Parametric Analysis of Wave-shaped Metal Sealing Ring Based on Hierarchical Solution Method

Zhang miaotian\textsuperscript{1, a}, Suo shuangfu\textsuperscript{2}, Feng yu\textsuperscript{1}, Shi jianwen\textsuperscript{2} and Meng guoying\textsuperscript{1}

\textsuperscript{1} School of Mechanical Electronic & Information Engineering, China University of Mining and Technology Beijing, China
\textsuperscript{2} School of Mechanical Engineering, Tsinghua University, Beijing, China

\textsuperscript{a}Email: zhangmiaotian1231@163.com;

Abstract. The wave-shaped metal sealing ring is widely used in the aerospace field, whose failure will directly affect the flight safety and even cause major personal accidents and economic losses. The performance optimization problem of the wave-shaped seal is a multi-objective optimization problem, and the multiple targets are affected by the geometric design factors, and are not completely independent of each other. In this paper, for the sealing problem under the severe conditions of aero-engine, the corrugated metal sealing ring is taken as the research object. The W-shaped metal sealing ring is selected as an example, and the finite element model is established by using ANSYS software. Sealing, stability and resilience are chosen as indicators to evaluate the sealing performance. The multi-objective optimization problem is transformed into a single-objective optimization problem by hierarchical solution method, and the sealing structure is parameterized. The optimization results of the geometric parameters of the sealing ring are highly consistent with the product manual of the sealing ring. The correctness and feasibility of the optimization design method based on the analysis of three aspects of performance and the hierarchical solution for dimension reduction are verified.

1. Introduction
With the vigorous development of aerospace technology at home and abroad, the development of aerospace technology and the manufacture of large aircraft are the needs of China's entry into an innovative country\cite{1}. Seals are key basic components in many high-tech fields (such as the aerospace industry, ergonomics industry)\cite{2-3}. It has been shown in the literature that whenever the seal leakage is reduced by 1%, the engine thrust can be increased by 1% and the fuel consumption rate can be reduced by 0.1%. Therefore, the United States has set a 60% reduction in flow system leakage in its national engine development plan to improve the overall performance of the engine\cite{4}. In the 1980s, the aerospace powerhouse headed by the United States invested a large amount of resources in aerospace sealing technology research, and elastic metal sealing is one of the research results\cite{5}. Domestic research started relatively late. Since the 21st century, the state has studied key basic components such as seals as the focus of research on aero-engine technology\cite{6}.

There is a lack of systematic methods for the active optimization design of seal rings in China. The finite element software is used to try to optimize the design of the sealing ring, but the optimization design goal is not closely related to the performance of the sealing ring. The result is quite different from the foreign product manual. The research in this paper is mainly aimed at the sealing problem under the severe conditions of aero-engines.
The performance optimization problem of the wave-shape seal is a multi-objective optimization problem, and the multiple targets are affected by the geometric design factors, and are not completely independent of each other. After a detailed analysis of the optimization problem of the wave-shaped seal, this paper finally chooses the method of layered solution and constructing the ranking optimization function to solve the multi-objective optimization problem.

2. Finite element model establishment

2.1 Structure and installation of corrugated metal seals
In the wave-shaped metal sealing ring, the C-shaped and W-shaped sealing rings are the most common. The C-shaped metal seal is easier to manufacture and has been widely used in the aerospace industry, the nuclear industry and the chemical industry. W-shaped seals have better compression resilience performance, and the permanent deformation after single compression rebound undergoing large deformation is small, even without permanent deformation. However, in China, the W-shaped seal is still in the research stage. Figure 1 Figure 2 is a schematic view showing the installation structure of the W-shaped seal ring. When installed, the seal is subject to a certain pre-deformation by the longitudinal pre-tightening compression force.

![Figure 1. Before installation.](image1)

![Figure 2. After installation.](image2)

2.2 Establishment of finite element model
The structure of the W-shaped metal seal is shown in Figure 1. Table 1 shows the initial structural parameters of the W-shaped seal ring.

| Geometric parameter              | Initial value (mm) |
|---------------------------------|--------------------|
| Outer diameter D                | 300                |
| Wall thickness T                | 0.3                |
| Wave height H                   | 2.15               |
| Free height FH                  | 6.1                |
| Contact surface radius          | 3.05               |
| of curvature R                   |                    |
| Peak radius R1                  | 0.75               |
| Valley radius R2                | 0.9                |

The material of the W-shaped seal ring is made of nickel-based superalloy GH4169. The GH4169 has excellent comprehensive performance in the high temperature environment below 700°C, and the yield limit $\sigma_{0.2}$ at 650°C is in the forefront of common superalloys [7]. Table 2 shows the relevant parameters of GH4169.
### Table 2. Mechanical properties of GH4169 material.

| Temperature / °C | Modulus of elasticity / GPa | Yield strength / MPa |
|------------------|----------------------------|----------------------|
| 20               | 205                        | 1030                 |
| 650              | 153                        | 865                  |

The calculation model of the W-shaped seal is simplified[7-8], and the finite element calculation model is established in an axisymmetric manner and the upper and lower flanges are treated as pure steel bodies. The analysis unit type selects the PLANE182 unit, and the sealing ring is in contact with the upper and lower flanges to select the CONTACT 172 unit.

As shown in Figure 3, the Von-Mises stress distribution cloud diagram with an operating temperature of 650°C, a medium pressure of 3 MPa, and a compression of 20% was calculated. The maximum Von-Mises stress in the figure is 907.6 MPa, located at two valleys of the W-ring.

![Figure 3. Von-Mises stress distribution of W-shaped seal.](image)

#### 2.3 Influence of structural parameters on sealing performance

According to the literature research, the comprehensive performance of the wave seal includes three aspects: resilience, sealing and stability, which are measured by the rebound rate, the maximum contact stress and the proportion of the shaped area.

**2.3.1 Resilience.** Figure 4 shows the change in rebound rate at different wall thicknesses. As can be seen from the figure, the smaller the wall thickness, the better the rebound resilience of the W-shaped seal. In the same wall thickness design, the higher the wave height, the better the rebound resilience. When the wall thickness is 0.2 mm, 0.25 mm, and 0.3 mm, there is a complete rebound, and in this region, the W-shaped seal has excellent resilience performance.

![Figure 4. Rebound rate of different wall thickness waves.](image)

**Figure 5. Maximum contact stress at different wall thickness waves.**

**Figure 6. The proportion of shaped areas with different wall thicknesses.**

**2.3.2 Sealing.** Figure 5 shows the maximum contact stress changes at different wall thicknesses. The maximum contact stress decreases as the wave height increases when the wall thickness is the same.
The maximum contact stress increases as the wall thickness increases when the wave height is the same.

2.3.3 Stability. Figure 6 shows the variation of the proportion of the shaped area under different wall thicknesses. It can be seen from the figure that when the wall thickness increases to a certain extent, it has a significant effect on the plastic deformation zone, and the proportion of the shaped area of the 0.35 mm wall thickness group is significantly higher than that of the other wall thickness groups. However, in the area with small wall thickness, the influence of wall thickness on the proportion of plastic deformation region could not be analyzed. As the wave height increases, the stability of the seal ring increases, and the proportion of the plastic deformation zone decreases.

By analyzing the influence of the structural parameters of the W-shaped seal on its comprehensive performance, it can be known that the influence of wall thickness and wave height on the comprehensive performance is complex, it is necessary to comprehensively consider the three factors of resilience, sealing and stability, and multi-objective optimization.

3. Parameter analysis of seal ring structure

3.1. Hierarchical Solution Method
According to the research results of the multi-objective optimization method of "Mathematical Planning", the hierarchical solution method is an effective method to convert multiple to fewer. The hierarchical solution method refers to: according to the optimization problem, the optimization sequence of the optimization target is discharged, and the first target $F_1(x)$ is first minimized to obtain the solution set $x_1$. Then the solution of the next target $F_2(x)$ is performed in the solution set $x_1$, so on and so forth, and finally the optimization result is obtained. In the optimization design problem of the wave-shaped seal ring, the rebound rate is determined to be the highest priority due to the leakage gap between the seal ring and the flange after the rebound failure. On the judgment of the subsequent sealing performance and stability performance, the objective function is solved by its single item ranking.

3.2. Boundary conditions and solutions
According to factors such as manufacturing process, manufacturing precision and dimensional design, a wall thickness of 0.05 mm and a wave height of 0.1 mm were selected as the minimum calculation interval. Xing Minjie[9] optimized the maximum contact stress under the condition of equivalent Von-mises stress, so that the sealing of the W-shaped seal is optimal. According to the feasible areas of the delineation factors, the feasible areas for setting the influencing factors are as follows:

$$0.2 \leq t \leq 0.35$$
$$2.1 \leq h \leq 2.6$$

(1)

In the formula, $t$ is the wall thickness of the sealing ring, the unit is mm; $h$ is the wave height of the sealing ring, the unit is mm.

The structure objective function is as follows:

$$Z(t, h) \text{ Optimal}$$
$$C(t, h) \text{ Optimal}$$
$$S(t, h) \text{ Optimal}$$

$$0.2 \leq t \leq 0.35$$
$$2.1 \leq h \leq 2.6$$

(2)

In the formula, $Z(t,h)$ is the proportion of the shaped area; $C(t,h)$ is the rebound rate; $S(t,h)$ is the maximum contact stress.
3.2.1 Rebound rate. If the rebound rate of the seal ring is not up to standard, there will be an interval between the seal ring and the flange, causing the internal high pressure medium to leak. In the JETSEAL product manual, the product's rebound rate is clearly described, and the product rebound rate of the high-pressure metal wave seal is 100%. Therefore, the objective function becomes:

\[
C(t, h) = 100% \\
Z(t, h) \text{ Optimal} \\
S(t, h) \text{ Optimal}
\]

\[
0.2 \leq t \leq 0.35 \\
2.1 \leq h \leq 2.6
\]

(3)

3.2.2 Maximum contact stress. Gong Xueting[10] conducted a leak test on the metal wave seal ring, and obtained a zero-leakage of the W-shaped seal ring with a wall thickness of 0.3 mm and a wave height of 3.5 mm in a medium pressure environment of normal temperature and 0-4 MPa. According to these conditions, the pressure is 1Mpa and 3Mpa, and the maximum contact stress is 79.5485Mpa and 105.377Mpa. The W-shaped seal under this condition is in a zero leakage state. That is, the objective function becomes:

\[
\text{Min } Z(t, h) \\
C(t, h) = 100% \\
S(t, h) \geq 79.5485 \text{Mpa} (p=1 \text{Mpa}) \\
S(t, h) \geq 105.377 \text{Mpa} (p=3 \text{Mpa})
\]

\[
0.2 \leq t \leq 0.35 \\
2.1 \leq h \leq 2.6
\]

(4)

3.2.3 Proportion of shaping area. The optimal search of \(Z(t, h)\) is performed in the feasible region with a wall thickness of 0.05 mm and a wave height of 0.1 mm as the minimum calculation interval. The specific calculation results are shown in Tables 3 and 4.

Table 3. Results at 650°C, 1 Mpa, 20% compression.

| Wall Thickness | Wave Height | Rebound Condition | Proportion of Shaping Area | Maximum Contact Load |
|----------------|-------------|-------------------|---------------------------|----------------------|
| 0.2            | 2.2         | Y                 | 0                         | 63.9846              |
| 0.2            | 2.4         | Y                 | 0                         | 62.4157              |
| 0.2            | 2.6         | Y                 | 0                         | 63.4863              |
| 0.25           | 2.2         | Y                 | 0                         | 75.4104              |
| 0.25           | 2.4         | Y                 | 0.001155268               | 73.8492              |
| 0.25           | 2.6         | Y                 | 0.000693161               | 69.3513              |
| 0.3            | 2.2         | N                 | 0                         | 99.4946              |
| 0.3            | 2.4         | Y                 | 0                         | 91.2081              |
| 0.3            | 2.6         | Y                 | 0                         | 84.9369              |
| 0.35           | 2.2         | N                 | 0.02310536               | 126.048              |
| 0.35           | 2.4         | N                 | 0.01155268               | 118.716              |
| 0.35           | 2.6         | N                 | 0                         | 110.899              |

Table 4. Results at 650°C, 3 Mpa, 20% compression.

| Wall Thickness | Wave Height | Rebound Condition | Proportion of Shaping Area | Maximum Contact Load |
|----------------|-------------|-------------------|---------------------------|----------------------|
| 0.2            | 2.2         | Y                 | 0.036968577               | 77.7646              |
| 0.2            | 2.4         | Y                 | 0.02564695               | 67.6086              |
| 0.2            | 2.6         | Y                 | 0.017560074              | 41.9445              |
According to the above calculation, the design with a wall thickness of 0.3 mm and a wave height of 2.2 mm was obtained as the optimal solution. This result is in good agreement with the wall thickness design results for high pressure seals (0.012 inch) in the JETSEAL product manual (wave height is not published in this product manual).

4. Conclusion

(1) Taking the W-shaped metal sealing ring as an example, the resilience, stability and sealing of the sealing ring are selected as the evaluation index of the sealing performance. Analyze the effect of different wall thickness and wave height on the rebound rate of the seal ring, the proportion of deformation of the shaped area and the maximum contact stress. It is concluded that the influence of wall thickness and wave height on the comprehensive performance is complex, and it is necessary to comprehensively consider the three factors of resilience, sealing and stability, and optimize it for multiple objectives.

(2) Selecting the rebound rate, the deformation ratio of the shaping area and the maximum contact stress as the optimization target of the W-shaped metal sealing ring, and applying the layered solving method to gradually transform the multi-objective optimization problem into a single-objective optimization problem. Through the dimension reduction solution, the optimal solution of the seal ring structure design under the required working conditions is obtained: the wall thickness is 0.3mm and the wave height is 2.2mm. The optimization results are in good agreement with the JETSEAL product manual. The correctness and feasibility of the optimization design method based on the analysis of three aspects of performance and the hierarchical solution for dimension reduction are verified.

Acknowledgments

The work described in this paper was supported by National Basic Research Program of China (973) (2014CB046404).

References

[1] Wen Jiabao 2008 Let China’s Big Plane Soar in the Blue Sky (Beijing: Defence Science & Technology Industry) p 6-9

[2] Craggs A 1971 The Transient Response of a Couple Plate-acoustic System using plate and acoustic finite elements (Nevada:Sound and Vibration) p 509-528

[3] S Suzuki 1989 Boundary Element Analysis of Cavity Noise Problems with Complicated Boundary (Nevada: Sound and Vibration) p 147-153

[4] Hwang M, Pope A N, Shucktis B 1996 Advanced Seals for Engine Secondary Flow Path (Reston: Journal of Propulsion and Power) p 794-799

[5] Hu Guangyang 2012 Application Research of Seal Technologies for Aeroengine (Shenyang:Aeroengine) p 1-4

[6] Tan Songlin, Zhang Jinrong 2004 The Application of Reliability Increasing in the Manned Spaceflight Rocket Engine (Xi’an:Journal of Rocket Propulsion) p 41-44

[7] Suo Shuangfu, Xing Minjie, Xue Qing, et al 2016 Research on Effect Factors of Axial Stiffness of Metallic W-ring (Guangzhou: Lubrication Engineering) p 14-17

[8] Wang Chenxi, Yang Yiyong, Suo Shuangfu, et al 2016 Research on Compression-resilience and
Sealing Performance of Metallic (Guangzhou: Lubrication Engineering vol 01) p 50-54

[9] Xing Minjie 2015 Study on Sealing Performance and Leakage of Metal W-ring in the Aircraft Engine (Beijing: Beijing Institute of Technology)

[10] Gong Xueting 2011 Study on Characters of Metal W-ring Sealing used on Aircraft Engine (Beijing: Beijing University of Chemical Technology)