Optimal design of pipeline layout to increasing tightening rate of spherical sealing joint

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Abstract: Spherical sealing joint airtight sealing structure (hereinafter referred to as “screw joint”) is an important part of the spacecraft propulsion system to realize airtight connection between the pipes in different cabins and between the pipe and the thruster. The screw joint realizes airtight sealing by deforming the metal of the spherical head and the conical surface, and it is very sensitive to scratches or indentation, so in operation, repetitive disassembly and assembly shall be avoided and it is necessary to realize airtight tightening in one shot. According to statistical results, in research and development of spacecraft, the success rate for one-shot tightening of the same screw joint differs with the type and the section of the spacecraft: in some sections, the success rate is close to 100%, but in some other sections, it reduces to 70%. This paper makes failure analysis for unqualified one-shot tightening of screw joints and sorts out the factors related to pipeline layout design that leads to the failures, on the basis of which it tries to optimize the design from the perspective of pipeline layout. By calculating the tightening force of the screw joint, this paper quantifies the requirements for degree of freedom (DOF) of the pipeline and the rigidity of the valve/pipeline supporting stand. It will be of great significance to ensure high reliability of the spacecraft propulsion system.

1. Introduction

Spherical sealing joint airtight sealing structure (hereinafter referred to as “screw joint”)[1] is an important part of the spacecraft propulsion system to realize airtight connection between the pipes in different cabins and between the pipe and the thruster. The screw joint realizes airtight sealing by deforming the metal of the spherical head and conical surface, and it is very sensitive to scratches or indentation. Besides, tightening of the screw joint can also incur indentation. Thus, in operation, it is expected to tighten the screw to achieve airtight sealing in one shot, and if it is not tightened in one shot, the success rate of tightening for the second time will be low and can only be made up by other methods such as adding gaskets. If it still cannot meet the tightening standard, the welded pipeline has to be cut, which will undermine the propulsion system’s reliability and the development progress.

According to statistical results, the one-shot tightening success rate of the same kind of screw joint produced in the same batch differs as the type and section of its connected parts change: in some sections, the success rate of one-shot tightening is close to 100%, but in some other sections, the figure declines to 70%. This phenomenon shows that the one-shot tightening success rate of screw joints is related not only to the processing precision and technical standard of the screw joint, but also to the layout of the spacecraft’s propulsion system. Good layout design is a premise to ensure a high success rate of one-shot tightening.
In the order of analysis of the airtight sealing mechanism of screw joints, tightening failure analysis and analysis of quantified requirements of layout design, this paper explores the relation between improvement of pipeline design and tightening of the screw joint, and proposes quantified and operable standards for pipeline layout design.

2. Airtight Sealing Mechanism of Spherical Sealing Joint Sealing Structure

The sealing mechanism of the screw joint is shown in Fig.1 [2] and Fig. 2 [3]. The screw joint is a subassembly consisting of three parts, namely the conical surface, the spherical head and the screw. Through slide precision design and mechanical processing, the spherical head and the conical surface are ensured to be coaxial. In the process of assembling, the operator screws the screw onto the conical surface and presses the conical surface with the spherical head with the pre-tightening force of the screw thread. The spherical head and the conical surface are both made of metal, the pre-tightening force imposed on which will cause elastic deformation, thus forming a ring-shaped airtight sealed space between the spherical head and the conical surface.

![Figure 1. Schematic diagram of spherical sealing joint](image)

![Figure 2. Contact surface stress distribution diagram](image)

When the screw joint is tightened, leakage check is conducted, and if the leakage rate meets the standard, the tightening is judged as qualified.

3. Failure Analysis of Unqualified One-Shot Tightening

3.1 Failure Tree Analysis

The success rate of tightening of screw joints is not stable, so whether the screw joint is tightened becomes a key factor that affects the assembly progress and reliability of spacecraft. According to the sealing mechanism of the screw joint, failure tree analysis is made herein about the unqualified tightening of screw joints.
In the failure tree, M1 and M2 refer to the processing errors of the screw joint which can be avoided by improving the design and processing techniques of the screw joint manufacturer. M3 is the final assembly standard, which entails large amounts of technical tests to achieve the reliable range of the moment of tightening force. M1~M3 have no direct connection with the layout of the propulsion system, thus not to be discussed herein.

M4 “poor alignment in the assembly process” is related to the operation process; M5 “stress caused by external factors” is related to changes of environment, the structure’s subsystem and the assembling operation. However, the influence of these two factors on the tightening success rate can be reduced through quantified layout design. The following two chapters will probe into these two factors respectively.

### 3.2 Poor Alignment

“Poor alignment” is an unquantified concept. When leakage occurs in the screw joint, poor alignment is usually identified as the cause for the failure, but the real problem is not accurately identified.

The tightening of screw joints herein is divided into two stages: “in the tightening process” and “after the tightening process”, to explore the influence of alignment on the screw joint.

#### A) After the Tightening Process

Calculation of the dimension chain of the shape and the position tolerance reaches the following result: components of the screw joint used in spacecraft – the spherical head, the conical surface and the screw, have strict positional relations, and under the mechanical limit, the angular deviation and the coaxial error allowed by the axis of the spherical head and that of the conical surface are small.

According to the formula for the pre-tightening force of the screw joint:

$$M = M_1 + M_2 + M_3 = 0.5F_f (d_w \mu_w + \frac{d_2 \mu_s}{\cos \alpha} + d_p (1.15 \mu_s + \tan \beta))$$  \hspace{1cm} (1)

Where M refers to the moment of the tightening force, M1 the moment of friction between the coated screw and the supporting plane of the spherical head, M2 the moment of friction between the spherical head and the conical surface, M3 the moment of friction between the internal and the external screw threads, Ff the pre-tightening force, d_w the equivalent diameter of the supporting plane, \(\mu_w\) the friction coefficient of the supporting plane, d_2 the pitch diameter of the screw threads, \(\mu_s\) the friction coefficient between the spherical head and the conical surface, \(\alpha\) the inclination of the conical surface, dp the effective diameter of the external screw threads, \(\mu_s\) the auxiliary friction coefficient of the screw threads and \(\beta\) the lead angle of the screw threads.
Calculation shows that the pre-tightening force of screw joints of different types increases from 5kN to 10kN, which is very large. Therefore, the following conclusion is reached: “for the screw joint tightened in line with the standard, under the large pre-tightening force and accurate mechanical limit, the alignment of its spherical head and the conical surface is only related to processing precision level of the screw joint”. The alignment of qualified screw joints is surely qualified after tightening. However, the sealing of the screw joint is unqualified because of poor alignment in the tightening process, and it causes displacement between the spherical head and the conical surface, which leads to scratches and hence leakage.

**B) In the Tightening Process**

The state before the screw joint is tightened (when the screw is screwed up to the conical surface manually, but not tightened by a wrench) is identified as the initial state herein, and the relative position of the spherical head and the conical surface is shown in Fig. 4. Between the spherical head and the conical surface, there are axial position deviation, horizontal position deviation and angular deviation between the axes. Wang Jianwu and et al. [3] referred to these deviations as “vertical tightness”, “horizontal tightness” and “declination tightness” respectively, and provided quantified definitions.

![Figure 4. Schematic diagram of assembly tightness](image)

Before addition of the tightening force by a wrench, if the operator can adjust the spherical head to a proper position by hand, that is, when the declination tightness is as small as possible, the horizontal tightness is small and only the vertical tightness is remained, then the relative displacement of the spherical head and the conical surface is tiny in the tightening process, which will be less likely to create scratches and thus ensure reliable sealing.

### 3.3 Stress Caused by External Factors

When the screw joint is tightened, the upstream and downstream pipes of the screw joint is integrated into a whole. When temperature change or structural deformation causes changes in the relative position of the upstream and downstream pipelines, there will be large stress on the screw joint, and when the stress approaches or exceeds the pressing stress between the spherical head and the conical surface, leakage occurs in the screw joint.

### 4. Quantified Standards for Layout Design

According to the failure tree analysis, the pipeline layout can be optimized by improving the alignment in the pipeline connection process and reducing the stress caused by external factors inside the screw joint.

#### 4.1 Ensuring Proper Degree of Freedom on the Contact Surface of the Screw Joint

According to the analysis in 2.2, to ensure that the operator can adjust the “vertical tightness”, “horizontal tightness” and “inclination tightness” between the spherical head and the conical surface before tightening the screw joint, five degrees of freedom shall be set for the spherical head and
defined by the coordinate system shown in Fig. 5, including translational motions in three directions \( \vec{x}, \vec{y}, \vec{z} \) and rotation in two directions \( \vec{y}, \vec{z} \).

**Figure 5. Definition of coordinate system of spherical pair**

1. If there is space for layout on one side of the spherical head, it is advisable to design a bend on the pipe on one side of the head to ensure the degree of freedom. If two bends can be designed between the fixing point of the pipe and the spherical head, then the five degrees of freedom can be achieved.

2. If only one bend can be designed, then only three degrees of freedom can be realized, including the translational motion in one direction \( \vec{x} \) and rotation in two directions \( \vec{y}, \vec{z} \). In this context, the mounting hole of the conical surface must be able to realize the translational motions in two directions \( \vec{y}, \vec{z} \); otherwise, the operator can by no means ensure alignment.

3. If there is only straight pipes between the spherical head and the fixation spot behind the head, the head section can realize rotation in two directions \( \vec{y}, \vec{z} \), and the mounting hole of the conical surface can realize translational motion in three directions, \( \vec{x}, \vec{y}, \vec{z} \). This method will make the final assembly difficult, thus not advisable.

**Figure 6. Pipeline nearby spherical sealing joint of ASTRIUM**

Engineers in some foreign countries even design the pipeline behind the screw joint into the shape of springs for the spacecraft to increase the degree of freedom of the pipeline, as is shown in Fig. 6.

### 4.2 Ensuring Proper Rigidity of Pipeline Connected to the Screw Joint

In the process of assembly, the operator needs to adjust the spherical head to a proper position manually, which leads to quantified standards for the rigidity of the pipeline.

The pipelines can be simplified into simply-supported beams. In light of the Mohr–Mascheroni theorem, when the cross section of the simply-supported beams remain unchanged:

\[
1 \cdot \Delta = \frac{\Delta F_N f N}{EA} + \frac{\Delta F_Q f Q}{GA} + \frac{\Delta M M}{ET} \tag{2}
\]

Where:

- \( \Delta \) refers to the linear displacement, 1 is the unit, and when \( \Delta \) refers to angular displacement, 1 is the unit moment of force; \( F_N \) refers to the axial force, \( F_Q \) the shearing force, \( M_N \) the torque, \( \Omega_{F_N} \) the area of the FN diagram, \( \Omega_{F_Q} \) the area of the FQ diagram, \( \Omega_M \) the area of M diagram.

In light of real-world engineering practice, the adjustment amount of the screw joint herein is expected to meet the requirements listed in Table 1.
Table 1. Adjustment at spherical sealing joint

| Direction | $\vec{x}$ (mm) | $\vec{y}$ (mm) | $\vec{z}$ (mm) | $\vec{y}$ (°) | $\vec{z}$ (°) |
|-----------|---------------|---------------|---------------|-------------|-------------|
| required value | 5             | 2             | 2             | 5           | 5           |

Operation of the screw joint mainly relies on the operator’s hand force, including grip and pinch. According to the Research on Manual Work Force Evaluation Index [5], the operator’s hand force indices are shown in Table 2.

Table 2. Strength statistics of operators\(^5\) (partial)

| Work efficiency | Value |
|-----------------|-------|
| physical strength |     |
| gripping/N      | Level of the palm | 257.2±52.0 | 411.2±88.1 |
| pinching/N      | The thumb and forefinger force | 56.0±12.3 | 79.6±10.8 |
| screwing/ (N·m) | The thumb and forefinger force | 0.61±0.23 | 0.84±0.10 |

In the design of pipeline layout, Formula 2, Table 1 and Table 2 shall be referred to in order to judge whether the operator has adjusted the spherical head into the required position.

4.3 Ensuring Proper Rigidity of the Pipeline/Value Fixed Supporting Stand

After the screw joint is tightened, the supporting stand of the upstream and downstream pipeline/valve will be fixed. When reliable fixation is ensured, the pipeline/valve supporting stand must allow certain space for deformation to ensure that the rigidity of the stand is smaller than that of the pipeline regardless of changes of the external environment, so that the deformation of the stand can bear the stress incurred by external factors.

5. Conclusion

To increase the success rate of tightening of screw joints in the spacecraft propulsion system, this paper analyzes the sealing principle of screw joints and figures out the factors leading to failures of one-shot tightening. Besides, from the perspective of the layout of the propulsion system, it proposes three layout design requirements: “ensuring proper degree of freedom on the contact surface of the screw joint”, “ensuring proper rigidity of the pipeline connected to the screw joint” and “ensuring proper rigidity of the pipeline/valve fixed supporting stand”, together with quantified indicators. This research will be of great significance to ensure high reliability of the spacecraft propulsion system.

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