Simulation and experiment of passive orbit disconnected support

Zihan Gao¹², Yidu Zhang¹², a and Qiong Wu¹²
¹Beihang University, School of Mechanical Engineering & Automation, 100083 Beijing, China
²Beijing Engineering Technological Research Centre of High-efficient & Green CNC Machining Process and Equipment, 100083 Beijing, China
aCorresponding author: ydzhang@buaa.edu.cn

Abstract. Research has been done on Passive Orbit Disconnect Support (PODS) using the Finite Element Method (FEM) and experiment to study its’ property. Through the FEM simulation of static structural analysis and steady-status thermal analysis, the results show that PODS can change its contact status as the force changes, thus change the force and heat transfer path. In the disconnected status, the heat leakage decreases because longer heat transfer path increases the thermal resistance. In the contact status, the PODS can bear larger force load. It is verified that the PODS can adaptively change its contact state as the load change using experiment. The gap between the stem and nut or end cold body can be calculated. This paper can provide some guidance for the PODS applications.

1. Introduction
With the development of the aerospace industry, higher requirements are placed on the operating time of spacecraft in orbit. In order to achieve that goal, one of the methods is to increase the life of the tanks which contain liquid oxygen and hydrogen [1]. Some studies show that the heat loss of the supports between the shell and tank accounts for 67% of the total heat leakage [2]. Thus it is very necessary to explore the property of the support structure.

In 1981, R. T. Parmle researcher designed, analyzed, fabricated and tested the PODS in the NASA-166473 contact in response to the problem of tank support heat leakage [3]. T. Nast and D. Frank found that S-epoxy FRP had the lowest thermal conductivity at the temperature of 50 K or more and it was the optimal low temperature support structure material [4]. Chunliu Yu studied the material selection of the PODS and figured out the order of the influence of the components was launch tube > orbit tube > the other part [5]. Tiangang Wang used Workbench to analyze the thermal-structural performance of the PODS and found that the deformation was the result of combination of the structural stress and thermal stress. Among them, thermal stress was the main factor affecting the deformation [6]. Fangfang Zhuang analyzed two support forms the rod system and shell system and realized that the rod system had better performance of reducing the heat leakage [7].

There are three forms of heat transfer, which are heat conduction, convection and radiation. Some studies had pointed out that heat conduction was the main cause of heat loss. So only heat conduction was considered in this paper. Passive Orbit Disconnected Support is a novel structure which can support the tank while reducing the heat conduction in orbit. It contains two parts which are end cold body as shown in Figure 1 and end warm body. It is worth noting that there are some gaps in PODS...
which are the key of reducing heat conduction. The gap 1 is between the nut and the stem and the gap 2 is between the end cold body and stem. Sample pieces were made to test the PODS functions. The material of the launch tube and orbit tube are respectively carbon fiber and PEEK, while the other components are 6061 Aluminium Alloy.

2. Theory and Experiment

2.1 Theory of changing force or heat conduction path

Different parts of the structure have different stiffness because of its materials and dimensions. One of the gaps might be reduced and eventually disappears as the force increases. The working status can be divided into three periods according to the status of the gaps. The contact between the stem and the nut is referred to as period 1; the contact between the stem and cold end body is referred to as period 2; it is referred to as period 3 while the gap 1 and gap 2 all exist. Period 1 and period 2 are called contact status and period 3 is called disconnected status.

![Figure 1. End cold body of the PODS](image)

Taking the axial force load as an example, each part of the structure is deformed due to force. The gap between the stem and cold body end roughly conforms the formula 1. As the force increases, the gap will decrease and eventually disappear when the force hits some certain value. The heat transfer path and the force load path are also changed because of the contact status is changed.

\[ \Delta = \sum_{i=1}^{n} \frac{F_i}{E_i A_i} \quad (1) \]

Where \( F \) stands for force load, \( l \) stands for the length of the part, \( E \) stands for the modulus of elasticity; \( A \) stands for the minimum cross-sectional area of the part and \( i \) stands for different part.

The gap size could be calculated using the FEM software Workbench. The dimensions of gap 1 and gap 2 are equal to 0.1mm. The end warm body is fixed and the end cold body is subjected to an axial force ranging from -2000N to 2000N. The relationship between force and displacement of the end cold body and can be calculated also the stress and strain distributions can be got.

2.2 Theory of reducing heat loss

In orbit, thermal conduction is the main reason of heat leakage. Formula 2 is a function of thermal conductivity. An \( R \) can be proposed from formula 2 to represent the thermal impedance as shown in the formula 3. Assuming that the working temperature is constant, increasing the parameter \( b \), decreasing the parameter \( \lambda \) or \( A \) can decrease the heat transfer rate \( \Phi \). It can be achieved by using lower thermal conductivity material and decreasing the contact area. In the different working period, the PODS is in different contact status. The thermal conductive path will increase while it switches to disconnected status. At the same time the contact area is decreased also.

\[ \Phi = \frac{T_1 - T_2}{\frac{b}{\lambda A}} = \frac{\Delta T}{R} \quad (2) \]

\[ R = \frac{b}{\lambda A} \quad (3) \]

Where \( \Phi \) represents the convective heat transfer rate; \( T_1 \) represents the temperature of the higher side; \( T_2 \) represents the temperature of the lower side; \( b \) represents the length of the PODS; \( A \) represents the heat transfer area; \( \lambda \) represents the heat conductivity of the material; \( R \) represents the thermal impedance.
In order to explore the characteristic of the PODS in different period, Steady-status thermal analysis is carried out using FEM software Workbench. The thermal property of the PODS in different period is different. The temperature of the end cold body is 3K while the temperature of the end warm body is 300K.

2.3 Principle of test contact

The key of whether the PODS works properly lies in the contact status which can adaptively change along the load. The PODS sample piece is fabricated to verify its function. The working status of the PODS can’t be measured directly. Luckily the material of orbit tube is not able to conduct electricity and there are some gaps around stem. It means that the electricity can’t be conducted in the disconnected status while it can be conducted in the contact status. The status of the PODS can be judged by measuring the electricity between stem and end cold body. The method principle is shown in Figure 2. Here are some instructions should be followed of the experiment.

1) Assemble the PODS and adjust the adjust bushing and nut to make sure the sizes of gap 1 and gap 2 in a certain value.
2) Connect the probes of the multi electricity meter to the stem and end cold body.
3) Assemble the PODS to the tensile-compressive force machine while make sure the axis of the PODS along with the direction of force.
4) Increase the load smoothly and record the force and displacement of the stem.

Figure 3. The heat transfer path in different statuses
3. Result and discussion

3.1 Variable stiffness of the PODS

Calculate the deformation of the PODS under different force load ranging from -2000N to 2000N and get the curve of force and deformation of stem as shown in Figure 5. It can be seen that the curve is divided into 3 parts corresponding to three different working status of the PODS obviously. Stiffness refers to the ability of the structure to resist elastic deformation when stressed. It can be calculated by the force required for a unit displacement. And that is the slope of the deformation – force curve. The stiffness of the PODS in status 1 and status 2 is larger than its in status 3 because of the contact occurs. The stiffness of the launch tube is smaller than the other parts. When it is working in status 3 the deformation of the PODS is mainly caused by the deformation of the orbit tube. In contrast in the status 1 and status 2, the launch tube can only meet a little part of the load and the contact transfer most of the load.

The deformation of the launch tube and others except orbit tube can be ignored because the stiffness of the PODS in status 3 is much less than the other two statuses. The relationship between the gap and the force is approximately equal to the relationship between the deformation and the force as shown in formula 6. And the gap can be calculated if the force can be measured while the contact occurs.

\[ y = 10^8 x - 12297 \]  \hspace{1cm} (4)
\[ y = 10^8 x + 13682 \]  \hspace{1cm} (5)
\[ y = 6 \times 10^6 x \]  \hspace{1cm} (6)

Where \( x \) is the displacement of the stem; \( y \) is the force.
3.2 Transfer path changes along force changing
The stress distribution and heat flux distribution of different statuses can be obtained by FEM Software Workbench. The stress of conical surfaces of stem and end cold body is larger than the other area of the parts in Figure 6 (a). That means the gap disappears and a contact occurs. The force is divided into two parts. One is through the orbit tube and the other is directly to the end cold body. In this status, the thermal transfer path is also divided into two parts which is the same with force path. The force path and the heat transfer path are similar which are shown in detail in Figure 6. But in status 3 as shown in Figure 6(c) and (f), there is almost the lowest stress and heat flux in the conical surface of the stem.

Comparing the heat transfer path in Figure 3, it can be clearly seen that the path of state 3 is shorter than the other path. Corresponding to the thermal resistance, the thermal resistance of the PODS in status 3 is larger so its thermal conductivity is the worst. The heat flux can be measured in the middle of the launch tube that can be used to characterize the thermal conductivity. The heat loss can be reduced about 71.28% in status 3.
Figure 6. Stress and heat flux distribution in different status. (a) represents the stress distribution in status 1; (b) represents the stress distribution in status 2; (c) represents the stress distribution in status 3; (d) describes the heat flux distribution in status 1; (e) describes the heat flux distribution in status 2; (f) describes the heat flux distribution in status 3.

3.3 Result of experiment

In the tensile loading experiment, during rotating the loading handle, it can be seen that the load increase in the panel of the machine. When the force reaches to 70N, the ohmmeter detects a short circuit. It means a contact occurred. While reversing the handle to apply compressing force the contact occurs when the force reaches to -110N. The contact can occur and disappear automatically while the load changes. The performance of the working status can change adaptively as the load changes. The Figure 7 can be obtained through the experimental data. The contacts occurred at the point A and point B. It can be seen that the forces which caused contact are different because the size of gap 1 and gap 2 were different. It can be calculated by the formula 6. The dimensions of the gap 1 and the gap 2 are respectively 0.0112mm and 0.018mm. The gaps can be changed by adjusting the adjusting bushing and nut.
4. Conclusion

Through the FEM simulation of static structural analysis and steady-thermal analysis, the results show that the PODS have many characteristics and some conclusion can be got as below.

The stiffness of the PODS in status 1 and status 2 is larger than that in status 3 because of the contact occurs.

PODS can change the contact status as the load changes, thus changing the force and heat transfer path. In the disconnected status, the heat leakage decreases because longer heat conduction path increases thermal resistance. In the contact status, the PODS can bear larger force load.

Verify the auto-change of different working status along various force load. The gap between the stem and nut or end cold body can be calculated by the switching status force. It can provide some guidance for the PODS applications.

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