Structure reliability design and analysis of support ring for cylinder seal

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Abstract: In this paper, the general reliability design process of the cross-sectional dimension of the support ring is introduced, which is used for the cylinder sealing. Then, taking a certain section shape support ring as an example, the every size parameters of section are determined from the view point of reliability design. Last, the static strength and reliability of the support ring are analyzed to verify the correctness of the reliability design result.

1. Introduction
Acting as a support on the piston and the piston rod, the support ring prevents the piston or piston rod from direct contact and friction with the cylinder during movement, minimizes eccentricity, reduces wear of the seal, and improves the durability of the seal [1]. Therefore, to the reliability and service life of the piston and piston rod seal even the entire sealing system, the reliability of the support ring have an important impact. So consider the reliability factor is essential in the support ring design process.

In this paper, we first introduced the general process of the reliability design of the support ring when only considering the lateral partial load. Then, based on the traditional design formula of the NOK support ring, taking a certain section shape of support ring as an example, from the perspective of reliability design, the cross-sectional dimension parameters are determined. Last, the static strength and reliability simulation analysis of the support ring are carried out to verify the correctness of the reliability design result. The research has some guiding significance to the reliability design of other types of seals.

2. General reliability design process of the support ring
The general reliability design process of the support ring is shown in figure 1.

2.1 Function and failure definition
The function of the support ring is support and guidance. The failure definitions are different according to the actual use.
2.2 Determination of the reliability index

The reliability index definition of the support ring generally includes three aspects: the environment and service conditions, time and reliability index.

2.2.1 Describe environment and service conditions. The definition of the reliability is the probability that the product complete the specified function which is under the certainty conditions and within the required time \(^3\). Therefore, before the reliability design, we should describe the service and environmental factors of the support ring (e.g. working pressure, temperature, surface roughness of rod or cylinder and so on).

2.2.2 Define the service time of the support ring. Reliability is a measure of time, so it is necessary to define the service time of the support ring before the reliability design \(^3\).

2.2.3 Quantitative description of reliability index. Generally, the quantitative description of the reliability index of the support ring has the following two ways:

- Define directly the reliability \(R\) required for the support ring;
- Define the MTBF of the support ring.

2.3 Reliability design of the support ring

2.3.1 Material and cross-sectional shape choice of the support ring. Under normal circumstances, we choose the material and cross-sectional shape of the support ring according to environment and the service conditions.

2.3.2 Section size reliability design of support ring. Taking the shape of the support ring as shown in figure 2 as an example, the general process of reliability design of the support ring cross-sectional dimension is illustrated when only considered the lateral eccentric load.

The support ring cross-sectional dimensions include the width \(H\) and the thickness \(t\). The cross-sectional and groove size which are respectively used in piston and piston rod is shown in figure 2.

- Traditional design formula of the support ring section size \(^4\)

The traditional design formula for the width of the support ring is as follows:

\[
H_{\text{min}} \geq \frac{3 \times F \times S_0}{\delta \times D \times \pi}
\]  

(1)

Where: \(H_{\text{min}}\) — Minimum width, mm; \(F\) — External load, N; \(S_0\) — Security coefficient; \(\delta\) — Tolerate compression, MPa; \(D\) — Cylinder bore diameter, mm

The thickness of the support ring is generally determined by the cylinder bore diameter and the groove inner diameter (piston support ring), or the groove outer diameter and the piston rod diameter.
(piston rod support ring).

Thicknss of the support ring which is used in piston:

\[ t = \frac{D - d_t}{2} \]  

(2)

Where: \( d_t \) — Groove bottom diameter, mm

- Reliability design process of supporting ring cross-sectional dimensions

Through the previous definition of the reliability index and the choice of material and cross-sectional shape, the reliability design process of the support ring width is as follows \(^{[3]}\):

1. Set the reliability of the support ring \( R \)
2. Calculate the probability of failure of the support ring, which is \( F=1-R \)
3. Check the normal function table according to \( F \), get \( \beta = \Phi^{-1}(R) \)
4. List the working stress expression (take the piston support ring as an example)

\[ S = \frac{F_1}{D \times H} = \frac{W \times L_2}{D \times H} \]  

(3)

Where: \( S \) — Working stress of the support ring, MPa; \( F_1 \) — External load, N; \( H \) — Support ring section width, mm; \( W \) — Lateral eccentric load, N; \( L_1 \) — Distance between the support ring which is used in piston and the support ring which is used in piston rod, mm; \( L_2 \) — Distance between the support ring which is used in piston rod and the lateral eccentric load, mm

5. Calculate the mean and standard deviation of the working stress
6. Select the width error of the support ring according to the processing method of the support ring, find the relationship between the mean value and the standard deviation of the support ring width (for example, when the support ring material is filled PTFE, the processing method is molded, the dimension error is \( \pm 0.05 \), then the tolerance of support ring width is \( \pm \Delta_w = \pm 0.05 \mu_w \), according to the 3\( \sigma \) principle, we can know that: \( \sigma_w = \frac{\Delta_w}{3} = \frac{0.05}{3} \mu_w \) .

7. Solve the coupling equation

\[ \beta = \frac{\mu_w \cdot \Delta_w}{(\sigma_w^2 + \sigma_{\alpha}^2)^{1/2}} \]  

(4)

Where: \( \beta \) — reliability index; \( \mu_w \) — mean of the strength, MPa; \( \sigma_{\alpha} \) — standard deviation of the strength, MPa; \( \mu_{\alpha} \) — mean of the stress, MPa; \( \sigma_{\alpha} \) — standard deviation of the stress, MPa

Substituting the relationship between \( \mu_w \) and \( \sigma_w \), and the \( \mu_{\alpha}, \sigma_{\alpha}, \mu_{\alpha}, \sigma_{\alpha} \) into equation (4), Then the mean and standard deviation of the support ring width can be obtained by simplifying and solving the equation (4), then, according to the 3\( \sigma \) principle, we can get the tolerance of support ring width.

8. Calculate the mean and standard deviation of the thickness (t) of the support ring

The mean and standard deviation of the support ring thickness which is used in the piston are:

\[ \mu_t = \frac{1}{2} (\mu_d - \mu_d), \sigma_t = \frac{1}{2} (\sigma_d^2 + \sigma_d^2)^{1/2} \]  

(5)

So, in order to ensure the reliability of the support ring, the width is \( H = \mu_w \pm 3\sigma_w \), thickness is \( t=\mu_t \pm 3\sigma_t \).

3. Reliability design example of support ring section size

Assume that a cylinder seal system is shown in figure 3. Take the support ring used in piston as an example, according to its service and environmental conditions, we select the filled PTFE as the material (specific formula and relevant parameter can refer to P231 which is made by Guangzhou
Mechanical Engineering Research Institute Co., Ltd. The cross-sectional shape is rectangular. The lateral eccentric load that the piston rod is subjected to is $W=200\pm 1\text{N}$. The distance between the lateral eccentric load and the support ring of the rod is $L_2=100\pm 1\text{mm}$. The distance between the support ring which is used in piston rod and the support ring which is used in piston is $L_1=80\pm 1\text{mm}$. The cylinder bore diameter is $D=50.062\text{mm}$, The groove bottom diameter is $d=46.9\pm 0.039\text{mm}$. By testing, the compressive strength of the filled PTFE is $55\pm 5\text{MPa}$. It is assumed that the probability of the support ring that meet the support function under the above-mentioned lateral eccentric load conditions for 3 years (reliability) is $R=99\%$. Now, we should determine the section width and thickness.

![Figure 3](image1.png) A cylinder seal system

![Figure 4](image2.png) Equivalent stress of the support ring

3.1 Calculate the width and thickness of the support ring according to the traditional design equation

From the equation (1), we can get the section width of the support ring is:

$$H_{\text{min}} \geq \frac{F \times S_0}{\delta \times \frac{D}{\pi} \times \frac{1}{3}} + 2C = \frac{250 \times 1.5}{55 \times 50.031 \times \frac{1}{3}} + 0 \approx 0.13$$

From the equation (2), we can get the section thickness of the support ring is:

$$t = \frac{D - d}{2} = \frac{50.031 - 46.88}{2} = 1.5755$$

3.2 Calculate the width and thickness of the support ring according to the reliability design equation

3.2.1 Calculate design failure probability

$$F=1-R=1\%=0.1$$

3.2.2 Calculate the reliability index. By checking the standard normal distribution table, when the failure probability $F=0.1$, the reliability index is:

$$\beta = \frac{\mu_s - \mu}{\sqrt{\sigma_s^2 + \sigma_r^2}} \approx 2.33$$

3.2.3 Calculate the mean and standard deviation of the working stress.

$$\mu_s = \frac{4.997}{\mu_H}, \sigma_s = \frac{0.08774647}{\mu_H}$$

3.2.4 Calculate the mean and standard deviation of the section width. According to the relationship between the mean and the standard deviation of the support ring width and the above coupling equation (equation (4)), the mean and standard deviation of the support ring width can be calculated, which is:

$$\beta = \frac{\mu_s - \mu}{\sqrt{\sigma_s^2 + \sigma_r^2}} = \frac{55 - 4.997}{\frac{0.08774647}{\mu_H}} \approx 2.33 \Rightarrow \mu_t \approx 0.0988, \sigma_t = \mu_t \times 0.05/3 = 0.00165$$
3.2.5 Calculate the mean and standard deviation of the section thickness.

\[
\mu_t = \frac{1}{2} (\mu_{D_D} - \mu_{D_d}) = \frac{1}{2} \times (50.031 - 46.8805) \approx 1.575, \\
\sigma_t = \frac{1}{2} \left( \sigma_{D_D}^2 + \sigma_{D_d}^2 \right)^{1/2} = \frac{1}{2} \times (0.0103^2 + 0.0065^2)^{1/2} \approx 6.1 \times 10^{-3}
\]

From the above design, we can see that the cross-section width and the thickness of support ring are respectively 0.0988 ± 0.0049 (mm) and 1.575 ± 0.0183 (mm), when the design reliability is 99%.

4. Static strength analysis of the support ring

According to the reliability design results, the static strength of the support ring is analyzed when it is subjected to the lateral eccentric load. The equivalent stress is shown in figure 4.

From figure 4, it can be seen that the maximum equivalent stress of the support ring is about 48.85MPa when it is subjected to the lateral eccentric load (W = 200 ± 1N) as shown in the example. The value is less than the compressive strength of the support ring material (55MPa). It is indicated that the results of the reliability design meet the requirement, when only considered the lateral eccentricity. Besides, compared with the traditional design, the reliability design result of the support ring cross-section width is smaller, which shows that the traditional safety factor design method is relatively conservative and the material is slightly surplus.

5. Reliability simulation of the support ring

In this paper, we simulated the reliability of the support ring using ANSYS/PDS module to verify the correctness of the structural design result based on reliability [5]. The distribution and the characteristics of the random parameters are shown in table 1.

| random factors          | distribution | mean    | standard deviation |
|-------------------------|--------------|---------|--------------------|
| lateral partial load W/(N) | Gaussian     | 200     | 0.33               |
| distance L1/(mm)       | Gaussian     | 80      | 0.33               |
| distance L2/(mm)       | Gaussian     | 100     | 0.33               |
| width h/(mm)           | Gaussian     | 0.0988  | 0.00165            |
| groove bottom radius r1/(mm) | Gaussian     | 23.44   | 0.0065             |
| cylinder bore radius r2/(mm) | Gaussian     | 25.02   | 0.01               |
| allow compression ss/(MPa) | Gaussian    | 55      | 1.67               |

The simulation method used in this paper is Monte-Carlo direct sampling method, the sampling times are 1000, and the confidence coefficient of the calculation results is 95%. The reliability analysis result is shown in figure 5. From the figure 5, it can be seen that the minimum value of the sample is -6.23, the maximum value is 1.63e + 001, and the reliability of the support ring is about 98.1349%.

![Figure.5 reliability analysis result](image)

![Figure.6 sensitivity of the support ring](image)
which is relatively small).

Through the above results, it can be seen that when only considered the lateral eccentric load, the reliability design method of the support ring section dimension is correct and effective. But, in actual use, we should not only consider the lateral partial load, but also need to consider other function (such as guidance, etc.), so the cross-section width of the support ring should broaden properly.

The sensitivity of the stochastic factors to the reliability of the support ring is shown in figure 6. It can be seen that when only considered the lateral eccentric load, the cross-sectional width and the allowable compression have a great influence on the reliability of the support ring, the other factors have little effect.

6. Conclusion

In this paper, we first introduced the general process of the reliability design of the support ring when only considered the lateral eccentric load. Then, taking a certain support ring as an example, the cross-sectional dimension is determined by the reliability design. Finally, the finite element simulation method is used to verify the correctness of the reliability design results. From the reliability design results, it can be seen that when only considered the lateral eccentric load, the width of the support ring is very small (only 0.0988). But, it is to be noted that, in practical use, the support ring should not only overcome the lateral eccentric load, but also need to have other functions, so the actual width of the support ring should be the width after considering of every function, the reliability design process of the support ring width which considered other function can learn from the reliability design process which is described in this article.

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