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VIBRATION ANALYSIS AND OPTIMIZATION OF CARBON FIBER + ALUMINUM MAGNESIUM ALLOY SKIN STRUCTURE

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To solve the problem of embedded parts cracking in the middle of the crossbeam of packaging side skin plate of an infrared camera during random vibration test, a finite element model of internal aluminum honeycomb layer + outer skin + embedded parts support structure was constructed, and a random vibration response simulation test was adopted to simulate the actual vibration condition of the product. The results show that the maximum stress at the beam of honeycomb core under vibration excitation is 1.14mp; through the combination design of+y side skin plate and+ Z direction thin skin structure, and the three sides of + y side skin plate are optimized with T800 carbon fiber reinforced rib, and the maximum stress response of random vibration in Y direction is less than the allowable strength of material. The structural design optimization combined with random vibration test and simulation analysis provides an effective method for product defect and failure detection, and an effective solution for structural optimization design.

Keywords: Random vibration; skin structure; stress nephogram; structural optimization; packaging and transportation

1. Introduction

In the process of transportation and use, the fixed support structure of the equipment outer packaging is often excited by various external vibrations, resulting in vibration fracture and damage of the packaging structure, and ultimately equipment damage. The statistical results show 27% possibility of vibration damage during packaging and transportation [1]. Therefore, it is very necessary to analyze the vibration characteristics of the outer packaging structure of the protective equipment.

Scholars at home and abroad have done a lot of research on the random vibration damage of product packaging in transportation and use. In terms of vibration research during transportation, Li Xiaogang [2] et al. studied the vibration characteristics of the packaging structure system caused by road conditions, and obtained the vibration law model of packaging parts under the circulation environment. Zhou [3] et al. proposed a method for simulating three high-speed road

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conditions and obtained vehicle vibration characteristics. In terms of packaging structure vibration, Sun Yucheng [4] et al. made finite element simulation analysis on damage failure of corrugated cardboard under random vibration excitation, and mastered the effect of humidity environment on the mechanical properties of corrugated cardboard. Fan Zhigeng [5] et al. studied and analyzed the vibration damage characteristics of honeycomb cardboard, and found the parameter change law of honeycomb cardboard under internal resonance. The above literatures mainly study the vibration characteristics of each product by simulation. In this paper, during the Y-direction vibration test on the initial identification sample of a certain infrared camera packaging fixed support structure, a 1/4 order of depression was carried out under the identification random test 100-120Hz, a1/4 order of depression was carried out under 425 -455Hz [6](The two frequencies of 100-120hz and 425-455hz are the resonance frequency of the equipment. In order not to damage the equipment, the undercut of 1 / 4 order is carried out during the test). After the appraisal level random vibration test, the product was inspected on site, finding that the embedded part cracked in the middle of the camera package + Y side skin plate crossbeam, as shown in Fig. 1. To find the reason for the vibration cracking, considering the actual working conditions of the equipment, a random vibration simulation model of the skin plate crossbeam support structure was established based on the finite element model of the inner aluminum honeycomb layer + external skin + embedded part support structure to master the vibration characteristics of the structure, find out the reasons for the structural damage, and provide a reasonable plan for the design and improvement of the packaging support structure.

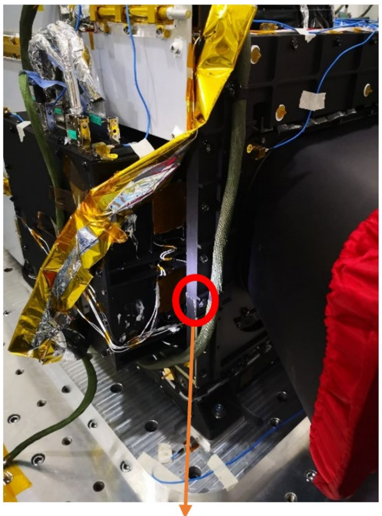
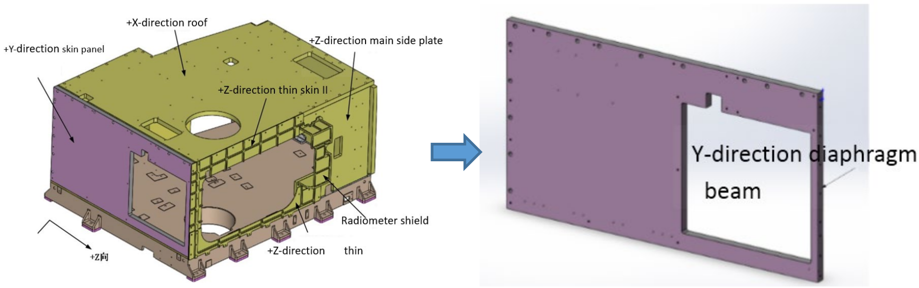


Fig.1 Cracking parts of packing and fixing crossbeam structure

2. Analysis of packaging skin support structure

2.1 Analysis of the original structure

The structural part with cracks is the +Y side skin plate in the camera packaging skin assembly. Its composition in the camera packaging skin assembly is shown in the figure below. Install two pieces of +Z-direction skin plate at the front end of the +Y side skin plate crossbeam, namely +Z-direction thin skin and +Z-direction thin skin II. Both +Z-direction thin skin and +Z-direction thin skin II are processed by magnesium alloy, and structural design drawing of the camera packaging skin parts is shown in Fig. 2(a) below. The fracture position is located at the skin plate crossbeam, as shown in Fig. 2(b) below. The crossbeam section size is 20×17mm, the honeycomb plate thickness is 20mm, the honeycomb core specification is 4×0.04mm, and the inner and outer plates are both carbon fiber M55J plates with a thickness of 0.3mm.



(a) Structural design of skin parts (b) Crossbeam of skin plates

Fig.2 Structure of camera packaging main skin and +y side skin plate

The load-bearing condition of the camera package +Y side skin plate is shown in Fig. 3 below. Install the cooling plate of the camera package refrigerator on the left side of the +Y side skin plate, which weighs about 2.3KG. Install the visible light cooling plate on the upper right side of the +Y side skin plate, which weighs about 0.3Kg. The visible light cooling plate is simultaneously installed on the top skin plate with auxiliary support. It can be seen from the load-bearing condition that the camera packaging + Y-side skin plate is a non-load-bearing structure, and the beam structure is to maintain integrity of the overall skin part structure. At the same time, the structure is sealed.

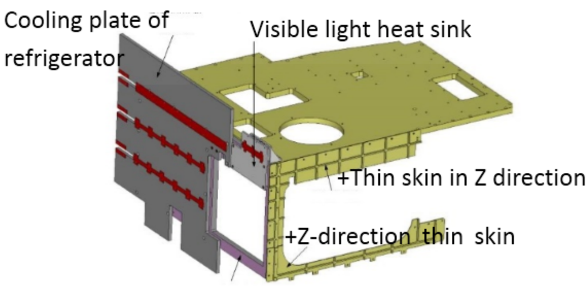


Fig.3 Load bearing diagram of+Y side skin plate

Analysis of the above design process data reveals the following problems:

1) The camera packaging + Y side skin plate is a non-load-bearing structure, but the honeycomb plate crossbeam has a small cross-sectional area of 20×17mm. At the same time, the crossbeam has a honeycomb core coupled with a carbon fiber plate structure, and no frame strengthening process is performed. As a result, there are weak links in the honeycomb plate crossbeams.

2) Two skins are installed on the front face of the +Y side skin plate crossbeam, which are the +Z-direction thin skin and the +Z-direction thin skin II, respectively. There is a certain stress concentration on the skin interface. During the test in the Y direction, the beam was bent, resulting in a fracture.

2.2 Structural improvement design

Based on analysis of the original structure, two structural improvements are adopted:

1) Reinforce the +Y side skin plate crossbeam, the outer three sides are reinforced with T800 carbon fiber frame, and J133 epoxy glue is used for bonding. T300 carbon cloth is laid on the inner plane for reinforcement, and J133 epoxy glue is used for bonding. The carbon cloth has 3 layers, and the total thickness of one side does not exceed 1mm. The schematic diagram about the reinforcement of the outer three sides of the Y-side skin plate crossbeam is shown in Fig. 4 below.

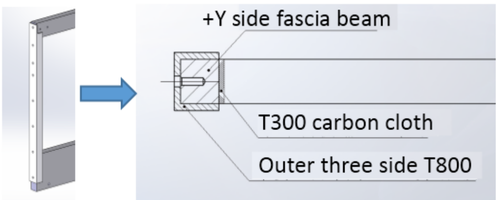


Fig.4 Cross section of Y side skin plate beam reinforcement

2) Install the camera package on the front face of the +Y side skin plate +Z-direction thin skin and +Z-direction thin skin. The two structural parts are combined and designed to form a structural part, which is installed on the front face of the +Y side skin plate to increase the rib design, as shown in Fig. 5.

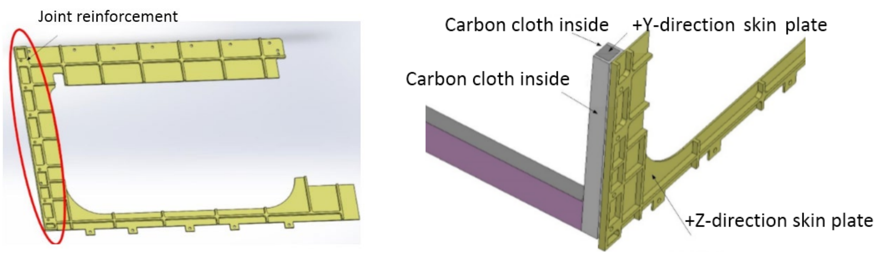


Fig.5 Structure of skin plate in + Y direction after improvement

3. Reconstruction of packaging skin support model

Based on the above analysis and improvement, finite element model is reconstructed for the adjusted structure. The modeling method of the adjusted five honeycomb skin plate is as follows: the external carbon fiber skin, the internal honeycomb aluminum and magnesium alloy embedded parts are subject to finite element modeling. The main idea of the finite element method is to convert the continuous structural solution engineering problem with countless degrees of freedom characteristics contained in the research object into limited grid cell with limited number, reduced degrees of freedom after discretization according to a certain meshing method. There are mainly 6 meshing methods commonly used in finite element, including three kinds of tetrahedrons and three kinds of hexahedrons, which are 4 points, 10 points and mixed tetrahedrons [7][8]; 8 points, 12 points and mixed hexahedron. The commonly used meshing software on the market mainly adopts secondary mesh. In the actual modeling process, the tetrahedral mesh exhibits outstanding advantages in terms of modeling speed and computational efficiency. In addition, 4-point tetrahedral mesh shows more advantages in mesh force analysis. Hence, in view of characteristics of the skin support structure, this paper uses a 4-point tetrahedron in construction of the structural finite element.

Based on the above analysis, the outer carbon fiber skin in this paper adopts isotropic carbon fiber material [9], shell unit [10] for modeling. According to the mechanical properties of the internal honeycomb aluminum, orthotropic method is adopted for modeling based on solid tetrahedral element. For the magnesium alloy embedded parts, the isotropic solid tetrahedral element is used for modeling, as shown in Fig. 6.

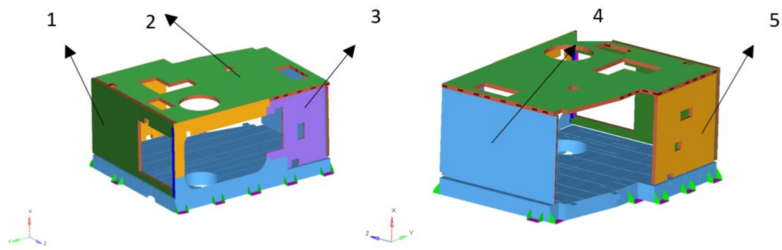


Fig.6 Reconstruction of finite element model of five skin plates

To describe the structure clearly, honeycomb skin plate 1 is taken as an example. The structure adopts internal aluminum honeycomb layer + external skin + embedded parts to construct a finite element model, as shown in Fig. 7. Due to space limitations, the remaining 4 honeycomb skins are designed in the same way without further elaboration.

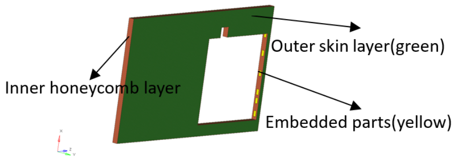
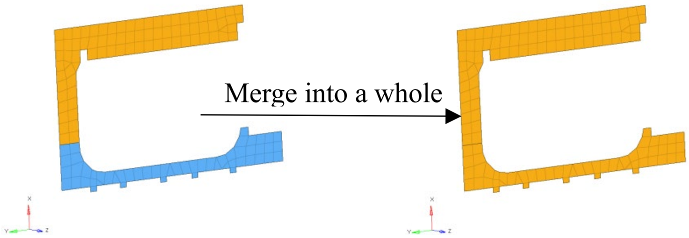


Fig.7 Structure of honeycomb skin plate

Two structural parts of +Z direction skins are integrated for reconstruction of the finite element model, as shown in Fig. 8 below.



(a) Before the integration (b) After the integration

Fig.8 +Z skin remodeling scheme

4. Vibration test analysis

4.1 Solution method for random vibration response

Under the action of external dynamic load, the structural parts will vibrate, and the product structure will be damaged due to vibration-induced resonance or over-stress damage. In the random fatigue design of the skin support structure in this paper, the first step is to learn the dynamic structural vibration characteristics of the skin structure, that is, to determine the value of the structural modal vibration parameters. The modal vibration parameters are the eigenvalues and eigenvectors of the motion differential equations of the mechanical system, which are generally derived from vibration equation of multi-degree-of-freedom linear system [11]. Next, import the structural models of the skin into the finite element analysis software to complete the meshing, add vibration parameters to obtain the stress function and stress power spectrum density of each structural element of the structure under random vibration excitation. After the stress power spectrum of each structural grid element is obtained, the structural strength life analysis is made based on fatigue damage theory and stress limit analysis of anti-fatigue design. The main calculation and analysis process are as follows:

First, use the finite element method to input random vibration excitation to the structure, obtain the displacement response stress power spectrum density. Designate the coordinate displacement matrix of any point (x, y, z) of the structural unit under the user-defined coordinates as [12] [13]:

$$Q^e = \begin{bmatrix} I(x,y,z,t) \\ J(x,y,z,t) \\ K(x,y,z,t) \end{bmatrix} = nq^e(t) \tag{1}$$

Where: I (x, y, z, t), J (x, y, z, t) and K (x, y, z, t) respectively indicate displacement vector of any unit grid point in the three coordinate axis directions. n represents the grid cell shape function matrix, $q^e(t)$represents the displacement vector of each element node in the user coordinate system. Therefore, the strain can be expressed as:

$$\varepsilon(t) = Aq^e(t) \tag{2}$$

Where: A is the strain conversion matrix. Therefore, the mathematical relationship between stress and strain can be expressed as:

$$\sigma(t) = H\,\varepsilon(t) = HAq^e(t) \tag{3}$$

Where: H is the elastic modulus matrix of the structural material.

Let $q_S^e\ (t)$be the element node displacement vector in the global structure coordinate system, $F_S^e\ (t)$ be the element node force in the global structure coordinate system, and B is the strain matrix, then the relationship between the element coordinate system and the global coordinate system is defined as:

$$\begin{bmatrix} q^e\ (t) \\ F^e(t) \\ K_S^e \\ M_S^e \\ C_S^e \end{bmatrix} = [B \quad B \quad B^T \quad B^T] \begin{bmatrix} q_S^e\ (t) \\ F_S^e\ (t) \\ K^e \\ M^e \\ C^e \end{bmatrix} [E \quad E \quad B \quad B] \tag{4}$$

Where: E is the identity matrix; K^e,M^e and $C^e$are local stiffness, mass and damping matrix in the structural element coordinate system, respectively; K_S^e,M_S^e and C_S^e respectively represent the element stiffness, mass and damping matrix in the global coordinate system of the structure. In this way, the vibration formula (1) of the degree of freedom linear system can be rewritten as element vibration equation in the global coordinate system:

$$M_S^e \ddot{q}_S^e(t) + C_S^e \dot{q}_S^t(t) + K_S^e q_S^e(t) = F_S^e(t) \tag{5}$$

By formula (4), the correlation of stress spectrum density under random vibration excitation at any point in the structural unit can be transformed into:

$$R_\sigma(\tau) = E[\sigma(t)\sigma^T(t+\tau)] = \mathrm{HB}R[R_{q\varepsilon}(\tau)]\, R^T B^T H^T \tag{6}$$

Where R is the coordinate transformation matrix; Therefore, the stress power spectrum density matrix at any point of the global structural unit is obtained as:

$$\square \mathrm{G}_\sigma(\omega) = HBR[\mathrm{G}_{q_s}(\omega)]R^T B^T H^T \tag{7}$$

Therefore, the frequency response function matrix can be obtained by performing Fourier transform on the vibration equation of any multi-degree-of-freedom linear system as shown in formula (5), and then the power spectrum density matrix function of the global structural stress response can be obtained as shown in formula (7). The random excitation load stress matrix method or the element node displacement excitation finite element method [14] can be used to calculate the response stress power spectrum density through the stress response displacement power spectrum density. Finally, the maximum stress limit of each node can be obtained.

4.2 Vibration test condition

Compared with harmonic vibration, random vibration has worse working condition. Random vibration is a kind of forced vibration under statistics, which reflects the probability statistics of the structure's response to random dynamic load. The response is expressed by the mean square value of stress.

According to the working environment of the camera packaging skin support structure, the working condition parameters of the system are set as shown in Tab. 1 below.

Tab.1

Random vibration test conditions

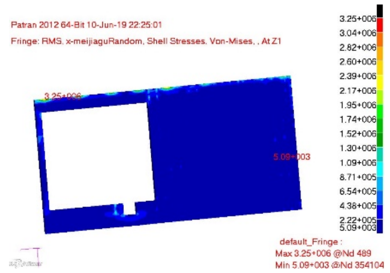
<table>
<tr><th>No.</th><th>Frequency Range (Hz)</th><th>Power Spectrum Density</th><th>Total Root Mean Square Acceleration</th><th>Test Direction</th><th>Test Time</th></tr>
<tr><td>1</td><td>10～65</td><td>+6dB/oct</td><td rowspan="5">10Grms</td><td rowspan="5">X, Y, Z Triaxial direction</td><td rowspan="5">2min/axial direction</td></tr>
<tr><td>2</td><td>65～100</td><td>$0.8g^2/Hz$</td></tr>
<tr><td>3</td><td>100～200</td><td>$0.8\sim0.08g^2/Hz$</td></tr>
<tr><td>4</td><td>200～450</td><td>$0.08g^2/Hz$</td></tr>
<tr><td>5</td><td>450～2000</td><td>-18dB/oct</td></tr>
</table>

Import the random vibration condition parameters into the finite element model to obtain the natural frequency and mode shape parameters through the finite element modal analysis [15]. Import the random vibration analysis module to complete the random vibration analysis: this process mainly includes two parts: the first part is the data pre-processing stage, in which, random vibration module is loaded on the structure basis of the finite element grid model, and random vibration analysis module is directly established through the module data sharing; the second part is the random vibration parameter setting: according to the power spectrum density function model given above, load the random vibration module, and import vibration characteristic parameters. The vibration analysis in this paper mainly targets at the Y direction, and the stress nephogram can be obtained by iterative calculation.

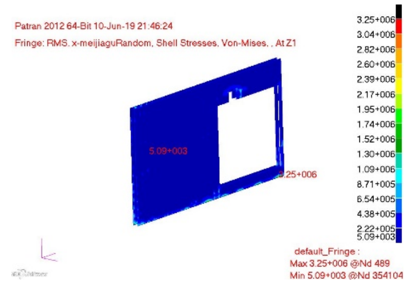
4.3 Modified stress analysis

Before the structural improvement, install two +Z-direction skin plates at the front end of the +Y-side skin plate crossbeam, namely +Z-direction thin skin and +Z-direction thin skin II. Both +Z-direction thin skin and +Z-direction thin skin II are processed by magnesium alloy, and the finite element random vibration response analysis method analyzed in this paper is used to obtain the stress response nephograms of the skin crossbeam, honeycomb skin, magnesium alloy embedded parts and honeycomb core, as shown in Fig. 9 below.

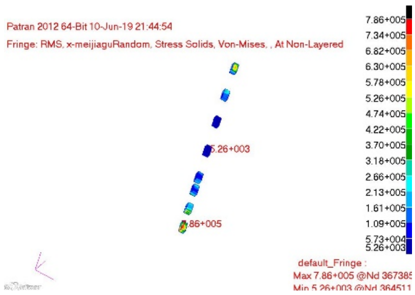
1) Vibration analysis before improvement



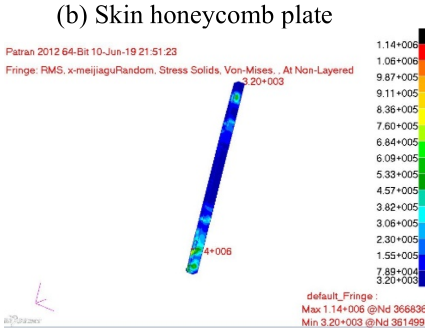
(a) Skin crossbeam



(b) Skin honeycomb plate



(c) Magnesium alloy parts



(d) Honeycomb core

Fig.9 Vibration stress response of skin structure (before adjustment)

Analyze stress of the skin structure vibration to obtain the maximum stress response of each structure as shown in Tab. 2.

Tab.2

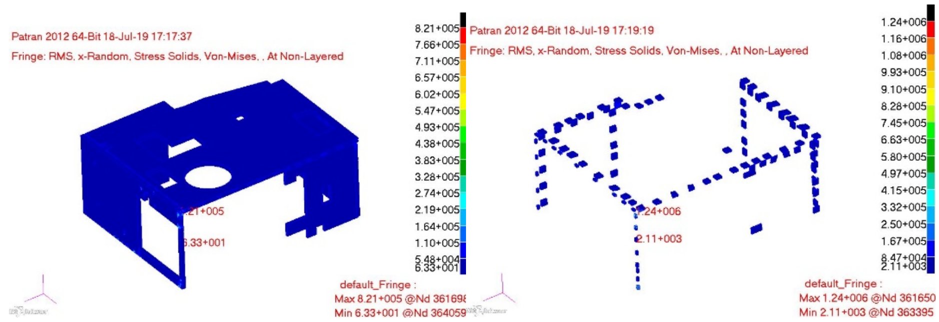
Random vibration stress response in Y direction

Maximum stress of each part in Y direction (MPa)					
Main Structure	bottom plate	Honeycomb plate skin layer	Magnesium alloy embedded parts	Honeycomb core crossbeam	Skin crossbeam
Maximum stress	28.1	3.25	0.786	1.14	3.25
Allowable stress	148	148	80	1	/

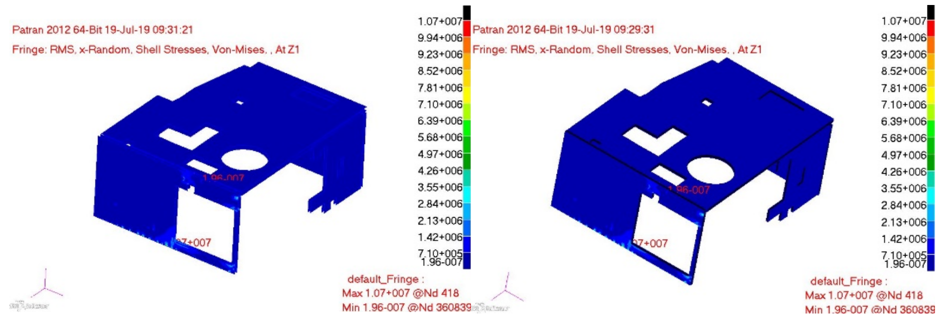
It can be seen from Fig. 9 and Tab. 2 that the stress response limits of the honeycomb plate skin, bottom plate and magnesium aluminum alloy do not exceed the allowable stress value, thus meeting the design requirements, but the stress at the honeycomb core crossbeam is 1.14 MPa, which exceeds the allowable stress 1 MPa of aluminum honeycomb and will easily cause skin plate damage.

2) Stress analysis after improvement

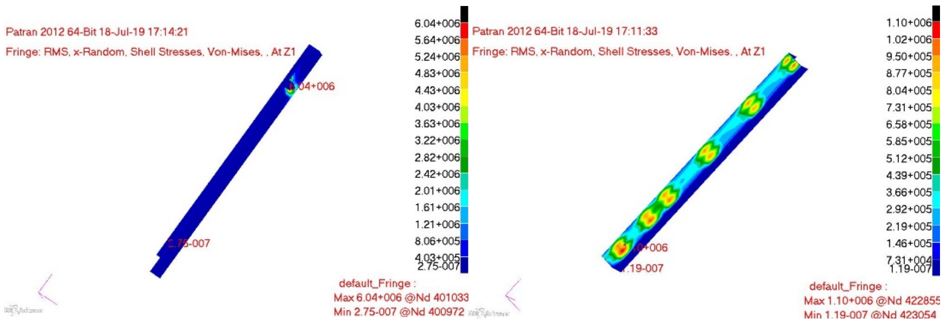
According to the previous structural model analysis and modal vibration test, the weak part of the honeycomb core crossbeam is redesigned, the +Y side skin plate crossbeam is reinforced, and the outer three sides are reinforced with T800 carbon fiber frames and bonded with epoxy glue. T300 carbon cloth is laid on the inner plate for reinforcement; the camera package is installed on the +Y side skin plate front face and +Z direction thin skin II structural parts for integrated overall design. Reinforcing rib design is added at the installation location at the front face of the +Y side skin plate. Therefore, by further stress response analysis on the improved structure, the main structural stress nephogram is obtained as shown in Fig. 10.



(a) Magnesium alloy embedded parts (b) honeycomb plate



(c) aluminum honeycomb plate (d) Five honeycomb plates



(e) T800 carbon fiber frame (f) T300 carbon fiber cloth

Fig.10 Vibration response of skin structure (after adjustment)

Table 3

Random vibration stress response in Y direction

Maximum stress of each part in Y direction (MPa)						
Main structure	T300 carbon fiber cloth	T800 carbon fiber frame	Magnesium alloy embedded parts	inner honeycomb layer of honeycomb plate	Five honeycomb plates	skin layer of aluminum honeycomb plate
Maximum stress	0.2	3.7	0.43	0.31	6.29	6.29
Allowable stress	111	148	80	1	/	148

It can be seen from Fig. 10 and Table 3 that the maximum stress response of magnesium alloy embedded parts, five honeycomb plates, inner honeycomb layer of honeycomb plate, skin layer of aluminum honeycomb plate, T800 carbon fiber frame and fabric random vibration is far less than the allowable stress strength.

5. Conclusion

In this paper, the infrared camera packaging supporting skin crossbeam used in the Y-direction random vibration experiment cracked. The Y-direction random vibration simulation of the skin structure before adjustment shows that, the skin plate crossbeam in the positive Y direction is relatively weak and prone to cracking. Further finite element modal analysis of the overall skin support structure found that the relatively slender crossbeam and the embedded parts caused discontinuous honeycomb at the crossbeam, which finally led to weak structural strength of the crossbeam. To verify rationality of the positive Y-direction skin crossbeam reinforcement scheme, the finite element model was further adjusted in view of the experimental results, and the optimized structure met the design requirements.

(1) The positive Y-direction skin crossbeam of the model before adjustment is in danger of cracking in both Y and Z directions;

(2) The simulation results verify the rationality and effectiveness in reinforcement of the positive Y-direction skin. The calculation results show that the reinforced skin crossbeam is safe;

(3) Through the organic combination of vibration modal test and finite element analysis, strong support is provided for structural defect search and structural improvement, making efficiency of structural optimization design increased.

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