( - \) wear rate, \( K_f \) - dimensionless; \( P(t) \) - contact pressure; \( t \) - service life, times.

In the formula (1), In order to solve \( K_f, \Delta V, \) and \( P(t) \), the concept of equivalent section diameter is introduced. It is assumed that the O-ring is worn uniformly in the process of wear, that is, wear only affects the change of O-ring diameter. The wear volume can be calculated from formula (2):

\[ \Delta V = \frac{\pi}{4} \left( \int_{d_1}^{d_1 + \Delta d_1} d_2^2 \, dx - \int_{d_2}^{d_2 + \Delta d_2} d_2^2 \, dx \right) \]  

\( d_1 \) - O-ring inner diameter; \( d_2 \) - O-ring section diameter; \( d_1' \) - O-ring equivalent inner diameter; \( d_2' \) - O-ring equivalent section diameter. The wear of O-ring is mainly on the contact surface with the inner wall of cylinder, It can be considered that,

\[ d_1 = d_1' \]  

According to the formula (1) (2) (3), it is concluded that:

\[ t = \frac{1}{\pi} \left( \int_{d_1}^{d_1 + \Delta d_1} d_2^2 \, dx - \int_{d_2}^{d_2 + \Delta d_2} d_2^2 \, dx \right) \frac{K_f P(t')}{\Delta V} \]  

The failure point of O-ring seal is recorded as \( F_P \), the leakage \( Q \) is greater than a certain threshold \( Q_{MAX} \); corresponding to the simulation calculation, the contact pressure \( P(t') \) is less than a certain threshold \( P_m \), forming a large number of leakage, and the hydraulic system fails, as shown in Figure 1 and Figure 2.

![Figure 1. Variation law of internal leakage of hydraulic components](image1)

![Figure 2. Variation of equivalent section diameter and contact pressure of O-ring](image2)

At the failure point, \( t \) and \( t' \) can be unified, and \( K_f \) can be calculated by formula (4). Through the finite element simulation, the change law of \( P(t') \) and \( d_2' \) under the current working condition can be obtained, and the residual life value of O-ring under different wear degree can be obtained by using formula (4).

3. Internal leakage experiment

3.1. Experimental methods

In order to collect the leakage of hydraulic cylinder, the performance degradation experiment of
A hydraulic cylinder is designed. The principle is shown in Figure 3.

Test conditions: working temperature is 20℃, working pressure is 12MPa, piston diameter of hydraulic cylinder is 63mm, theoretical displacement of gear pump 5 is 6cc, theoretical output flow is 5.4l/min, load is provided by spring 18, stiffness is 8000 (n / M), holding time is 300s. Set the speed of motor 4 at 900r / min, set the pressure of relief valve 8 at 12MPa, and collect the data as the displacement X of the hydraulic cylinder under the pressure maintaining state.

3.2. Experimental data processing
Every time the hydraulic cylinder reciprocates for 100 times, the pressure is maintained for 300 seconds. The displacement is measured by the displacement sensor, and a total of 30000 points are collected in 300 seconds, as shown in Figure 4. The total number of actions of the hydraulic cylinder is 2000 times. The deterioration trend curve of the hydraulic cylinder in Figure 5 was obtained by linear fitting [5].
4. Finite element simulation experiment

4.1. establishment of finite element simulation model
The O-ring, piston rod and piston of hydraulic cylinder are axisymmetric, and the load of O-ring in axial direction is also axisymmetric under ideal condition. Therefore, the three-dimensional model of O-ring is transformed into two-dimensional problem research, and a part of its axisymmetric section is taken for research. The mechanical behavior and analysis results of this part ideally reflect the mechanical behavior and analysis results of O-ring [6].

The hardness of cylinder block and piston is large, so it is considered as the same rigid body without considering the difference of material. The O-ring is considered as a flexible body. Figure 6 shows the finite element model processed by the intelligent meshing method.

![Finite element model](image)

Figure 6. ANSYS finite element model

4.2. ANSYS simulation analysis results
Figure 7 shows that after the O-ring is loaded, under the action of working pressure and wall extrusion, the O-ring is obviously deformed, and the compressed side is far away from the groove wall of the O-ring, and a tight filling is formed on the opposite side, so as to form a good sealing state.

![Contact pressure distribution](image)

Figure 8. Distribution of contact pressure at $d' = 0.95d$

Figure 9. Distribution of contact pressure at $d' = 0.9d$

Figure 8 and Figure 9 show the calculation results of O-ring contact pressure after the O-ring $d' = 0.95d$ and $d' = 0.9d$ are loaded respectively.

It can be seen from Figure 8 that the contact pressure is mainly distributed in the area where the O-ring contacts the cylinder block and piston, and the size and distribution of the contact pressure in each area are different. The maximum contact pressure range is $16.0922 \sim 18.1038$ mpa, and there is a
large range of maximum pressure distribution area on both sides, and the contact pressure at this time
is greater than the working pressure of 12MPa, which can ensure effective sealing. In Figure 9, the
maximum contact pressure drop is 14.354 ~ 16.1483mpa, and there is a large range of maximum
pressure distribution area on both sides. Although the contact pressure is reduced, it can still ensure
that it is 12MPa higher than the working pressure, so it can be effectively sealed. When the maximum
contact pressure is reduced to 12MPa, $d_2 = 0.86d_1 = 4.60mm$, the seal will fail.

5. Establishment of response surface for life distribution of hydraulic components

Through ANSYS simulation, it is calculated that the minimum equivalent section diameter of O-ring
is 4.60mm under the test condition, and the life of this failure point is 10000 times. The wear rate can
be obtained from formula (5).

$$K_f = \frac{1}{3} \pi \left( \int_0^{d_1 + d_2} d_2^2 dx - \int_0^{d_1 + d_2} d_2 \int_0^{d_1 + d_2} d_2^2 dx \right) \approx 9.315 \times 10^{-3}$$

The parameters C10 and C01 in the Mooney Rivlin elastic model of O-ring are calibrated experimentally [7].
According to C10 and C01, the contact pressure under different working conditions can be calculated,
and the minimum equivalent section diameter of O-ring under different working conditions can be
calculated. Combined with formula (5), the life value under different working conditions can be
calculated, as is shown to Table 1.

| Oil temperature | 8Mpa   | 12Mpa  | 16Mpa  | 20Mpa  |
|-----------------|--------|--------|--------|--------|
| 10℃             | 15434  | 8691   | 3801   | 2346   |
| 20℃             | 15827  | 10026  | 4442   | 2520   |
| 30℃             | 16414  | 10421  | 5284   | 2695   |
| 40℃             | 17381  | 11072  | 6720   | 3041   |
| 50℃             | 16219  | 10290  | 6416   | 3298   |
| 60℃             | 14642  | 9929   | 5905   | 2520   |
| 70℃             | 9730   | 4200   | 1935   | 1099   |
| 80℃             | 3871   | 2132   | 1147   | 644    |
| 90℃             | 2749   | 1226   | 576    | 370    |

The data in Table 1 are fitted with curved surface to obtain the response surface of O-ring life
distribution under different working conditions, as shown in Figure 10.

Figure 10. life distribution response surface fitting
The O-ring uses the contact pressure (the sum of the precompression force produced during assembly and the elastic contact pressure produced by the elastic deformation under the oil pressure) to realize the contact seal. With the accumulation of wear, the contact pressure gradually decreases until it is less than the working pressure, and the sealing effect is lost. The working pressure has the greatest influence on the sealing effect of O-ring, followed by the oil temperature. As can be seen from FIGURE 15, with the increase of working pressure, the service life presents a decreasing trend, and the service life changes with the oil temperature in a bipolar manner, that is, the maximum service life is around 40 °C ~ 60 °C. Heating or cooling will lead to the decrease of service life, and the high temperature will cause a sharp drop in the service life of O-ring.

6. Conclusion
Using the proposed method of fusing the internal leakage life test of hydraulic components with the simulation experiment based on the equivalent cross-sectional diameter of the O-ring, taking the internal leakage life test of the hydraulic cylinder as an example, the oil temperature and the oil temperature that have the greatest impact on the leakage life of the hydraulic cylinder are taken into consideration. The working pressure is a covariate, and the life distribution of the piston hydraulic dynamic seal O-ring is studied by this method. Using this method to design the hydraulic cylinder internal leakage life test and simulation program, the life distribution of the O-ring is solved, and the life distribution response surface is finally established, which proves that the method is feasible. This provides a solution for the lack of large data on the reliability of hydraulic components and the inability to use data-driven methods to study the reliability of hydraulic components.

References
[1] ZHAO Zhizheng. Several factors that determine the ability of rubber to seal[J]. World Rubber Industry, 28(5), 2001: 31-37.
[2] LOU Weitao, ZHANG Weifang, WANG Hongxun, et al. Influence of hydraulic oil on degradation behavior of nitrile rubber O-rings at elevated temperature[J]. Engineering Failure Analysis, 2018, 92: 1-11.
[3] Pan J, Bai GH, CHEN WH. Lifetime estimation of nitrile butadiene rubber O-rings under storage conditions using time-varying copula[J]. Proceedings of the institution of mechanical engineers part O-journal of risk and reliability, 2018, 232(6): 635-646.
[4] Cláudio R. Ávila da Silva, Pintaude G. Uncertainty analysis on the wear coefficient of Archard model[J]. Tribology International, 2008, 41(6): 473-481.
[5] Ministry of industry and information technology of the people's Republic of China, China Federation of machinery industry. JB / t10205-2010 hydraulic cylinder[S]. Beijing: China Standards Press, 2010.
[6] DU Xiaqiong, Chen Guohai, Xian Xiaoliang, et tl. Finite Element Analysis Model of O-ring Considering Installation Process[J]. Chinese Hydraulic & Pneumatics, 2017, 10: 27-33.
[7] HU Qi. Hydraulic Servo Actuator O-Ring Test And Finite Element Analysis[D]. Harbin: Harbin Institute of Technology, 2011.