Research on Optimization of Cross-sectional shape for Aircraft Door Rubber Seal

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Abstract. Rubber seals are widely used in aircraft door structures, which play important roles on sealing, sound insulation and heat preservation. Aircraft door rubber seals are critical to the normal flight of the aircraft and the safety of the passengers. In this paper, a finite element model of rubber seals for aircraft door with different cross-sections is established. The deformation and stress distribution of the seals under the action of concentrated force and compressive displacement are analyzed, and the calculation results of seals with different cross-sections are compared. The optimal structural form of the cross-sectional shape of the seal is obtained. The research results are of great significance to improve the safety and durability of seals and enhance the sealing performance.

1. Introduction
The sealing performance evaluation of the aircraft door seal [1, 3] is of great significance for airplane safety performance. The seal is mainly composed of rubber material, and the nonlinear constitutive relationship of rubber materials has caused large displacement and large strain after carrying. There is a complex boundary condition in the solution process, and contain contact problems, with nonlinearity. Traditional experience design is not foreseeable before the performance evaluation of the sealing structure, and excessively depends on the designer's experience, which does not meet the requirements of modern precise design. It is necessary to use finite element calculation methods to analyze the work stress and deformation of the seal [4,8].

This paper mainly introduces the interface contact stress and contact deformation of the aviation rubber seal, which is of great significance for studying the sealing principle and sealing measures of rubber seals.

2. Calculation model

2.1. Constructive of rubber material
It is often described with the Mooney-Rivlin material model for rubber. The Mooney-Rivlin formula is simple and easy to apply. It can almost simulate the mechanical behavior of all rubber materials.

Under the ideal incompressible, constant temperature, the continuous body structure model, Rivlin proposed can be expressed as:

$$ W = \sum_{i+j=1}^{N} C_{ij} (I_1 - 3)^i (I_2 - 3)^j $$

(1)
W is strain energy density. Cij can be considered as material parameters, but it is actually not very clear physical significance. Which is used only as the regression coefficient of test data. I1, I2 represents the first and second Green strain invariant.

If the first two of the formula (1) is expanded, get the Mooney-Rivlin model:

\[ W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \tag{2} \]

In the formula (2), C10, C01 is the first two items of Cij. For uniaxial stretching and compression, this constitution is:

\[ \frac{\sigma}{\lambda} - \frac{1}{\lambda^2} = 2C_{10} + \frac{1}{\lambda^2}C_{01} \tag{3} \]

In the formula (3), \( \sigma \) is positive stress and \( \lambda \) indicates an elongation. The material parameters in the formula (3) can be obtained according to different test data. In this paper, the Mooney-Rivlin model is used to describe the relationship between rubber sealing materials.

2.2. Geometric model

In this paper, five sections commonly used in aviation rubber seals are selected for analysis: one kind of Eccentric circular section and four kinds of heart shaped sections. They are as shown in Figure 1.

![Geometric model of the rubber seals](image)

(a) Eccentric circular section  (b) Heart shaped section 1 (thick)  (c) Heart shaped section 1 (thin)

(d) Heart shaped section 2 (thick)      (e) Heart shaped section 2 (thin)

Figure1 Geometric model of the rubber seals

2.3. Finite element model

The seal geometric model of the five cross-sectional forms has been treated it as a flat strain problem using the ABAQUS to establish models.

3. Analysis and comparison of calculation results

3.1. Analysis of mechanical properties under concentration force

The seal in the five cross-section is subjected to 1000 N concentrated force. Stress and deformation calculation results are shown in Table 1, and Table 2.
### Table 1: Maximum stress of five structures (unit: MPa)

| section                | S.Mises | S11  | S22  | S12  |
|------------------------|---------|------|------|------|
| Eccentric circle       | 13.28   | 9.19 | 10.26| 2.83 |
| Heart shaped 1 (thick) | 7.23    | 6.32 | 5.28 | 1.23 |
| Heart shaped 2 (thick) | 5.31    | 5.12 | 3.57 | 1.53 |
| Heart shaped 1 (thin)  | 11.92   | 12.88| 6.79 | 3.80 |
| Heart shaped 2 (thin)  | 14.61   | 16.42| 7.08 | 5.01 |

### Table 2: Maximum displacement of five structures (unit: mm)

| section                | U.Magnitude | U1  | U2  |
|------------------------|-------------|-----|-----|
| Eccentric circle       | 188.74      | 76.02| 188.74|
| Heart shaped 1 (thick) | 180.58      | 40.52| 180.58|
| Heart shaped 2 (thick) | 248.83      | 65.63| 248.84|
| Heart shaped 1 (thin)  | 1191.90     | 255.84| 1191.90|
| Heart shaped 2 (thin)  | 1456.83     | 400.64| 1456.83|

From the five section seal Mises stress distribution, the five cross-section members are large in the top, 45 degrees or more, and connecting point with the base. The Mises stress of the thin-walled heart-shaped structure 2 is the largest (its value is 14.61 MPa). The thick-walled heart structure 2 is the smallest (its value is 5.31 MPa). Among the eccentric circular structure, the heart structure 1, the heart shaped structure 2, with the same wall thickness of 3 mm, heart-shaped structure 2 has the smallest stress (its value is 5.31 MPa). The eccentric circular structure has the largest stress (its value is 13.28 MPa). The heart-shaped structure 1 is located in the middle (its value is 7.23 MPa). The maximum stress appears in the vicinity of centralized load, which is due to local stress concentration under concentration.

1. Direction of immediate stress, 2 direction positive stress and shear stress distribution are as follows:

   In the positive stress in the 1 direction, the thin-walled heart structure 2 is also the largest (having a value of 16.42 MPa), and the thick-walled heart structure 2 is minimized (its value is 5.12 MPa). In the 2 direction (concentrated force direction), the eccentric circular structure has the maximum stress (its value is 10.26 MPa), and the thick-walled heart structure 2 is the smallest (its value is 3.57 MPa). In the shear stress, the thick-walled heart structure 1 has the smallest shear stress (1.53 MPa), the thin-walled heart structure 2 is the largest (its value is 5.01 MPa).

   Overall, the shear stress of the thin wall structure is larger than the thick wall structure, and the eccentric circular structure is in the middle.

   The displacement distribution of 5 structural sealing members is as follows:

   The displacement of the thin-walled heart structure 2 is the maximum (its value is 1456.83), the thick-walled heart structure 1 is the smallest (its value is 180.58). The thick-walled heart structure 2 has the largest displacement in the three structures with the same thickness. The thick-walled heart structure has the minimum displacement. The eccentric circular structure is in the middle. The displacement in 1 direction is much small than that in 2 direction. The displacement distribution in 2 direction is similar to the overall displacement.

   The contrast of the maximum stress and displacement of the five structures in concentration is shown in Figure 2.

   In summary, under the concentration force, if the structure is controlled by intensity (i.e., the maximum stress is the smallest), the thick-walled heart structure 2 is optimally, and each of its stress is small.
3.2. Analysis of mechanical properties under compression displacement

Five different structural seals are loaded with a rigid plane by moving 5mm downwards. The stress and displacement calculation results under the action of compression displacement are shown in Table 3, and Table 4.

Table 3: Maximum stress of five structures (unit: MPa)

| section                  | S.Mises | S11  | S22  | S12  |
|--------------------------|---------|------|------|------|
| Eccentric circle         | 67.50   | 48.58| 52.69| 30.03|
| Heart shaped 1 (thick)   | 120.58  | 74.91| 105.46| 46.49|
| Heart shaped 2 (thick)   | 95.518  | 57.19| 81.03| 37.16|
| Heart shaped 1 (thin)    | 58.628  | 34.069| 50.24| 24.71|
| Heart shaped 2 (thin)    | 44.70   | 21.65| 36.71| 19.32|

Table 4: Maximum displacement of five structures (unit: mm)

| section                  | U.Magnitude | U1  | U2  |
|--------------------------|-------------|-----|-----|
| Eccentric circle         | 5.05        | 1.82| 5.05|
| Heart shaped 1 (thick)   | 6.19        | 1.84| 6.19|
| Heart shaped 2 (thick)   | 6.12        | 1.86| 6.12|
| Heart shaped 1 (thin)    | 6.22        | 1.85| 6.22|
| Heart shaped 2 (thin)    | 6.01        | 1.92| 6.01|

Under compression displacement, thick-walled heart-shaped structure 1 stress is the largest, its maximum Mises stress is 120.58 MPa. The stress in 1 direction is 74.91 MPa, 2 direction is 105.46 MPa, and the shear stress is 46.49 mPa. The maximum stress of the thin-walled heart-shaped structure 2 is minimum, and its maximum Mises stress is 44.70 mPa. 1 direction stress is 21.65 mPa, 2 direction is 36.71 MPa, and shear stress is 19.32 MPa. The maximum Mises stress of eccentric circular structure is 67.50 MPa, which is smaller than the heart shaped structure 1 and heart shaped structure 2 with the same thickness. The stress of eccentric circular structure is larger than the heart structures 1 and heart structure 2 with thick wall. The stress of eccentric circular structure in 1 direction is 48.58 MPa, 2 direction is 52.69MPa, and shear stress is 30.03MPa. The maximum stress of the five structures under the pressure of compression displacement is distributed at the maximum horizontal width and the root connected to the holder. These locations are easy to destroy, and protection should be enhanced.

The rigid plane moves down 5mm, while the maximum displacement of the five structures in the 2 direction exceeds 5mm: the eccentric circular structure is 5.05 mm, the thick-walled heart structure 1 is 6.19 mm, thick wall heart structure 2 is 6.12 mm, thin wall heart shape Structure 1 and the thin-walled heart structure 2 are 6.22 mm, 6.01mm, respectively. The maximum displacement of the five structures is distributed in the middle, and corresponding measures should be taken to prevent gas leakage in the largest displacement distribution area. The contrast of the maximum stress and displacement of five structures in the displacement load is shown in figure 3.
In summary, under the pressure of compression displacement, if the structure is controlled by intensity (i.e., the maximum stress is the smallest), the thin-walled heart structure 2 is optimal, and each of its stress is smaller. If the structure is controlled by displacement (i.e., the maximum displacement is the smallest), the eccentric circular structure is optimal, and each of its displacement is smaller.

4. Conclusions
(1) Under the concentration of 1000 N, if the structure is controlled by intensity (i.e., the maximum stress is minimum), the thick-walled heart structure 2 is optimally, and each of its stress is smaller. Under the concentration of 1000 N, if the structure is controlled by displacement (i.e., the maximum displacement is minimum), the thick-walled heart structure 1 is optimal, and each of its displacement is smaller.
(2) Under 5 mm compression displacement, if the structure is controlled by intensity (i.e., the maximum stress is minimum), the thin-walled heart structure 2 is optimally, and each of its stress is smaller. Under 5mm compression displacement, if the structure is controlled by displacement (i.e., the maximum displacement is the smallest), the eccentric circular structure is optimal, and each of its displacement is smaller.
(3) The research results are of great significance to improve the safety and durability of seals and enhance the sealing performance.

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