Multi-objective Structural Optimization of VL Seal Ring Based on Isight

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Abstract. To obtain the best geometric size of VL sealing ring and improve its sealing performance, this paper carried out multi-objective optimization research on VL sealing ring by Isight software. Firstly, according to the working principle and geometric size of the VL seal ring, determined the constraint conditions, established the optimization objective equation, and given the value range of the structural parameters was. Then, verified the validity of the approximate model by fitting the radial basis neural network model provided. Finally, analyzed the sensitivity of influencing factors of oil film thickness at lip, and established the optimization module by NSGA-II multi-objective optimization algorithm. As a result, the best geometric size is obtained from multi-objective optimization, and the structure of VL seal ring has achieved the goal of more suitable high speed dynamic seal and longer service life.

1. Introduction

VL seal ring can apply to high-pressure and high-speed environment [1, 2, 3]. It is composed of a slip ring (also known as a V-ring) and a rubber O-ring, as shown in Figure 1.

The cutting edge where the V-ring contacts with the inner wall of the cylinder is called the lip of the seal ring (hereinafter referred to as the lip). Lips angle $\alpha$ is located in the side of lip high-pressure and the after lip angle $\beta$ is located in the side of atmospheric pressure, as shown in Figure 2. The contact stress distribution of three seal face of VL seal ring I, II, III determines the sealing performance of the whole seal ring.

Friction and oil film thickness are important factors to determine the performance and service life of VL seal ring. In this paper, the structure of VL seal ring was optimized by the multi-objective optimization algorithm based on the optimization software Isight. Under the premise of maintaining the sealing performance, increase the thickness of dynamic-pressure oil film at the lip seal and reduce the maximum value of Von-mises stress of rubber sealing O-ring, this makes the VL seal ring more suitable for seal at a condition of high-speed sliding and has longer service life.
2. Construction of Structural Optimization of VL Seal Ring

2.1. Constraints and Optimization Objectives

The structural optimization of VL seal ring is carried out on the premise of ensuring the sealing performance, so the constraint condition is that the maximum contact stress $P_{1c\text{max}}$, $P_{2c\text{max}}$ and $P_{3c\text{max}}$ at the three sealing contact surfaces must all be greater than the working pressure in the VL seal ring. In this paper, the working pressure is 9 MPa. The purpose of optimization is to increase the maximum applicable-speed and extend the service life of VL seal ring. Therefore, the optimized goal of VL seal ring is to maximize the thickness $h$ of dynamic-pressure lubricating oil film at the lip and the value of maximal Von·mises stress $P_{v\text{max}}$ of rubber O-ring can become minimum, as shown in the following equation

$$\begin{cases} \max & h \\ \min & P_{v\text{max}} \\ \text{s.t.} & P_{1c\text{max}}, P_{2c\text{max}}, P_{3c\text{max}} > 9\text{MPa} \end{cases} \quad (1)$$

2.2. Structural Parameter Variables and Ranges of Value

Because the size of O-ring is limited by the international standard, the structural parameters of V-ring are modified and adjusted only. The selected key parameters of structure: the anterior lip angle, the posterior lip angle, the distance from the mouth to the center of the O-ring, the radius of the over-rounded corner of the V-ring, the height of the V-ring, and the thickness of the bottom of the V-ring. Their values of parameter are represented by $\alpha$, $\beta$, $r$, $L$, $H_1$, $H_2$, as shown in the following Figure 2.

The influence of structural parameters on the shape of VL seal ring, the wide range of variation and the smooth calculation which is guaranteed are considering synthetically. The value range of each structural parameter is shown as follows.

$$\begin{cases} 45^\circ \leq \alpha \leq 60^\circ \\ 5^\circ \leq \beta \leq 20^\circ \\ 4\text{mm} \leq r \leq 6\text{mm} \\ 1.8\text{mm} \leq L \leq 2.5\text{mm} \\ 1\text{mm} \leq H_1 \leq 1.5\text{mm} \\ 4\text{mm} \leq H_2 \leq 7\text{mm} \end{cases} \quad (2)$$
3. Modeling and Validation of Approximate Model

3.1. Modeling Method of Approximate Model
Method of approximate model is to approximate a set of independent variables and response variables by using mathematical model [4]. It can replace the complex and high cost simulation in practice and improve the efficiency of calculation. The wizard of modeling approximate model is provided by Isight, the creation process is easy. The essence of approximate model is to fit the input and output. In this paper, the radial basis neural network model that is provided in Isight software is selected for fitting.

3.2. Establishment of Structural Optimization and Approximate Model of VL Seal Ring
According to the range of variable value of structural parameter, the samples were sampled by the optimized Latin hypercube experimental design method. 80 groups of sample spatial data are generated, and the target response value of sample point optimization is obtained by finite element calculation. The radial basis neural network structure model was used to train the sample data, and the approximate model of structural optimization of VL seal ring was obtained. The approximate model components are shown in the following Figure 3.

![Figure 3. Approximate Model of Structural Optimization of VL Sealing Ring](image)

3.3. Validation of Effectiveness of the Approximate Model

3.3.1. Analyzing of Error
Five groups of data were randomly selected from the samples to analyze the error of the above approximate model of structural optimization of VL seal ring, and the maximum relative error between the calculation results of the radial basis network approximate model and the simulation results is 6.52 %.

3.3.2. Analysis of Variance
According to the analysis of variance, the total variance of the response comes from the contributions of two parts, they are the approximate model itself and the fitting error. $R^2$ was used to describe the fitting accuracy of the approximate model, as shown in Figure 4 below. The $R^2$ of the approximate model which is used in this paper is 0.934, which is close to 1 and has high accuracy. Therefore, this approximate model can be used to replace the finite element simulation model.

![Figure 4. Analysis of variance $R^2$](image)

4. Sensitivity Analysis of Influencing Factor of Oil Film Thickness of at the Lip

4.1. Analysis of Influencing Factors
The anterior lips $\alpha$ and posterior lip $\beta$ have a greater influence on the thickness of oil film at the contact surface and contact stress at the lip mainly. As well as having a certain influence on the contact stress at the sealing face II, because $\alpha$, $\beta$ directly affect the changing of contact width of the
contact surfaces and the distribution law of contact stress at the contact surface. Excessive rounded radius $r$ of V-ring mainly affects the distribution of Von Mises stress of O-ring, because excessive rounded Angle affects the joint stiffness between the upper left lip and the bottom of V-ring, and has a great influence on the deformation of V-ring. The height $H_1$ of V-ring and the change of distance from $L$ lip to the O-ring center affect the sensitivity that seal ring has an influence on the change of working pressure, V-ring lip not only has a weak rigidity but also is easy to detormate and more sensitive to the change of working pressure when the distance $L$ is lesser, part of lip is thicker and not easy to deformate and has a strong rigidity when distance $L$ is larger, lip wear become worse because hyperelastic compensation of O-ring cannot deliver timely. The thickness of $H_2$ at the bottom of the V-ring affects the stability of the seal ring. If the thickness of $H_2$ is too small, the seal ring will easily flip when the piston slides at high-speed. However, it is not easy to install if the thickness is too large.

4.2. Sensitivity Analysis of Influencing Factor of Thickness of the oil Film at the Lip

Sensitivity analysis of influencing factors can make complex optimization solution more efficient and accurate. Therefore, it is necessary to optimize the parameters again that have a great influence on the thickness of oil film at the lip in order to improve the performance. The method of multiple-quadratic logistic regression is adopted to analyse sensitivity of influencing factor of thickness of the oil film at the lip in special working condition. The selected sensitivity of the six influencing factors is shown in Figure 5 and 6. The bar on the left of the coordinate in the figure represents the negative effect, while the bar on the right represents the positive effect.

![Figure 5. First-order Effect Analysis Pareto Map](image)

Figure 5 shows the analysis results of linear principal effect of the influencing factors. It can be seen that the order of the sensitivity from linear part which is impacted by thickness $h$ of oil film at the lip is: $n$, $r$, $L$, $H_1$ and $H_2$. Figure 6 shows the analysis results from second-order effect of the influencing factors with greater sensitivity in the first six groups. Second-order effect analysis includes second-order principal effect analysis and mutual effect analysis. It can be seen that the order of the sensitivity from the second-order effect which is impacted by thickness $h$ of oil film at the lip is in the following order: $\beta$, $r$, $a$, $c$, $L$, $r_2$, $a-H_1$ and $L-H_2$. In conclusion, the factors that have a great influence on the thickness $h$ of oil film at the lip seal include: the posterior lip angle $\beta$, the over-fillet radius of V-ring $r$, the anterior lip angle $a$, and the distance $L$ from the lip to the center of O-ring. The height $H_1$ of V-ring and the thickness $H_2$ at the bottom of V-ring have little influence on it.

![Figure 6. Second-order Effect Analysis Pareto Map](image)
5. Optimized Solution and Results Analysis

Based on the approximate model, NSGA-II multi-objective optimization algorithm was used to establish the optimized module. After 360 times operation, Figure 7 is the historical curve of optimization objective. After optimization which adopts multi-objective method, the thickness $h$ of oil film and the maximum value of Von-mises stress $P_{v_{\text{max}}}$ of O-ring at the lip were improved well. Finally, the structure of VL seal ring that has a comparison between previous and later optimization is shown in Figure 8.

![Figure 7. Optimization process](image1)

By the Table 1, the results of the simulation show that the maximum contact stress reduce 7% in lip seal interface I after optimization, the maximum contact stress in sealing interface II, III have a little change. That can ensure the reliability of sealing performance. The thickness of oil film of the lip increased by 28.15%, the effect of lubrication of the lip is enhanced and the maximum value of the O-ring Von-mises stress decreased by 13.23%, so the structural optimization of the VL ring is more suitable for high-speed dynamic seals and extends service life.

![Figure 8. Comparison of VL seal ring structure before and after optimization](image2)

6. Summary

The approximate model was established based on the Isight optimization software, which replaced the complex simulation calculation. The structural optimization of VL seal ring was completed by using the multi-objective optimization algorithm. The optimization results show that while ensuring good sealing performance, the dynamic lubrication performance during sliding was improved, and the wear was also reduced. Thereby, the VL seal ring is better for high speed dynamic sealing and has longer service life.

7. Acknowledgments

The authors gratefully acknowledge the financial supports from the National Natural Science Foundation of China (NO. 51303081), China Scholarship Council (NO. 201906845017), Natural Science Foundation of Jiangsu Province of China (NO. BK20170837,) and Postgraduate Research & Practice Innovation Program of Jiangsu Province of China (NO. KYCX19_0327).
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