Topological optimization design for support structure under multiple loading conditions

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Abstract. In view of the lightweight and high stiffness requirements of a certain type of spacecraft support, combined with the special performance and environment of the support, topology optimization technology is introduced into the optimal design of the support structure in the space field. The topology optimization and design of the support are carried out with the stiffness as the objective function and the quality as the constraint condition, and the design of "space hugging configuration" is proposed, and the simulation verification and experimental verification are carried out. Firstly, different load conditions of the support were analyzed and studied. Secondly, the initial model was established based on the relative position relationship between the support and the mounting surface of the loaded equipment. Finally, a design method of the support structure was established based on the combination of topology optimization under multi-load conditions and size optimization considering the influence of strength. The stiffness and strength of the optimized structure were checked under multiple load conditions, and the fundamental frequency was 2.05 times of the index requirement. The maximum response stress is lower than the yield limit of the material used, which meets the strength requirement. Finally, the vibration test is carried out to verify the support. After the test is completed, the position accuracy of the support interface meets the requirements of the index. The obtained bracket has high structural stability, meets the high performance requirements of the load equipment, verifies the feasibility of the topology optimization method, and provides an effective method for the design of lightweight high-stiffness structures.

Keywords: Support; multi-load condition; topology optimization; variable density method.

1. Introduction

Spacecraft in the launch process to experience rocket engine ignition, inter-stage separation noise, impact, vibration and other external loads, so the spacecraft load bracket needs to have good dynamic characteristics, stable performance, high reliability characteristics, and with the increase in the mechanical properties of the bracket structure, its mass also increases, the increase in mass is not conducive to the launch of spacecraft. Therefore, in order to solve this contradiction, the method of optimization design is introduced to carry out lightweight design, so as to achieve the goal of reducing the quality of the support under the condition of high mechanical characteristics.

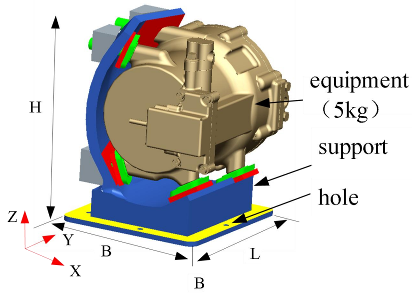
Topology optimization can provide a conceptual layout design at the initial stage of scheme design. On the premise of meeting the design requirements, the optimal distribution of materials can be achieved by changing the shape and size of the structure, and the optimal scheme can be adopted in the layout of the structure. By changing the topological relationship of the structure, the structure can achieve the optimal performance under the premise of meeting the constraints [1.2]. Structural optimization plays an increasingly irreplaceable role in the design process. According to the types of design variables, structural optimization design can be divided into size optimization, shape optimization and topology optimization [3]. Compared with size optimization and shape optimization, topology optimization has more obvious effects and has more theoretical significance and application value, so topology optimization methods are increasingly widely used [4]. Cheng Long et al. [5] carried out topological optimization of the star-sensitive support on a micro-satellite, and obtained a structural design scheme with high mechanical properties through optimization analysis and design. Kober M et al. [6] optimized the aero-engine parts by adopting the topological optimization algorithm based on the optimality criterion, which showed lower stress and lighter weight compared with the structure before optimization. Qi Guang et al. [7] carried out topological optimization analysis of the support structure used for the space camera mirror. Under the premise of satisfying the structural stiffness, position accuracy and surface shape accuracy of the mirror, the weight of the support structure was removed to the maximum extent, and the structural configuration superior to the quality index was obtained. Wei Lei et al. [8] applied the topology optimization method to the micro-satellite main load bearing structure, and obtained a satellite main load bearing structure whose single installation point acceleration response root mean square value meets the index requirements. Pei Yanwei [9] et al. optimized the design of the star sensor bracket by using the topology optimization design method to obtain a better structural form and meet the strict index requirements of structural lightweight and pointing accuracy.

At present, common topology optimization design methods include:, level set method [10], independent continuous mapping method [11], guided weight method [12], variable density method [13], etc. In this paper, a certain type of bracket involving on-orbit operation and installation of connectors is taken as an example, the topology optimization design of the bracket under multi-load conditions is carried out by variable density method, and the vibration test is carried out to verify the structure of the bracket. The results show that the support structure can meet the functional requirements and mechanical properties, and meet the design requirements.

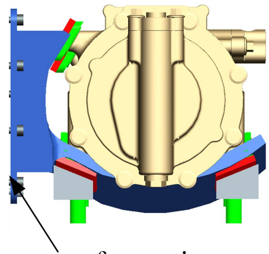
2. On-orbit operating environment

The installation model of bracket and load device is shown in Figure 1 below. The mass of the load equipment is 5kg, the envelope size is $\Phi 132 \times 184$mm, installed on the side of the support, the support into a "half encircling" type wrapped load equipment, load equipment 6 mounting surface contact with the support, 6 mounting surface is different structure, that is, each other are not in the same plane. There are pipe interfaces above the load equipment, and other single machines together form the whole system. The bottom surface of the support is connected to the spacecraft through six screws. As can be seen from Figure 1-b, the support is mounted to the spacecraft in a lateral manner, and the mounting surface of the load equipment is on the upper right side of the support, and the span between the load equipment and the mounting surface is large, forming a cantilever state. Therefore, when the load equipment and the support are subjected to large external disturbance, the position accuracy of the pipe interface is easy to change. When the rocket is going through the process from launch to orbit, the load equipment and support experience the noise, shock, vibration and other working environment of the rocket, and the direction is random, especially in the large Angle of attack or the large maneuver flight, the direction is more uncertain. In order to facilitate calculation and analysis, the Cartesian coordinate system is taken as the reference, and the XYZ triaxial direction is taken as the main load direction, where X is the flight direction, the acceleration value of the main load direction is 7.5g, and the total root-mean square acceleration value of random vibration is 12.45g. Therefore, the topology optimization is calculated with the load under the most dangerous condition of 12.45g.

When the load device is launched into orbit, the load device starts to work, and the work is that the load device generates continuous vibration, so the support is also affected by the vibration load P of the load device, the direction of the load P is Z, and the acceleration value is 2g.



a）Support and equipment model



b）The support is mounted on the spacecraft

Fig.1 Schematic view of the installation environment and operation

3. Topology optimization design

3.1 Basic theory

The optimization of structural topology is aimed at: to optimize the mechanical properties of the structure or to reduce the quality of the structure. Through calculation and analysis, the best distribution form of the material in the design area (i. e., the best force transfer path of the structure) is obtained. Topology optimization is realized by discretizing the materials in the optimized space. Assuming the structure using isotropic materials, introduce an intermediate density unit penalty model, the material is defined as a variable material between 0~1, when the relative density 0 represents the material deleted, when the relative density 1 represents the material should be retained, the relative density value to 0 and 1 respectively, the relative density of the unit and the elastic modulus relationship exist as follows:

$$\rho(\rho_i) = \rho_i \rho_0 \tag{1}$$

$$E\cdot(\rho_i) = \rho_i^P E_0, \rho_i \in [0,1] \tag{2}$$

Where: $\rho(\rho_i)$ is the material density corresponding to the relative density; ρ_i is the relative material density of the unit; ρ_0 is the actual material density of the structure;

$$E\cdot(\rho_i) = \rho_i^P E_0, \rho_i \in [0,1] \tag{2}$$

Where: $E(\rho_i)$ is the elastic modulus corresponding to the relative density coefficient; E_0 is the elastic modulus of the actual structure; and P is the penalty factor.

According to SIMP density-stiffness interpolation function model, the following mathematical relationship can be obtained by discretizing variables using variable density method:

$$find\ \rho = \{\rho_1, \ \rho_2, \ \cdots, \ \rho_i\}^T \quad i = 1, \ 2, \ \cdots N \tag{3}$$

$$minC(\rho) = U^T KU = \sum_{i=1}^{n} (\rho_i)^P u_i^t k_0 u_i \tag{4}$$

Where: C is the total flexibility of the structure; U is the displacement matrix; K is the total stiffness matrix of the structure before optimization;

The constraint conditions are:

$$s.t. \begin{cases} F = KU & (5) \\ V = aV_0 \geq \sum_{i=1}^{n} \rho_i v_i & (6) \\ 0 \leq \rho_{min} \leq \rho_i \leq 1 & (7) \end{cases}$$

Where: F is a column vector; u_i is the unit displacement column vector; k_0 is the element initial stiffness matrix;

V is the total volume after structural optimization; V0 is the initial total volume of the structure; a is the volume fraction. v_i is the optimized volume of the unit.

ρ_{min} is the lower limit of the design density. ρ_i is the actual relative density.

For the discrete continuum structure, the smaller the value of the compliance function C, the greater the stiffness of the structure, the more stable the structure.

3.2 Initial model establishment.

The structural material of the support is aluminum alloy, and the material parameters are shown in the following table. The initial model mass of the support is 1.97kg. The stent is divided into two areas according to the topology theory rules in ANSYS. The blue area is the area for topology optimization, and the material can be removed according to the optimization results. The red is the holding area, that is, the area where the material cannot be removed in the calculation. The area around the mounting hole of the support and the contact area with the mounting surface of the loading equipment are the areas where the material cannot be removed. The finite element model is shown in the figure below.

The mounting holes of the support and spacecraft are set as fully constrained boundary conditions, and the loaded equipment is loaded at the position of the mounting holes of the support by equivalent mass point. The finite element model is shown in the figure below.

Table 1. Material parameters

Material	Density kg/m^3	Elastic modulus GPa	Poisson's ratio	Yield stress MPa
Aluminium alloy	2800	68	0.3	155

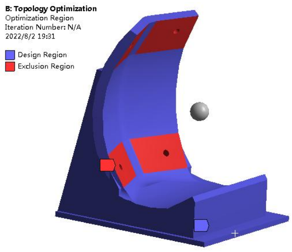


Fig.2 Topology calculation model

3.3 Topology calculation based on mode

Topology optimization setting based on the established equivalent finite element model. The boundary condition is that the lower plane of the bottom plate is fixed with six degrees of freedom, and the mathematical model of maximizing the base frequency topology optimization under the 30% mass constraint is:

Through the topological calculation of the above various conditions of the stent, the calculated results are shown in the figure below. By analyzing the results, the retained material area is the area with large force, the unit with the optimization result density value tends to 1, and the removed material area is the area with less force, and the unit with the optimized result density tends to 0. According to the following figure, the upper plane of the bracket is retained to ensure the reinforcement of the transverse translation stiffness. In the middle of the longitudinal part, the force is small, so most of the material is removed. Part of the material is also removed in the middle of the diagonal reinforcement behind the bracket.

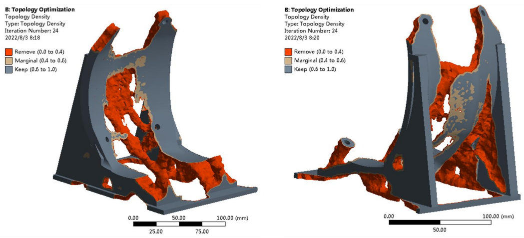


Fig.3 Results of the topology calculations

3.4 Optimization design

Through the analysis of the above calculation results, comprehensively considering the retention area of the support material, the detailed design of the support, because the load equipment in working vibration conditions, the large cantilever support is difficult to ensure the interface accuracy, so by adjusting the layout of the moon surface heat pump overall pipeline, the load equipment rotation 5°, and the support, put forward the "space around configuration" design. The support model after the rotation of the load equipment is shown in Figure 5 below. The surface in contact with the installation position of the load equipment is designed to reduce the weight, and the reinforcement is retained, while the wrench operation area is reserved, and most other intermediate areas are removed. Keep 5 vertical reinforcement bars on the facade, and reserve the installation area near the installation hole position. Through comprehensive comparative analysis and combined with process implementation, the results of stent optimization design are shown in the figure. The optimized stent mass was 0.73kg, a 63% reduction compared to the initial stent mass (1.97kg).

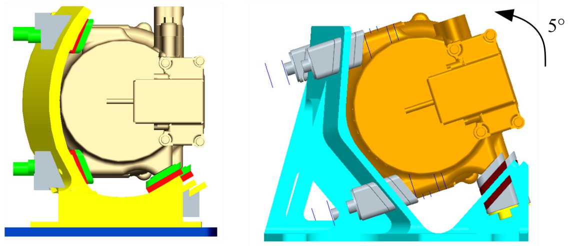


Fig.4 Rotational signal of the equipment

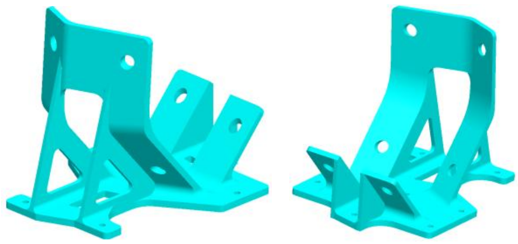
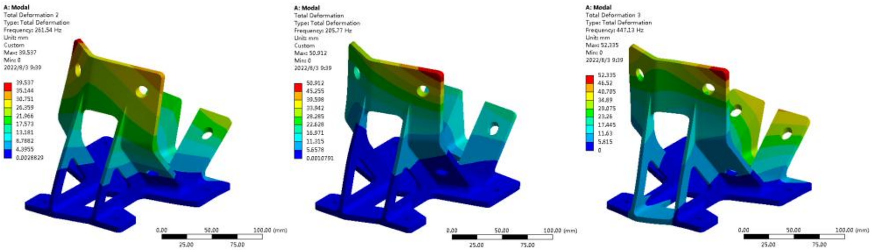


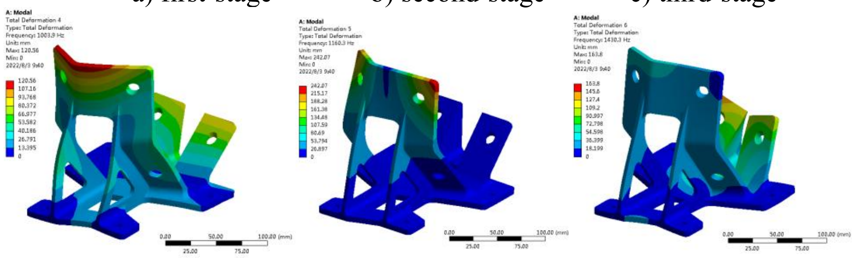
Fig.5 The support model

4. Mechanical properties check

The mode of the scaffold was calculated and the stiffness performance was checked. The load equipment weighs out in the form of a mass point. After mode calculation, the first 6 order frequency results are obtained. The vibration type is shown in Figure 6. The first order frequency is 205Hz, which meets the requirements of the base frequency index and is the vibration of the top of the bracket.



a) first-stage b) second-stage c) third-stage



a) fourth-stage b) fifth-stage c) sixth-stage

Fig.6 Modal calculation results

The acceleration load condition of the support is calculated to check the strength of the structure. Load equipment is weighted in the form of mass points. As shown in the following figure, the maximum response stress in the three axial directions is 20.2MPa, 17.1MPa and 21.9MPa respectively, all of which are lower than the yield strength of the material, so the strength of the support meets the design requirements.

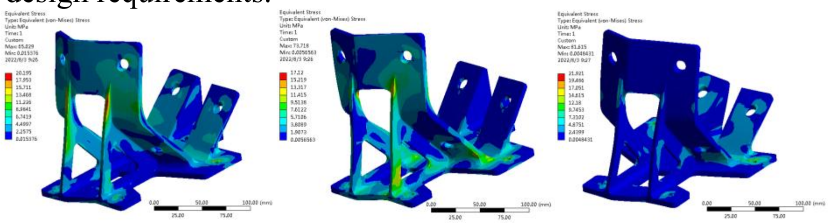


Fig.7 Simulation results of acceleration loading conditions

5. Summary

1) According to the harsh load environment and high stiffness bearing demand of the support, the most dangerous working conditions are selected as the input conditions of the structural optimization design, and then the initial design model is established according to the spacecraft installation environment.

2) Based on the theory of variable density method and topology optimization, the finite element model for topology optimization is established by using ANSYS software. Through calculation and optimization design, the overall base frequency of the stent and the connector is 205Hz, and the quality of the stent is reduced by 63% compared with the initial model.

3) through a variety of mechanical conditions strength check, optimized stent meet strength requirements, verify the rationality of the stent structure design, thus shows that topology optimization design method has high global and accuracy, topology optimization technology successful application in the field of spacecraft stent makes the product to speed up the optimization process, improve the efficiency of stent design, greatly reduce the subsequent iteration design frequency.

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