Effect of Temperature and External Load on Pre-Tightening Force of Satellite-Rocket Belt

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Abstract. The satellite-rocket unlocking device is an important part for the smooth separation of the satellite and the rocket after they arrive the scheduled orbit. This paper aims to study the temperature and the external load effect on the belt pre-tightening force, which is an important design parameter that directly determines the reliability of the connection between satellite and rocket. Formula is given for calculating preload change of the belt. Along with the temperature change, the percentage error between the calculation results and test results is 0.88%-6.9%, and with the external load increasing the preload is increasing which follows the increase of the press on the interface surface, and the percentage error between calculation results and test results is 1.7%-9.4%, the result is very useful to calculate the preload of the satellite-rocket belt.

1. Introduction

The satellite-rocket unlocking device is installed between the satellite and the rocket, which is used to connect and unlock the satellite and the rocket. The satellite-rocket unlocking device is an important device for the smooth separation of the satellite and the carrier after the launch mission, which can ensure the reliable connection between the satellite and the rocket. When the satellite is launched to a specified altitude, it can release the constraints between the satellite and the rocket according to the instructions and prepare for the separation of the satellite and the rocket. Therefore, the belt pre-tightening force is one of the important design parameters of the satellite-rocket unlocking device, which directly determines the reliability of the connection between satellite and rocket. The pre-tightening force of the belt is determined by the mass characteristics of the satellite and the load at launch. Because the material of the belt is different from that of the connecting parts, the pretension force of the belt will be affected by the external environment after the installation of the satellite rocket unlocking device. In order to ensure the connection intensity and rigidity between the satellite and the rocket during ground transportation and launching, it is necessary to accurately calculate the pre-tightening force of the belt and consider the influence of various factors on its size.

The satellite-rocket belt tester is a ground test equipment used to test and evaluate the pre-tightening force of satellite-rocket unlocking device. Its main function is to accurately calculate the stress of satellite-rocket belt in different states by measuring the resistance change of strain gauge pasted on the belt when preloading force is installed in the process of satellite assembly, and to collect and monitor
the data. It is characterized by accurate calculation of the pre-tightening force data of the belt of the satellite and arrow unlocking device, and less affected by the environment.

When the satellite unlocking device is installed on the satellite, the ambient temperature of the field is generally controlled strictly, ranging from 15 to 25°C. At the same time, relative to the pre-tightening force applied on the envelope, the change of the pre-tightening force caused by the external load is limited. Therefore, the influence of temperature and external load is seldom considered when calculating the pre-tightening force of the envelope. Temperature and external load are the main factors affecting the pre-tightening force of the belt after the installation of the satellite-rocket unlocking device.

2. Constructure of satellite-rocket unlocking device
The satellite-rocket unlocking device is mainly composed of belt, clamping block, explosive bolt and other parts. The installation status is shown in Figure 1. Its working principle is that the docking frame between satellite and rocket is clamped by several V-shaped blocks, and then the blocks are clamped by the belt along the circumference direction, and the belts are connected by explosive bolts. By applying pre-tightening force to the belt through explosive bolts, the V-shaped clamp block is pressed to the docking frame, thus realizing the reliable connection of the satellite and the rocket.

When the satellite is transported and powered on the ground, the connecting load is borne by the belt, clamping block and explosive bolt. When the satellite-rocket need to be separated, power supply the explosion bolt, detonate the explosion bolt, break it from the preset groove, release the pretension force of the wrapping belt, and drive the wrapping belt and clamp to break away from the docking frame of the satellite-rocket, release the connection state of the two, complete the unlock between the stars and arrow, and prepare for the separation of the satellite and arrow.

![Diagram of satellite-rocket unlocking device.](image)

Figure 1. Diagram of satellite-rocket unlocking device.

3. Analysis of pre-tightening force of the satellite-rocket belt

3.1. Pre-tightening Force Calculation
In the process of satellite launching, the belt-type satellite-rocket unlocking device should be able to withstand the conditions of satellite centroid overload load, ensure the reliable connection between satellite and rocket, and meet the requirements of connection strength and stiffness. The load at the interface between satellite and rocket can be decomposed into axial load $P$, transverse shear $Q$ and bending moment $M$ acting on the interface, as shown in Figure 2. Minimum pre-tightening of belt is $F_{min}$, which can be computed as follow.
\[ F_{\text{min}} = K \cdot \frac{1}{n\Delta \phi} \cdot \left( \frac{2M}{R} + \frac{Q}{f_1} + P \right) \frac{\tan(\theta/2) - f}{1 + f \tan(\theta/2)} \tag{1} \]

Where \( K \) is the correction factor, \( n \) is the number of the clamping blocks, \( \Delta \phi \) is the circumferential angle occupied by a single block, \( R \) is the junction radius, \( f_1 \) is the friction coefficient between the interface frames of the satellite and rocket, \( \theta \) is the inner angle of the clip, \( f \) is the friction coefficient between the clamping block and the interface frame.

![Figure 2. Force analysis sketch of the satellite-rocket unlocking device.](image)

3.2. **Analysis of influencing factors**

The influence of temperature and external load on the pre-tightening force of the satellite belt is analyzed through the test data of the satellite belt tester. The calculation method is deduced and verified with the calculation method of the pre-tightening force of the satellite belt.

3.2.1. **Temperature Effect.** The satellite-rocket belt is usually made of titanium or steel, and the interface frames and clamping blocks are usually made of aluminium alloy. The thermal expansion coefficients of the two materials are different. Therefore, after the belt unlocking device is installed on the interface frames of satellite and rocket, the pre-tightening force of the belt will change with the temperature. If the change of pre-tightening force caused by temperature is \( \Delta F_t \), the radial deformation of the interface frame and the clamping block is

\[ \Delta_1 = D \cdot \alpha_1 \cdot \Delta T - \frac{\Delta F_t \cdot D}{\kappa_1} \tag{2} \]

Where \( D \) is the diameter of the circle surrounded by the belt, \( \alpha_1 \) is the thermal expansion coefficient of the clamping block and interface frame, \( \Delta T \) is the temperature change. The tension and compression stiffness of the combination of interface frame and clamping block is \( \kappa_1 = E_1 \times A_1 \), \( E_1 \) is the modulus of elasticity of aluminium alloy, \( A_1 \) is the cross-sectional area of the interface frame.

The radial deformation of the belt is

\[ \Delta_3 = D \cdot \alpha_2 \cdot \Delta T + \frac{\Delta F_t \cdot D}{\kappa_2} \tag{3} \]

Where, \( \alpha_2 \) is the thermal expansion coefficient of the belt. The tensile stiffness of the belt is \( \kappa_2 = E_2 \times A_2 \), \( E_2 \) is the elastic modulus of the belt and \( A_2 \) is the cross-sectional area of the belt.

Because of \( \Delta_1 = \Delta_2 \),
\[ \Delta F_i = \frac{k_i k_2}{k_i + k_2} \cdot \Delta T \cdot (\alpha_i - \alpha_2) \]  

3.2.2. Effect of external load. The dynamic and static loads acting on the satellite-rocket interface during launching form the axial tension and compression loads, bending moments and transverse shear forces on the interface. When the bending moment acts on the interface surface, the force symmetrically distributed along the circumferential direction, but in opposite direction will be exerted on the interface frame, that is, one side of the interface frame is pulled while the other side is compressed. In addition, the transverse shear force at the butt joint is borne by the shear cone of two butt frames. The influence of bending moment and transverse shear force on the pre-tightening force of the belt can be neglected here. When the interface frame is subjected to axial tension and compression load, it will change along the transverse direction (diameter direction). Its value is related to the Poisson’s ratio \( \mu \), and these changes will affect the pre-tightening force of the belt.

It is assumed that the inner diameter and the outer diameter of the docking frame are \( d_1 \) and \( d_2 \) respectively. When the satellite bears the axial load, the strain along the axis of the interface frame is

\[ \varepsilon_1 = \frac{P}{E_1 \cdot A_1} \]  

Where \( A_1 = \pi (D_1^2 - d_1^2)/4 \).

The pretension force is

\[ \Delta F = \frac{k_3 k_6}{k_3 + k_6} \cdot \Delta_3 = \frac{k_3 k_6}{k_3 D + k_6 D} \cdot D \cdot \mu \cdot \varepsilon_1 \approx \frac{k_3 k_6}{k_3 + k_6} \cdot \mu \cdot \varepsilon_1 \]  

4. Test results

4.1. Temperature test

During the temperature test of a satellite, the pre-tightening force of the envelope was tested at 20 ~ 32°C, respectively. The test results are shown in Table 1. The thermal expansion coefficient of butt frame (aluminum alloy) is \( \alpha_1 = 1.82 \times 10^{-5}/^\circ C \), The cross-sectional area is \( A_1 = 1.0 \times 10^{-4}m^2 \), elastic modulus of aluminum alloy material is \( E_1 = 7 \times 10^{10} Pa \), The coefficient of thermal expansion of belt (titanium alloy) is \( \alpha_2 = 1.02 \times 10^{-5}/^\circ C \), The cross-sectional area of the tape is \( A_2 = 1.85 \times 10^{-4}m^2 \), Elastic modulus of titanium alloy material is \( E_2 = 1.05 \times 10^{11} Pa \), the variation of pre-tightening force caused by temperature are shown in Table 1. It can be seen that the calculated value of the pre-tightening force of the belt is 0.88%-6.9% of the measured value when the temperature changes. The test results of the pre-tightening force of the belt are basically consistent with the calculated results.

| Times       | Scheme 1          | Scheme 2          | Scheme 3          | Scheme 4          |
|-------------|-------------------|-------------------|-------------------|-------------------|
| Test value  | 1593.6            | 1676.9            | 1638.3            | 1546.4            |
| Calculated  | 1662.2            | 1662.2            | 1662.2            | 1662.2            |
| Error       | 4.10%             | 0.88%             | 1.40%             | 6.90%             |

4.2. External load test

The pre-tightening force of a satellite before and after loading is calculated according to formula (6). The variation of pre-tightening force under different external loads (Poisson’s ratio of aluminum alloy is 0.33). The test values are compared when loaded to 3300 N, 34000N and 35000N, as shown in Table 2.
Table 2. Test results of pre-tightening force affected by external loads.

| Project | 33000N  | 34000N  | 35000N  |
|---------|---------|---------|---------|
| Test value | 602.0   | 563.5   | 775.9   |
| Calculated value | 612.3   | 510.4   | 746.6   |
| Error    | 1.7%    | 9.4%    | 3.7%    |

From the data in Tables 2, it can be seen that under the action of external loads, the greater the pressure on the butt surface, the greater the pre-tightening force. The calculated value is consistent with the experimental results, and the difference between the calculated value and the measured value is 1.7%-9.4%. After analysis, there are two reasons for the deviation: first, the strain gauge is used in the test of the pre-tightening force of the belt, and there are measurement errors; second, the satellite-rocket unlocking device in this paper is composed of three belts. During the static test, the bending moment and transverse shear force at the butt face make the force of each belt different, but it is very difficult to calculate the change of the pre-tightening force of each belt theoretically. When the trend of pre-tightening force changes, the average values of three pre-tightening forces are used to analyze, ignoring the influence of bending moment and transverse shear force, thus resulting in errors.

5. Conclusion

In this paper, the influence of temperature and external load on the pretension force of satellite belt is analyzed through the test data of satellite belt tester, and the calculation method is deduced, which is verified by the calculation method of the pretension force of satellite belt. The results show that when the temperature changes, the difference between the calculated value and the measured value is 0.88%-6.9%. Under the external load, the greater the pressure on the butt surface, the greater the pre-tightening force increases. The calculated value is consistent with the experimental result, and the difference between the calculated value and the measured value is 1.7%-9.4%. When the satellite-rocket unlocking device is installed on the satellite, the temperature and external load will cause the change of the pre-tightening force of the belt.

References

[1] Wangmin Yi, Spacecraft intelligent assembly technology and equipment, China Aerospace Press, Beijing, 2019.
[2] Liemin Chen, Spacecraft structure and mechanism, China Science and Technology Publishing House, Beijing, 2005.
[3] Wenhong Liu, Material Mechanics Course, Machinery Industry Press, Beijing, 1993.
[4] Qingfei Jiang, Yang Xu, etc., Dynamics analysis of swing arms in the satellite-rocket unlocking and separation device, Noise and Vibration Control, Vol 37 (2017) 51-59.
[5] NASA. NASA-STD-7002 payload test requirements, Washington D. C., NASA, 1996.
[6] NASA. NASA-STD-5001 structural design and test factors of safety for spacecraft hardware, Washington D. C., NASA, 1996.
[7] National Defense Science, Technology and Industry Commission. GJB 1027A-2005 vehicle, upper level and spacecraft test requirements. Beijing: National Defense Science, Technology and Industry Commission, 2005.