Research on Sealing Assembly and Adjustment Method of Assembled Cabin Door of Space Station

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Abstract—For the new assembled sealed cabin door of space station, its structural characteristics, sealing working principle and sealing assembly and adjustment difficulties are analyzed. The static simulation based on the minimum loading point deformation is studied to obtain the minimum compression ratio boundary. Based on the maximum operating force, the sealing stress calculation and simulation analysis are carried out to obtain the maximum compression rate boundary. It realizes the transformation of multiple open constraints into the compression rate interval, which effectively improves the assembly and adjustment accuracy and efficiency of the assembled cabin door.

1. Introduction
In manned spacecraft, the living quarters of astronauts must be sealed to ensure the life safety\cite{1,2}. The sealed cabin door is the channel for astronauts to enter and exit the sealed cabin. It is essential for manned spacecraft, space laboratory, space station and so on. There is a pressure difference of approximately one atmospheric pressure between the cabin environment in which astronauts work and live in space and the vacuum environment outside the cabin. Manned spacecraft has high requirements for the sealing performance of the cabin door. The sealing performance will directly affect the life safety of astronauts.\cite{3-4} The sealed cabin doors of manned spacecraft and space laboratory are assembled, adjusted and tested at the ground assembly stage, and will not be repaired or replaced in orbit. Since the space station will be in orbit for more than 10 years\cite{5}, in order to avoid the failure of the sealing ring during the long-term service of the cabin door, the sealing ring needs to be replaced and repaired regularly. In order to ensure the maintenance and replacement of sealing ring, an assembled cabin door is designed.

This paper analyzes the structural characteristics and sealing working principle of the assembled cabin door, and studies the method of realizing high-precision and rapid sealing assembly and adjustment under multiple open constraints.

2. Analysis of structural features, sealing working principle and difficulties in sealing assembly and adjustment of the assembled cabin door

2.1 Structural features of assembled cabin door
The structure of assembled cabin door is shown in Fig.1. It is mainly composed of door structure, compression components and seal. The main differences between it and the traditional sealed cabin
door of manned spacecraft are as follows:

1. The traditional sealed cabin door is an integrated structure, and the assembled cabin door is composed of two semicircular doors connected by screws. Compared with the traditional circular sealed cabin door, the assembled cabin door has weak overall rigidity and poor central symmetry.

2. For the traditional sealed cabin door of the same size, the number of pressing points is 6, but the number of pressing points of assembled cabin door is only 3, which is 1/2 of the traditional cabin door.

3. The traditional cabin door is installed in the ground assembly stage. The assembled cabin door is launched with the cargo spacecraft in the state of loose parts. It is assembled and used by astronauts in orbit for the first time. The accuracy of sealing assembly and adjustment is required to be high.

2.2 Sealing principle of assembled cabin door

The sealing between the assembled cabin door and the door frame depends on manually locking the compression components to gradually compress the sealing ring between the door and the door frame to produce a certain compression rate. The sealing structure is shown in Fig.2. If the compression rate is too small, the sealing cannot be guaranteed. The greater the compression rate, the better the sealing performance, but the greater the pressing operation force. When three pressing points are pressed, the compression rate of each position of the sealing ring is different. When the position where the sealing ring produces the minimum compression rate meets the sealing requirements, the sealing of the whole assembled cabin door is realized. At the same time, the operating force should not be too large.

2.3 Analysis of difficulties in sealing assembly and adjustment of assembled cabin door

The constraint conditions for the assembly and adjustment of the assembled cabin door are to meet the following three conditions at the same time:

1. The compression ratio of compression point ≥ 12.5%;
2. The compression ratio of the intermediate point (the point between the two compression points) ≥ 6%;
3. The operating force ≤ 120N.

For the above open constraints, the conventional method is to place shims at the compression point for many times, measure and calculate the sealing compression rate of the compression points and the
middle points, measure operating force step by step, and finally obtain the assembly and adjustment scheme that meets the above three constraints at the same time.

Due to the weak structural rigidity and poor central symmetry of the assembled cabin door, the relationship of the compression rate between the compression point and the intermediate point is not clear; Due to the less quantity of compression points, the deformation of compression points has less effect on the deformation of intermediate points. If the above method is adopted, the accuracy control is poor, the operation workload is large and the efficiency is low.

3. Assembly and adjustment method of assembled cabin door

In view of the above problems, this paper researches on the methods to improve the accuracy and efficiency of assembly and adjustment, adopts the principle of "boundary control". Based on the sealing compression rate of the deformation of the minimum loading point and the maximum operating force as the boundary, the assembly and adjustment range of the sealing compression rate is determined.

3.1 Determine the minimum boundary of compression rate

According to the sealing working principle of the cabin door, under the compression load of three compression points, the minimum load position of the cabin door is three intermediate points. Therefore, the minimum boundary to realize the sealing of the assembled cabin door is the compression rate of intermediate points is≥6%.

According to the calculation formula of compression rate:

\[ Z = \frac{E - D}{E} \]

The Z is the compression ratio of sealing ring; the D is the size of the sealing ring after being pressurized; the E is the size of the sealing ring before compression, and the design value is 8mm.

The calculation shows that when the compression rate of the intermediate points is≥6%, the compression deformation (E-D) of the intermediate points is≥0.48mm.

Based on ANSYS simulation software, carry out static simulation analysis on the relationship between the deformation of the compression points and the intermediate points, as shown in Fig.3. By applying a certain displacement to the three compression points, the deformation of the three intermediate points can be obtained by simulation. The results show that when the compression deformation of the three intermediate points is≥0.48mm, the compression deformation of the compression points is≥1.16mm.

Fig.3 Deformation relationship between pressing points and intermediate points

According to the calculation formula of compression rate, when the compression deformation of the compression points is≥1.16mm, the compression rate of the compression points is≥14.5%, meeting the requirements of the design index (≥12.5%). Thus, the minimum boundary of the compression rate of the pressing points of the assembled cabin door is 14.5%.

3.2 Determine the maximum boundary of compression rate

According to the sealing working principle of the cabin door, the maximum boundary depends on the
compression rate of the compression points under the action of the maximum compression operating force.

According to the moment formula:

\[ F_1L_1 = F_2L_2 \]

The \( F_1 \) is the pressing operation force; the \( L_1 \) is the force arm for the pressing operating force, and the design value is 180mm; the \( F_2 \) is the reaction force at the compression point; the \( L_2 \) is the force arm of the reaction force at the compression point, and \( L_2 \) is 2mm in the compression state.

According to the pre tightening force formula of seal connection:

\[ F_m = \pi BDY \]

The \( D_0 \) is the diameter of the reaction force at the compression point; the \( B \) is the effective width of the shim, the \( B \) is taken as 0.5\( D \), and the \( D \) is the section diameter of the sealing ring; the \( D \) is the specific pressure, or sealing stress [6].

Taking \( F_m = 3F_2 \), it is calculated that the sealing stress:

\[ Y = \frac{3F_1L_1}{\pi BD_0L_2} \]

According to the section size of the seal shown in Fig.4, when the maximum pressing operation force is 120N, the sealing stress is 1.97MPa when the cabin door is pressed.

Based on ADINA simulation software, carry out the simulation analysis of sealing stress, and get the relationship between the compression amount of sealing ring and sealing stress, as shown in Fig.5. When the sealing stress is 1.97MP, the simulation analysis shows that the compression amount of the sealing ring is 1.45mm. According to the calculation formula of compression rate, the maximum boundary of compression rate of assembled cabin door is 18.2%.

In conclusion, the compression rate of the compression points of the assembled cabin door is

\[ 14.5\% \leq Z \leq 18.2\% \]

4. Assembly and adjustment verification of assembled cabin door

According to the above analysis, the compression rates of the three compression points of the assembled cabin door are assembled and adjusted to 15.8%, 14.5% and 15% respectively, the compression rates of the middle points are calculated, and the pressing and unlocking operating forces are measured, as shown in Fig.6. The results are shown in Table 1, which meet the requirements of the compression rate of the intermediate points \( \geq 6\% \) and the operating force \( \leq 120N \).
Fig.6 Assembly and adjustment verification of assembled cabin door

Table 1 Results of assembly and adjustment test

|                  | Compression point 1 | Intermedia point 1 | Compression point 2 | Intermedia point 2 | Compression point 3 | Intermedia point 3 |
|------------------|---------------------|--------------------|---------------------|--------------------|---------------------|--------------------|
| Compression rate (%) | 15.8%               | 6.1%               | 14.5%               | 6.5%               | 15%                 | 7.9%               |
| Pressing force (N)    | 83.2                | /                  | 93.8                | /                  | 92                  | /                  |
| Unlocking force (N)   | 43                  | /                  | 45.9                | /                  | 49.6                | /                  |

After assembly and adjustment, quick leak detection and vacuum leak detection are carried out for the assembled cabin door, and the test leakage rate meets the design index requirements.

5. Conclusion

Through the analysis of the sealing working principle of the assembled cabin door and the effective conversion of the assembly and adjustment constraints based on theoretical calculation and simulation analysis, the following conclusions are obtained:

1. The minimum boundary of compression rate of the assembled cabin door is the compression rate when the minimum load loading points meet the sealing requirements.

2. The sealing performance of the assembled cabin door is related to the operating force. The greater the compression rate of the sealing ring, the better the sealing performance and the greater the operating force. The maximum boundary of the assembly and adjustment of the assembled cabin door is the compression rate under the action of the maximum operating force.

3. The example shows that the above method based on theoretical calculation and simulation analysis to determine the compression rate range of the compression points is effective, and can effectively improve the assembly and adjustment accuracy and efficiency of the assembled cabin door.

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