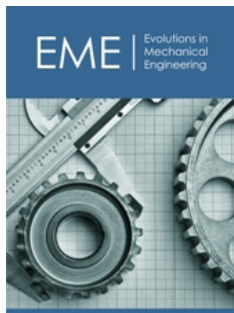


Vibration-based Structural Optimization of Microsatellites

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Abstract

A rectangular communication satellite, due to its configuration and carrying multiple loads, caused low fundamental frequency and could not meet the rocket carrying requirements. In order to strengthen the satellite structure, this paper adopts three options to enhance the satellite structure, such as increasing the thickness of the skin, adding X-shaped I-beam to the satellite-rocket separation interface and increasing the thickness of the Satellite-rocket Separation Interface structural plate. After the comparison of four options, it was found that adding X-beam on the docking surface of the star and arrow to enhance the stiffness of the whole star was the most effective and enhanced the force transmission path. While increasing the weight of the satellite structure by only 8.15%, the satellite fundamental frequency was increased from 25.14Hz to 32.39Hz, an increase of 22.3%. Meanwhile, the satellite structure was analyzed for sinusoidal and random vibrations and the addition of X-beams greatly reduced the acceleration response and Root Mean Square (RMS) values. Therefore, adding X-beams to the satellite-rocket separation interface can be the preferred method to optimize the structure of microsatellite.

Keywords: Communications satellite; Structure optimization; Fundamental frequency

Introduction

Communication satellites communicate between satellites and earth stations or between satellites by reflecting or retransmitting radio signals. As the short development cycle of small satellites and the advantages of low project costs become more and more obvious, the large satellites, long development cycles and high costs of communication satellites are gradually revealing their drawbacks [1]. Due to the small size, light weight and short force transmission path of the microsatellite, the exogenous load will cause a direct impact on it, which will easily produce harmful deformation. To ensure that the microsatellite will not be damaged in the harsh mechanical environment of the launch vehicle and to ensure the safety and reliability of the payload and on-board equipment, it is crucial to enhance the structural strength and stiffness of the satellite [2-5].

The satellite fundamental frequency is an important indicator of the design strength of the satellite structure, reflecting the structure's ability to respond to external loads. The corresponding acceleration of sinusoidal vibration and the Root Mean Square (RMS) of random vibration response of the satellite structure show an obvious nonlinear relationship with the whole-satellite frequency and it is difficult to coordinate the two during the satellite structure and it is usually impossible to make them optimal at the same time. However, by providing a reasonable configuration scheme to reduce the damaging effect of these vibrations on the structure and making full use of all the properties of the structure, a balance between structural stiffness and dynamic properties is achieved [6-7].

In this paper, the engineering development of a microsatellite is used as the background to analyze the problems of low fundamental frequency and large response of small satellite structure. Due to the constraints of space and mechanical environment, structural optimization is carried out for the structure configuration of compartmentalized satellites and the stiffness of the whole satellite is improved at a minimum weight cost by adding buried beams in the

structural plates and increasing the thickness of the skin as well as increasing the structural thickness of the separation surface of the star and arrow, in order to obtain an optimal solution that can effectively improve the structural stiffness of small satellites.

Satellite Structural Design

Design requirements

A communication satellite is mainly used for communication between satellites and satellites and between satellites and ground stations and the inter-satellite communication between satellites and satellites is through the load for the laser communication load and the satellite and the earth satellite communication through the navigation antenna. The whole satellite envelope size is 1270mmX1182mmX826.5mm due to the space limitation on board. In addition to the conventional platform equipment installation, the structure also needs to carry deployable rigid solar wings, communication antennas and four laser communication loads. Two lasers are used for interplanetary communication in the same orbit and two lasers are used for interplanetary communication in different orbits. The weight of the whole satellite is 92.5kg.

To ensure that the satellite structure has sufficient equipment layout controls and good mechanical properties, the shaping structure adopts a hexahedral structure, and in order to meet different loads, the whole satellite adopts a compartmentalized structure design, divided into a platform module and a payload module. The platform module mainly provides installation space for platform equipment and the payload module mainly provides installation space for payload equipment. The platform module and the payload module are connected by an intermediate partition,

which can not only increase the structural strength of the satellite, but also provide the mounting surface for the on-board equipment.

Design requirements: Whole satellite fundamental frequency greater than 25Hz, Acceleration response is not greater than 12g. And the RMS value of the equipment is less than 10.

Structural design

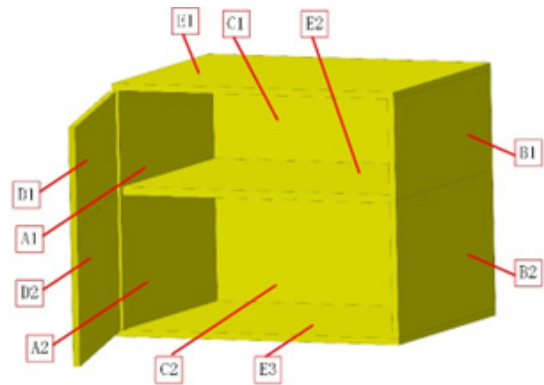


Figure 1: Satellite structure.

The satellite structure is shown in Figure 1. In order to facilitate batch launches and rapid adaptation to carry different loads, the satellite is divided into a platform module and a payload module, with a total of 11 structural panels forming the satellite structure through lap splicing. All the payloads pass through the structural plates and transfer the forces to the E3 plates, which are connected to the rocket through the satellite separation device and the E3 plates play a key role in the stability of the structure. The parameters of each structural plate are shown in Table 1.

Table 1: Parameters of structure plate.

Name	Length/mm	Width/mm	Thickness/mm	Aluminum Skin	Honeycomb Size
A1, B1	730	300	15	0.3	5*0.03
A2, B2	730	410	15	0.3	5*0.03
C1, D1	860	300	15	0.3	5*0.03
C2, D2	730	410	15	0.3	5*0.03
E1, E3	900	730	15	0.3	5*0.03
E2	860	690	20	0.3	5*0.03

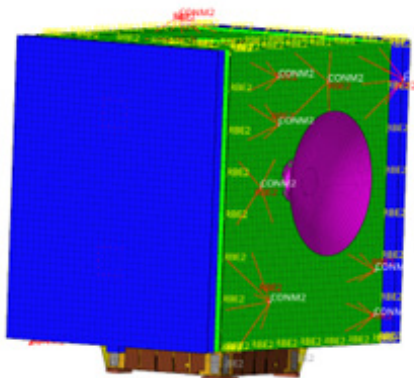


Figure 2: FEM of the satellite.

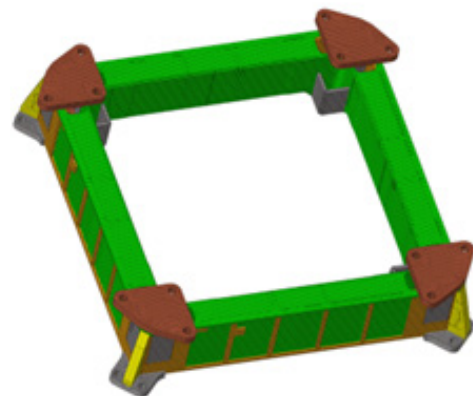


Figure 3: FEM of satellite separation mechanism.

The finite element modeling of the satellite is shown in Figure 2. The E and F base plates, B and C plates, D and G plates are all honeycomb sandwich panels, which are simulated according to the composite material and the four-node plate and shell cells are used to model the joints of each plate by the common node method. All the equipment on the star, except the navigation antenna, is treated as a concentrated mass at the center of mass and the effect of its rotational inertia is not considered. The star-arrow separation device is created using solid units, as shown in Figure 3.

Through the comparison of the four schemes, the structure design form is optimized and the stiffness of the whole satellite is improved with the minimum weight cost.

Scheme 1: Without any local reinforcement.

Scheme 2: On the basis of Scheme 1, the thickness of aluminum skin is increased to 0.5mm.

Scheme 3: On the basis of Scheme 1, the aluminum alloy X-shaped buried beam is added to the satellite-rocket separation interface and the structure layout of X-shaped beam is shown in Figure 4.

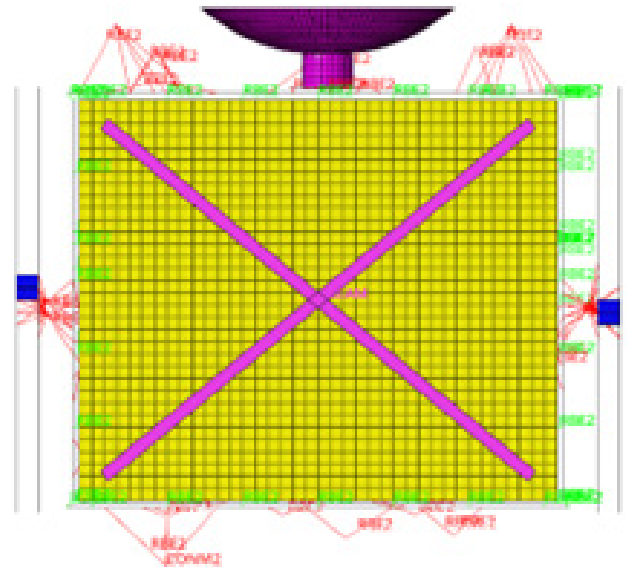


Figure 4: FEM of satellite with X-shaped beam.

Analysis Results

Modal analysis

Table 2: Comparison of fundamental frequency improvement.

Improve Scheme	Fundamental Frequency/Hz	Structure Weight/kg	Weight Increment/%	Base Frequency Increment/%
Scheme 1	25.14	13.5		
Scheme 2	26.11	14.2	5.19	3.86
Scheme 3	32.39	14.6	8.15	22.38
Scheme 4	27.88	15.1	11.85	10.9

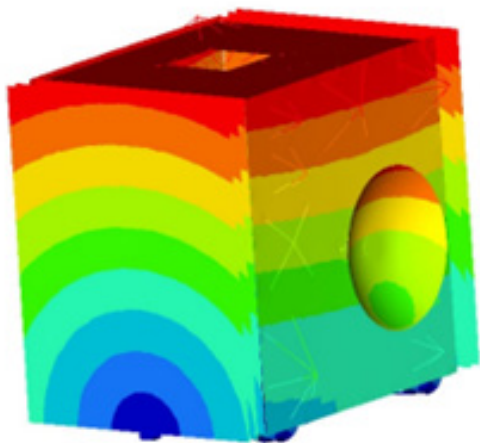


Figure 5: First-order X-directional vibration.

The modal analysis of the whole satellite can quickly determine the degree of fundamental frequency coupling between the satellite and the rocket, so as to avoid resonance between the satellite and the rocket due to the close frequency. In addition, the modal analysis results of the satellite will also provide the basis for the subsequent structural optimization and dynamics analysis. The modal analysis

is performed for different scheme and the modal analysis results are shown in the Table 2. Scheme 3 increases the fundamental frequency by 25% with relatively less increase in structural weight, so scheme 3 is the optimal scheme. The first three order modes of the satellite in the case of scheme 3 are shown in Figure 5-7.

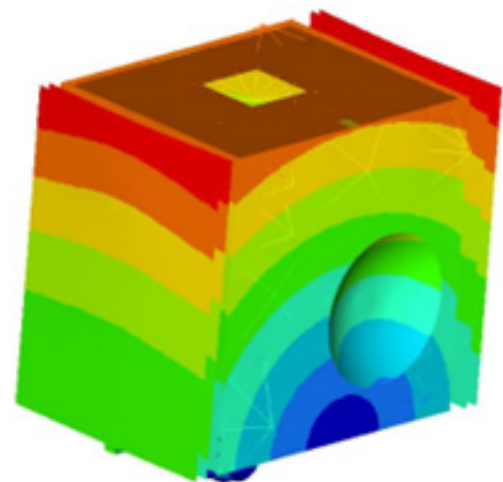


Figure 6: First-order Y-directional vibration.

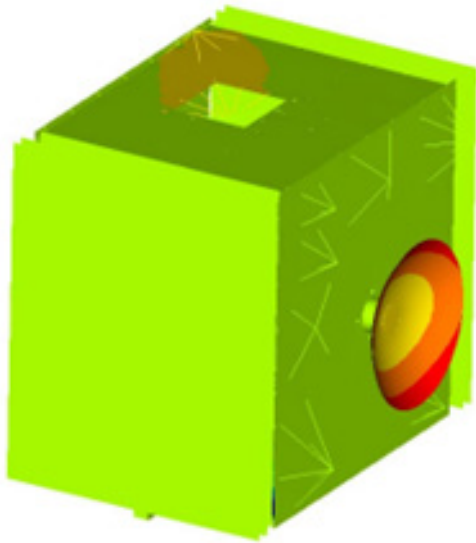


Figure 7: First-order Z-directional vibration.

Sinusoidal vibration analysis

According to the design requirements, this section performs satellite frequency response analysis in the frequency range of 5Hz to 100Hz to obtain the vibration response values of the components and key parts of the satellite to verify whether the structural design scheme is reasonable. According to the rocket conditions, sinusoidal vibration analysis is performed for four schemes and the results of the sinusoidal vibration analysis are compared with those of the laser payload, navigation antenna and solar wing, which are of more concern to the satellite. Comparison of the different scenarios of acceleration of the main equipment on board the satellite for the four Schemes shown as Table 3-6.

Table 3: Acceleration response of the main equipment in Scheme 1.

A indicates acceleration and F indicates frequency.

Name	X-direction	Y-direction	Z-direction			
	A/g	F/Hz	A/g	F/Hz	A/g	F/Hz
Laser	6.76	57.9	1.54	33.7	1.68	25.14
Solar Array	7.96	57.9	13.08	33.7	11.1	25.14
Navigation Antenna	7.46	57.9	6.21	33.7	7.99	25.14

Table 4: Acceleration response of the main equipment in Scheme 2.

Name	X-direction	Y-direction	Z-direction			
	A/g	F/Hz	A/g	F/Hz	A/g	F/Hz
Laser	6.62	59.4	1.51	35.1	1.65	26.1
Solar Array	7.73	59.4	13.05	35.1	11.08	26.1
Navigation Antenna	7.47	59.4	6.14	35.1	8.07	26.1

Table 5: Acceleration response of the main equipment in Scheme 3.

Name	X-direction	Y-direction	Z-direction			
	A/g	F/Hz	A/g	F/Hz	A/g	F/Hz
Laser	3.88	71.9	1.11	41.2	1.49	32.4
Solar Array	6.15	71.9	9.25	41.2	11.57	32.4
Navigation Antenna	4.93	71.9	4.6	41.2	6.43	32.4

Table 6: Acceleration response of the main equipment in Scheme 4.

Name	X-direction	Y-direction	Z-direction			
	A/g	F/Hz	A/g	F/Hz	A/g	F/Hz
Laser	4.1	62.4	1.32	37.5	1.76	27.7
Solar Array	5.91	62.4	11.53	37.5	10.93	27.7
Navigation Antenna	4.62	62.4	5.38	37.5	8.44	27.7

Sine vibration analysis results show that the acceleration response of the main equipment in Scheme 4 is the smallest compared to other options and Scheme 3 is the second, but the weight of the structure of Scheme 4 is increased by more than 9% compared to Scheme 3, so it is a better structural strengthening method compared to Scheme 3.

Random vibration analysis

The loads on satellites are not always deterministic and the instantaneous correspondence of random vibrations is unpredictable. Under random excitation, the RMS value reflects the magnitude of the vibration response [8]; the power spectral density reflects the statistical characteristics at each frequency component. Stochastic vibration is a wide frequency domain vibration, usually in the range of 20Hz to 2000Hz and it is assumed that the stochastic vibration of a structure is a linear, smooth and ergodic stochastic physical process.

According to the rocket conditions, random vibration analysis is carried out for four scenarios. The random vibration analysis is mainly concerned with the root mean square value of the equipment and the random vibration analysis results of three devices, namely, laser load, navigation antenna and solar wing, which are of more concern to the satellite, are taken for data comparison and the data are shown in the Table 7-10.

Table 7: RMS of the main equipment in Scheme 1.

Name	X-direction	Y-direction	Z-direction
	RMS/g	RMS/g	RMS/g
Laser	3.58	3.95	5.96
Solar Array	3.62	5.37	3.62
Navigation Antenna	3.42	3.38	4.8

Table 8: RMS of the main equipment in Scheme 2.

Name	X-direction	Y-direction	Z-direction
	RMS/g	RMS/g	RMS/g
Laser	2.34	4.07	5.89
Solar Array	2.72	2.83	2.17
Navigation Antenna	2.57	3.11	2.84

Table 9: RMS of the main equipment in Scheme 3.

Name	X-direction	Y-direction	Z-direction
	RMS/g	RMS/g	RMS/g
Laser	2.3	3.8	6.1
Solar Array	2.69	2.75	2.17
Navigation Antenna	2.51	2.95	2.85

By comparing the RMS values, it is found that the three main devices in Scheme 3 have the smallest RMS values and are the best for reducing the random vibration response of the structure.

Table 10: RMS of the main equipment in Scheme 4.

Name	X-direction	Y-direction	Z-direction
	RMS/g	RMS/g	RMS/g
Laser	2.2	3.74	5.91
Solar Array	2.6	3.04	2.28
Navigation Antenna	2.38	2.95	2.74

The honeycomb plate structure is more maturely used in the satellite structure [9-10], so the satellite will not be subjected to static test assessment, but only to vibration test assessment. The satellite laser equipment was selected as the assessment object and the characteristic level curves before and after the random vibration test at the installation point of the laser equipment were compared, as shown in Figure 8-10 and the curves matched well, indicating that the satellite structure was not changed after the vibration test, and the structural performance design met the requirements.

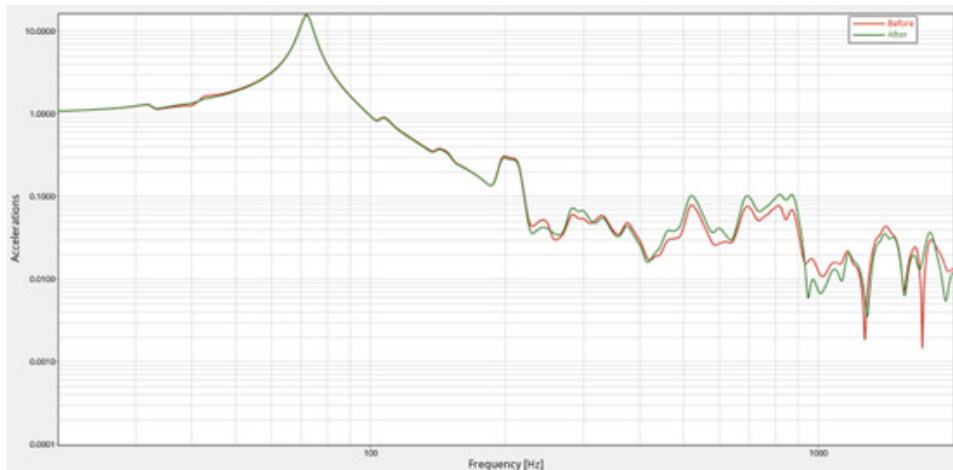


Figure 8: Characteristic grade curve before and after X-direction test.

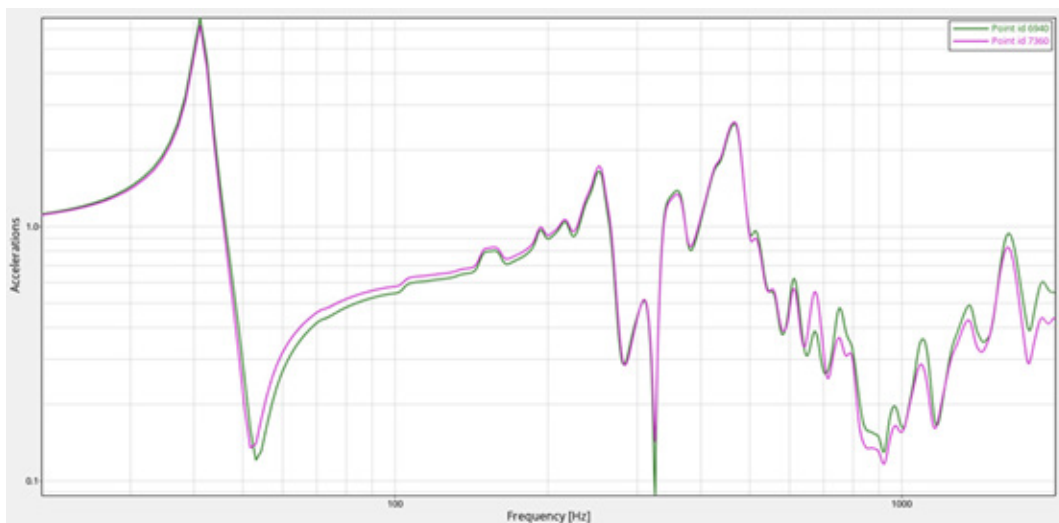


Figure 9: Characteristic grade curve before and after X-direction test.

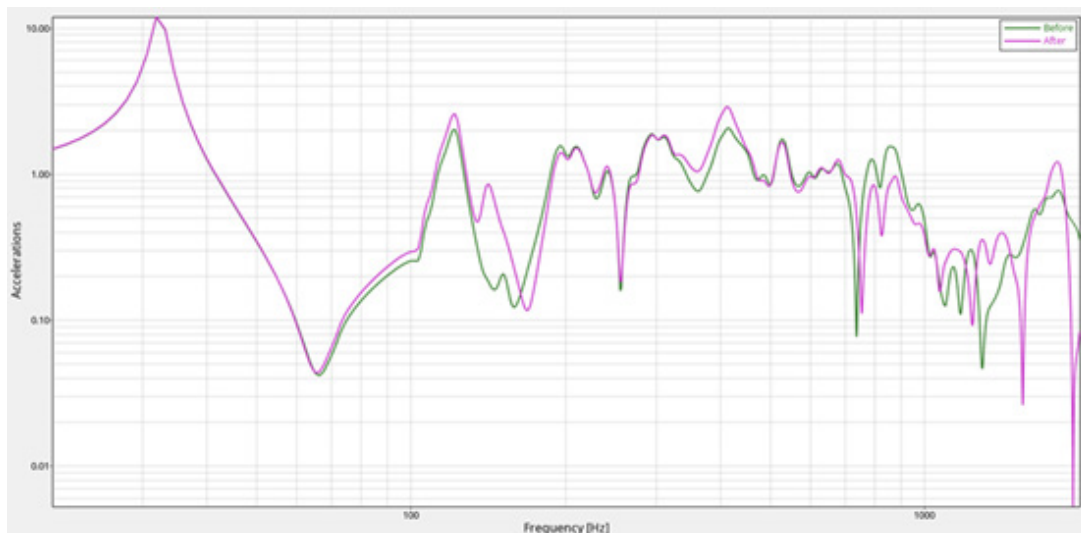


Figure 10: Characteristic grade curve before and after X-direction test.

Conclusion

A. By comparing the four structural optimization solutions, it is found that adding X-shaped beams on the star-arrow separation surface has a significant effect on enhancing the fundamental frequency of the satellite structure.

B. Adding X-beam to the separation surface of the star and arrow can significantly reduce the acceleration response of the satellite structure equipment installation position and at the same time, the RMS value of random vibration is also significantly reduced and this method is the preferred method for the optimization of the satellite structure.

C. Although the addition of X-beam is the optimal method when comparing the four options, it is still necessary to keep searching and verifying better methods to optimize the satellite structure.

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