Research on reliable sealing technology of spacecraft rectangular hatch based on boundary control

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Abstract: In view of the large size of the sealing surface of the space large diameter rectangular cabin door, the large number of locking mechanisms and long service life, it is difficult to adjust the multi degree of freedom attitude in the assembly process, the complex assembly and adjustment of the mechanism, the synchronization accuracy is not easy to ensure, the consistency of the multi-point seal compression rate is high, and it is not easy to control. Based on the rotation law of the spatial linkage mechanism, the precise dimension chain control of the hatch is carried out, and the attitude of the multi degree of freedom linkage is adjusted to realize the synchronous compression of multiple compression units of the compression mechanism; Based on the minimum and maximum operating force as the boundary, through the sealing stress simulation, the "boundary control" coupling assembly and adjustment technology is proposed to optimize the sealing structure and realize rapid and efficient assembly. The results show that the vacuum leakage rate is still less than 2.5×10⁻³ PaL/s after 2000 door opening and closing tests and sealing compression ratio are better than 15%. The long-life test verifies the feasibility and effectiveness of this method, and forms a set of high reliable and long-life sealing assembly and adjustment method of space hatch, which provides technical guidance and reference for the subsequent assembly of similar space hatch mechanisms.

1. Introduction

As a key component of the sealed cabin of the manned spacecraft, the hatch shall ensure reliable sealing performance when closed. When opened, it shall support the cargo load and astronaut's cabin penetrating function. Its structure shall not only bear the air tight load in the cabin, but also ensure the sealing performance of the manned spacecraft. It is an essential equipment on the spacecraft that determines the life safety of astronauts [1-2]. The quality and precision of its seal assembly directly determine the reliability and service life of spacecraft. With the rapid development of aerospace technology, spacecraft is developing towards large size and high precision, and the requirements for product accuracy are higher and higher, which puts forward higher requirements for aerospace manufacturing technology and product assembly accuracy [3-7].

Due to the complex hatch mechanism and high requirements for precision installation and commissioning, experts, scholars and engineering technicians at home and abroad have conducted
multi-directional and multi angle research on the hatch. Guo Aimin \cite{8} used the decoupling solution method of sealing load to calculate the sealing load of aircraft hatch, avoiding the problems of difficult modeling and constraints in traditional finite element analysis, and improving the calculation efficiency of hatch sealing load. Wang Donghui \cite{9} studied the influence of pre compression ratio and inflation pressure on the sealing performance of hatch through the finite element analysis of sealing structure. Chang Jie \cite{10} effectively avoided seal failure by improving the deformation relationship between the seal and the seal groove. According to the existing literature, at present, the research on the sealing performance of circular hatch is mostly focused on, and the research on the sealing performance of rectangular hatch is rare.

Aiming at the characteristics of uneven pressure deformation and difficult adjustment of seal compression rate consistency of large diameter rectangular hatch, the high-precision sealing reliability technology of rectangular hatch under multiple constraints of spacecraft is studied by using the method of "boundary control" coupling assembly and adjustment technology and experimental verification.

2. Sealing structure characteristics of rectangular hatch

Because the loading sequence of uplink replenishment cargo is enlarged to large scale, the hatch door of the spacecraft is a rectangular sealed hatch with large diameter and high passing rate. It is mainly composed of door body, door frame, door shaft hinge mechanism, locking mechanism, connecting rod mechanism, sealing structure and other components. The locking mechanism is composed of crank assembly, compression assembly, connecting rod assembly, etc., as shown in Fig. 1.

The cabin door body and the door frame together form an end face sealing structure, and the end face of the door body is equipped with two sealing rings. When the cabin door is closed, the door lock mechanism is used to apply a pressing load on the door body, so as to compress the end seal ring of the door body and provide the initial compression rate; When the cabin door is opened, use the door lock mechanism to unlock and release the pressing load on the door body, pull the door body to rotate around the door shaft until it turns to the predetermined position to avoid the passage of the cabin door.

The role of end seal in the cabin door is mainly reflected in two aspects: first, by applying pressure and tightening load at multiple points around the door body, the door body produces overall displacement relative to the door frame, and then compresses the sealing ring. By improving the stiffness of the door body, the local deformation of the door body under the compression load is reduced, so as to ensure the uniform compression of the sealing ring around the door body; The second is to prevent the vibration of the cabin door during use, buffer the closing of the door, and prevent the pressure leakage in the cabin.

Therefore, the sealing ring plays an irreplaceable role in the end face seal of the whole hatch. Unreasonable adjustment of the compression ratio of the sealing ring will aggravate the wear and extrusion of the sealing ring, which may affect the service life of the material or lead to the failure of the sealing system. The assembly and commissioning of the compression ratio of the sealing ring has a great impact on the sealing performance of the hatch.

![Fig. 1 Schematic diagram of hatch 1-door body, 2-door frame, 3-door shaft assembly, 4-door lock assembly, 401 crank assembly, 402 compression assembly, 403 connecting rod assembly, 5-door lock drive assembly](image-url)
3. Synchronization analysis of cabin door pressing mechanism

The cabin door locking mechanism adopts a compact, flexible and reliable spatial RSSR linkage mechanism (Fig. 2). The door lock mechanism includes eight pressing units. When the cabin door is closed, the eight pressing units are controlled by the spatial linkage mechanism to lock and realize sealing. The kinematic characteristics of spatial RSSR linkage mechanism are complex and diverse, there are many assembly and debugging links, and the requirements for installation and debugging accuracy are high. Its assembly accuracy directly affects the accuracy and flexibility of the door trajectory and the opening and closing operation force. Due to the influence of transmission amplification, there is a slight deviation in the relative angle or key support position of each part on the rotating shaft of the mechanism. After a series of mechanisms are transmitted, the start and stop positions of the end of the mechanism will be greatly offset, and the coordination and consistency of eight pressing unit is not easy to ensure.

![Fig. 2 Schematic diagram of spatial RSSR linkage](image)

The pressing mechanism adopts spatial RSSR mechanism, which is mainly composed of two spherical pairs and two rotating pairs. The motion can be converted from the swing of \( L_1 \) to the swing of \( L_2 \). The \( H-D \) matrix method \([11-12]\) is used to solve each mechanism, and the position coordinates of points \( B \) and \( C \) are respectively:

\[
B = [l_1 \cos \varphi_{01}, \ l_1 \sin \varphi_{01}, \ s_0]
\]

\[
C = [l_3 \cos \varphi_{03} + h_0, \ l_3 \cos \lambda_{30} \sin \varphi_{03} + s_3 \ \sin \lambda_{30}, \ -l_3 \sin \lambda_{30} \sin \varphi_{03} + s_3 \ \cos \lambda_{30}]
\]

B. C length of rod length \( L_2 \) between two points:

\[
|C - B| = l_2
\]

The general solution equation of spatial RSSR mechanism can be obtained from the length of rod length \( L_2 \) between two points \( B \) and \( C \):

\[
(s_0 \sin \lambda_{30}/l_1 - \cos \lambda_{30} \sin \varphi_{03}) \sin \varphi_{03} + (h_0/l_1 - \cos \varphi_{01}) = 0
\]

According to formula (1), the input and output parameters of spatial RSSR mechanism are mainly \( L_1, L_2, L_3, H_0, S_0, S_3, \varphi_{01} \) and \( \varphi_{03} \). According to the given unknown quantity, the rod lengths \( L_1, L_2 \) and \( L_3 \) of AB rod, BC rod and CD rod can be calculated. By adjusting the length of the rod and the position of the fixed hinge point a or D, and using the high-speed photogrammetry technology, the spatial position of the calibration points of the eight compression units is accurately captured, and the time deviation of the eight compression units is obtained based on the displacement and time curve of the calibration points of the eight compression units. Through multi-point comparative analysis, the pose of the pressing unit with large time deviation is corrected, and finally the time deviation of eight pressing points reaching the locking position is up to 0.5s.

4. Simulation analysis of cabin door sealing compressibility

The sealing surface of the door body contains two sealing rings, and there are eight pressing units at the sealing surface. When the cabin door is closed, the eight pressing units are controlled by the spatial
linkage mechanism to lock and realize sealing. In the process of assembly, the compression rate of eight compression points and 16 intermediate positions of eight compression points need to be adjusted for a single ring seal ring, and 32 compression rates need to be adjusted for a double ring seal ring. See Fig. 3 for the schematic diagram of measuring points of sealing ring compression ratio, where points 1, 2, 3, 4, 5, 6, 7 and 8 are the position of compression points, and 1-2, 2-3, 3-4, 4-5, 5-6, 6-7, 7-8 and 8-1 are the middle position of two compression points. There are many test points for sealing compression ratio commissioning; Moreover, the time deviation of eight pressing points to the pressing position is less than 1 second. In order to meet the accuracy requirements, multi-point comparative analysis is required, and it is difficult to assemble and debug; The transmission direction of the driving force is from both sides of the handle to the door shaft. The driving forces received by the eight compression points are not synchronized, resulting in inconsistent compression rates at the eight compression points. The traditional compression rate debugging method needs to be measured and calculated for many times, resulting in heavy workload and low efficiency.

Fig. 3 Schematic diagram of measuring points for sealing compressibility of hatch sealing surface

Fig. 4 Schematic diagram of hatch seal clearance

In this paper, two parameter Mooney Rivlin\textsuperscript{[9]} pseudo material deformation is used to describe the deformation capacity of rectangular sealing ring under external force, which is related to the strain state. The strain energy density function $W$ is:

$$W = C_{10} (I_1 - 3) + C_{01} (I_2 - 3)$$

In the Formula:

- $W$ is the strain potential energy

- $I_1$, $I_2$——The first and second strain tensor invariants are related to material deformation;

- $C_{10}$, $C_{01}$——Mooney Rivlin model material coefficient, MPa.

stress $\sigma$ And strain $\varepsilon$ The relationship is:

$$\sigma = \frac{\partial W}{\partial \varepsilon}$$

In the Formula:

- $\sigma$——stress, MPa;

- $\varepsilon$——Deformation.

According to formulas (2) and (3), when the material coefficients $C_{10}$ and $C_{01}$ of Mooney Rivlin model are determined, the relationship between stress and strain of sealing ring under external force is also unique, and its Mises stress and contact pressure will also be unique.

The compression ratio $K$ of sealing ring is:

$$K = \frac{H - h}{H} \times 100\%$$

In the Formula:

- $H$——Dimension of sealing ring in free state,

- $h$——Dimension of seal ring after compression.

According to formula (4), when the compression ratio $K$ and the seal ring size $h$ are determined, the
compression amount of the seal ring can be calculated.

Different compression rates are simulated by applying displacement load to the compression unit to realize the sealing performance of the hatch. The Mises stress and contact pressure distribution of the sealing ring are shown in the figure. The compression ratio of the hatch is known by the backstepping method, and the displacement exerted by the compression unit under different compression loads can be obtained. That is, the maximum and minimum compression boundary can be obtained through the sealing stress simulation of the maximum and minimum operating force of the door. The "boundary control" assembly and adjustment principle is adopted to obtain the thickness of the pressing point adjusting element, and the rapid sealing is realized by accurately and quantitatively repairing and adjusting the thickness of the element, which greatly improves the assembly efficiency.

![Simulation analysis diagram of sealing ring](image1)

**Fig. 5 Simulation analysis diagram of sealing ring**

5. **Sealing performance test verification**

In order to verify the high reliability and long-life performance of the sealing performance of the cabin door, the cabin door has undergone 2000 opening and closing life tests. After each opening and closing of the cabin door 100 times, the leakage rate of the cabin door is detected by the rapid detector leakage detection method and the vacuum helium mass spectrometry leakage detection method, and the sealing compression rate of the cabin door under different opening times is calculated.

Because the sealing surface of the door body, the two sealing rings of the door body and the sealing surface of the door frame can form a sealing cavity, as shown in Fig. 6. Therefore, the differential pressure method is used for rapid leak detection of the cabin door. During leak detection, the cabin door is closed, and the internal and external pressures of the cabin door are equal (100 KPa ± 3 KPa). The gas cylinder equipped with the cabin door rapid detector fills the sealing cavity between the two sealing rings of the cabin door with nitrogen, and the pressure sensor monitors the sealing surface of the door body. The gas pressure change in the chamber composed of two sealing rings of the door body and the sealing surface of the door frame can be calculated by formula (5) to obtain the leakage rate within a certain time.

\[
q = \frac{d(PV)}{dt} = V \frac{dP}{dt}
\]

![Diagram of quick leak detection and sealing small chamber of hatch](image2)

**Fig. 6 Diagram of quick leak detection and sealing small chamber of hatch**
Simulate the vacuum outside the cabin door as required ($\leq 1 \times 10^{-3}$ Pa) and the overall leakage rate of the cabin door under the normal pressure (100 KPa ± 3 KPa) inside the cabin door, a special vacuum leak detection device (as shown in Fig. 7) is designed, and the vacuum helium mass spectrometry leak detection method is used to carry out vacuum leak detection on the cabin door. During leak detection, the cabin door is closed, the inside of the cabin door is sealed after filling helium with a flexible sealed helium cover, and the outside of the cabin door is connected with the vacuum device. Compare with the standard leakage hole with known leakage rate to calculate the leakage rate value, as shown in formula (6).

$$Q = Q_0 \frac{\Delta N}{\Delta N_0}$$  \hspace{1cm} (6)

- $Q$—Leakage rate of actual leakage hole under one atmospheric pressure air
- $Q_0$—Leakage rate value of standard leakage hole under one atmospheric pressure air
- $\Delta N_0$—Net transfer value of standard leakage hole
- $\Delta N$—Net deflection value of actual leakage hole

![Diagram of vacuum leak detection for hatch](image)

Fig. 7 Diagram of vacuum leak detection for hatch

The leakage rate and sealing compression rate of the hatch under different opening and closing times are plotted respectively (Fig.8, Fig. 9 and Fig. 10). The test results show that after 2000 life tests, the value of rapid leakage detection rate changes gently with the increase of opening times, and the rapid leakage detection rate is less than 0.37 PAL / s, which is better than 63% of the required value of 1pal / S; The value of vacuum leak detection rate increases with the increase of door opening times, but the maximum value of vacuum leak detection rate is less than $2.5 \times 10^{-3}$ PAL / s, better than 75% of the required value of $1 \times 10^{-2}$ pal/s; With the increase of door opening times, the sealing compression ratio shows a decreasing trend, but the minimum sealing compression ratio can still meet the index requirements of $\geq 15\%$. In order to explore the reasons, after 2000 door opening and closing operations, the adjusting element at the pressing point of the door was disassembled. Through inspection and measurement, it was found that there was obvious wear on the surface of the adjusting element, and the thickness of the adjusting element decreased. Through analysis, it can be seen that the door experienced 2000 door opening and closing operations, the adjusting element at the pressing point was rubbed and worn, and the sealing clearance increased. As a result, the vacuum leakage rate increases and the sealing compression rate decreases. However, the maximum vacuum leakage rate and the minimum sealing compression rate are still better than the index requirements, which further realizes the high reliability and long life performance of the cabin door.
6. Conclusion
Through the analysis and Experimental Research on the assembly and Commissioning Technology of the consistency of sealing compressibility of spacecraft hatch under multiple constraints, the main conclusions are as follows:

(1) Based on the rotation law of spatial linkage mechanism and optical photogrammetry technology, accurate dimension chain control and multi degree of freedom linkage attitude adjustment, multiple pressing units of the pressing mechanism are pressed synchronously, and the time deviation of eight pressing points at the locking position to the pressing position is up to 0.5s.

(2) The "boundary control" coupling assembly and adjustment technology is adopted to realize the efficient debugging of hatch seal compression ratio under multiple constraints.

(3) The reliability of hatch seal assembly and adjustment is verified by rapid leak detection method and vacuum helium mass spectrometry leak detection method. The compression rate of hatch end seal is better than 15% and the vacuum leak rate is less than $2.5 \times 10^{-3}$ PAL / s, switch life greater than 2000 times and other technical indicators.

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