Optimal Design of Satellite Antenna Based on Sandwich Structure with a Novel Re-entrant Honeycomb Considering Thermal Load

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Abstract. In order to optimize the thermal deformation of satellite antenna, a new type of negative thermal expansion metamaterial with the re-entrant honeycomb for sandwich structure was designed and optimized. Coefficient of thermal expansion (CTE), Poisson's ratio and Young's modulus of the metamaterial were calculated by finite element method (FEM). After sensitivity analysis, five parameters of the metamaterial were optimized by response surface method (RSM) and multi-island genetic algorithm (MIGA). It is found that the satellite antenna with the optimized re-entrant honeycomb shows better mechanical properties and its thermal deformation is reduced effectively.

1. Introduction

As one of the important equipment of modern communication, astronomical science and radar research, satellite antenna has been widely used. Its research level is directly related to a country's national defense, military, aerospace and aviation capabilities [1]. The traditional satellite antenna is shown in figure 1, which consists of upper and lower composite skin and hexagonal honeycomb core [2], as shown in figure 2. The main advantage of paraboloid satellite antenna is its high directivity, which can converge radio waves in one direction or receive radio waves from a certain direction. Due to temperature variation, radiation and other factors in the space, the paraboloid reflector often deforms greatly, so it cannot meet the accuracy required. With the deepening of research and application, the demands of accuracy, sensitivity and gain are higher and higher. The satellite antenna working in space will be affected by the high temperature of 400K and the low temperature of 5K [3]. The huge difference in temperature will lead to serious geometric deformation of the reflector, thus affecting the signal reception and transmission [4].
Nowadays, there is a method to control the thermal deformation of satellite antenna by optimizing the honeycomb core. Conventionally, the honeycomb core is generally hexagonal aluminum honeycomb, which is characterized by light weight, simple structure and mature manufacturing process [5]. Usually, the Poisson's ratio and CTE of hexagonal honeycomb cell structure are positive. With the in-depth research of researchers, people gradually pay attention to the advantages of negative Poisson's ratio structure and regulable thermal expansion (RTE) structure. Negative Poisson's ratio structure has special mechanical properties. Compared with traditional materials, negative Poisson's ratio structure is superior in shear resistance, fracture resistance and energy absorption [6]. At the same time, RTE structure can also play a great role in the thermal deformation control of satellite antenna [7]. With the development of 3D printing technology, it is possible to focus these two properties on a metamaterial structure.

Based on the re-entrant honeycomb, we proposed a novel metamaterial which can achieve negative thermal expansion and negative Poisson's ratio simultaneously. In order to make the metamaterial have the best properties, the parameters of the honeycomb cell were simulated and optimized by FEM. And in the rest of the manuscript, this metamaterial will be applied to the satellite antenna, which effectively reduces the thermal deformation of the satellite reflector and improves the accuracy of the reflector.

2. A metamaterial with RTE and negative Poisson's ratio
The satellite antenna whose honeycomb core is replaced with a metamaterial is shown in figure 3. The metamaterial is shown in figure 4, two bi-material ribs are added on every inclined panel of the re-entrant honeycomb, and the bending direction of the two ribs is opposite. The honeycomb is made of material 1 (represented by the blue) and the upper tier of bi-material ribs are made of material 2 (represented by the red), and there is no gap between the two materials.
Due to CTEs of the two materials are different, the thermal deformation of the inclined panels can be mitigated. The CTE of this metamaterial can be regulated by changing the thickness of the two materials, the length of ribs and the inclination of the inclined panel. When the CTE of material 2 is greater than that of material 1, a metamaterial with negative CTE is constructed. As shown in figure 4(b), the length of panel AB is $2L$, and the length of AD is $H$. The horizontal inclination of panel AB is $\phi$. The straight-line distance between the two ends of the bi-material ribs is $l$, and the included angle is $\theta$. The thickness of material 1 is $t_1$, and the other is $t_2$.

3. FEM simulation and optimization of the metamaterial

3.1. FEM simulation for mechanical properties

The CTE, Young's modulus and Poisson's ratio of the metamaterial were calculated by FEM. The model shown in figure 5(a) is used for thermal expansion analysis, and the model shown in figure 5(b) is used for force analysis.

Table 1. Value of geometric parameters.

| Parameter | $L$(mm) | $l$(mm) | $H$(mm) | $t_1$(mm) | $t_2$(mm) | $\phi$ | $\theta$ |
|-----------|---------|---------|---------|-----------|-----------|--------|--------|
| Value     | 7       | 3.5     | 16      | 0.5       | 0.5       | $5\pi/36$ | $\pi/3$ |
The deformations of cells under temperature load and force load are shown in the figure 6, and figure 6(c) and (d) are displacement cloud diagrams of cells without material 2. It can be found in figure 6(a) and (b) that the structure shrinks inward when heated and expands up and down when in tension, which means the metamaterial has negative CTE and negative Poisson's ratio. In figure 6(c) and (d), the structure expands outward when heated and expands in the same trend as in figure 6(b) when in tension, so the additional material 2 has an effective influence on CTE but little influence on Poisson's ratio.

![Figure 6](image_url)

**Figure 6.** The deformation of cells: (a) Under temperature load, (b) Under force load, (c) Under temperature load without material 2, (d) Under force load without material 2.

By obtaining the relative displacement of the corresponding nodes between cells, CTE, Young's modulus and Poisson's ratio can be calculated by equations (1), (2), (3) and (4).

\[
\varepsilon_x = \frac{u_2 - u_1}{x_2 - x_1}, \varepsilon_y = \frac{v_2 - v_1}{y_2 - y_1}
\]

\[
\alpha_x = \frac{\varepsilon_x}{\Delta T}, \alpha_y = \frac{\varepsilon_y}{\Delta T}
\]

\[
E_x = \frac{\sigma_x}{\varepsilon_x}
\]

\[
v_{xy} = -\frac{\varepsilon_y}{\varepsilon_x}
\]

Where \( u \) is the X-direction displacement of the node, and \( v \) is the Y-direction displacement of the node. And \( x, y \) is the position of the node before displacement. Then the calculated mechanical properties are shown in the table 2. The \( \alpha_x, \alpha_y \) and \( v_{xy} \) are less than zero, which are the same as the conclusions found from the cloud diagrams.

**Table 2.** Mechanical properties of the metamaterial.

| Mechanical property | Value  |
|---------------------|--------|
| \( \alpha_x/(K) \)  | -1.45e-5 |
| \( \alpha_y/(K) \)  | -4.07e-5 |
| \( E_x/(Pa) \)      | 4.94e7  |
| \( v_{xy} \)        | -2.993  |
3.2. Pretreatment of optimization

Before optimizing parameters of the metamaterial, it is necessary to do some optimization pretreatments, mainly about design of experiment (DOE) and sensitivity analysis.

There are seven parameters of the metamaterial, and the value ranges of them are shown in table 3. Latin Hypercube Sampling (LHS) was used to conduct DOE. When sampling, add a restriction that \( C = H/2 - 2L\sin\varphi > 0 \) to ensure that the model will not interfere. Through DOE, we analyzed the sensitivity of parameters to mechanical properties including \( \alpha_x, \alpha_y, E_X, E_Y \) and relative density \( \rho_r \), shown in figure 7.

**Table 3. Value ranges of DOE parameters.**

| Parameter | L(mm) | l(mm) | H(mm) | \( t_1 \)(mm) | \( t_2 \)(mm) | \( \varphi \) | \( \theta \) |
|-----------|-------|-------|-------|--------------|--------------|-----------|---------|
| Min       | 6     | 3     | 14    | 0.5          | 0.5          | \( \pi/9 \) | \( 5\pi/18 \) |
| Max       | 8     | 4     | 18    | 1            | 1            | \( \pi/6 \) | \( 7\pi/18 \) |

![Figure 7. Sensitivity of parameters: (a) To \( \alpha_x \), (b) To \( \alpha_y \), (c) To \( E_X \), (d) To \( E_Y \), (e) To \( \rho_r \).](image)

The blue indicates positive correlation and the red indicates negative correlation. The contribution of \( t_1 \) is always the largest to the five mechanical properties, which means \( t_1 \) has the greatest impact on these properties. Through comparison, we selected five parameters \( t_1, L, l, H \) and \( \varphi \) to do the following optimization design. The influence of \( t_2 \) and \( \theta \) is relatively small, so they are omitted to economize computational cost.

3.3. Optimization process

Before the optimization, we used the response surface method (RSM) to establish an approximate model based. Approximation model method is a process which establishes the relationship between input parameters and output parameters through mathematical model to replace the internal complex relationship on the premise of ensuring accuracy [8]. Through verification, the fitting coefficients (R-Squared) of the approximation model are greater than 0.98, indicating that the model has good reliability. Based on the approximate model, we optimized the parameters of the metamaterial. The optimization mathematical expression is shown in equation (5). The objective of optimization is to make CTE of the metamaterial tend to zero and the Young’s modulus as large as possible while ensuring lightweight. The value ranges of parameters that can be optimized are shown in table 4.
\[
\begin{cases}
\min: |\alpha_x|, |\alpha_y|, -E_x, -E_y, \rho_r \\
\text{find}: L, l, H, t_1, \varphi \\
S.T. \frac{H}{2} - 2L \sin \varphi > 0 \\
\Delta_{\text{min}} \leq t_1, H, l, \varphi \leq \Delta_{\text{max}}
\end{cases}
\] (5)

Table 4. Value ranges of optimized parameters.

| Parameter | \(L\) (mm) | \(l\) (mm) | \(H\) (mm) | \(t_1\) (mm) | \(\varphi\) |
|-----------|-------------|-------------|-------------|-------------|-------------|
| Min       | 6           | 3           | 14          | 0.5         | \(\pi/9\)   |
| Max       | 8           | 4           | 18          | 1           | \(\pi/6\)   |

The optimization method is multi-island genetic algorithm (MIGA), which searches many designs and multiple locations of the design space. After iterative calculation, the optimized parameters are obtained and shown in table 5 and the optimization results are shown in table 6. It can be found that CTE and Young's modulus are improved on the premise of reducing the relative density by 15.01%. The improvement here means that CTE is closer to zero and the Young's modulus increases.

Table 5. Value of optimized parameters.

| Parameter | \(L\) (mm) | \(l\) (mm) | \(H\) (mm) | \(t_1\) (mm) | \(\varphi\) |
|-----------|-------------|-------------|-------------|-------------|-------------|
| Value     | 6.91        | 3.17        | 17.63       | 0.56        | \(\pi/9\)   |

Table 6. Optimization results of properties.

|               | \(\alpha_x\) (K) | \(\alpha_y\) (K) | \(E_x\) (Pa) | \(E_y\) (Pa) | \(\rho_r\) |
|---------------|------------------|------------------|-------------|-------------|-------------|
| Initial       | -1.45e-5         | -4.07e-5         | 4.94e7      | 6.95e6      | 0.102926    |
| Optimal       | -6.86e-6         | -2.52e-5         | 7.97e7      | 1.07e7      | 0.087472    |
| Improve (%)   | 52.69            | 38.08            | 61.34       | 53.96       | 15.01       |

4. Optimization design of satellite

The reflector of the satellite is a paraboloid, which is formed by rotating the parabola equation (6) around the Z axis. A reflector paraboloid model was established, in which the core is aluminum hexagonal honeycomb cells, as shown in figure 8 (The upper surface is transparent). The upper and lower surfaces of the reflector are carbon fiber composites. In order to reduce the calculation cost, only half of the satellite reflector is used for calculation and the condition of symmetry is added. As shown in the figure 9, regularly arranged red dots are probes in order to calculate root mean square (RMS) of thermal deformation by equation (7).

\[
\begin{align*}
\begin{cases}
 x = 0 \\
y = 200 \cdot t \\
z = 40 \cdot t^2
\end{cases}
\end{align*}
\] (6)

\[
RMS_{x,y,z} = \sqrt{\frac{\sum_{i=1}^{N} \varepsilon_i^2}{N}} = \sqrt{\frac{\sum_{i=1}^{N} (\varepsilon_t - \varepsilon_e)^2}{N}}
\] (7)

Where \(N\) is the sum of probes on the reflecting surface, and \(l\) is the number of probes. \(\varepsilon_i\) is the deformation value of probes. \(\varepsilon_t\) and \(\varepsilon_e\) are the positions before and after deformation respectively.
A temperature load of 400K is applied to the upper surface, and the obtained cloud diagram of thermal deformation is shown in figure 10. The core layer of the reflector shown in figure 10(a) is a traditional hexagonal honeycomb, and that shown in figure 10(b) is the optimized re-entrant honeycomb. For fair comparison, the hexagonal honeycomb cell and the re-entrant honeycomb cell can be circumscribed by circles with the same radius. The maximum deformation of the reflector with the traditional hexagonal honeycomb is 0.0251mm, and that with the optimized re-entrant honeycomb is 0.0172mm, which reduced by 31.47%. The RMS of thermal deformation are shown in table 7. The thermal deformation values in Z direction and the total are effectively reduced. The increase in $RMS_x$ and $RMS_y$ means the form of thermal deformation is changed.

![Figure 8. Reflector paraboloid model.](image1)

![Figure 9. Positions of the probes.](image2)

![Figure 10. Cloud diagram of thermal deformation: (a) With traditional hexagonal honeycomb, (b) With optimized re-entrant honeycomb.](image3)

|         | RMS_x  | RMS_y  | RMS_z  | RMS_total |
|---------|--------|--------|--------|-----------|
| Hexagonal honeycomb | 0.0029880 | 0.0029791 | 0.0164441 | 0.0169767 |
| Re-entrant honeycomb | 0.005004 | 0.005771 | 0.006873 | 0.010275 |
| Improve (%) | -67.47 | -93.72 | 58.20 | 39.48 |

5. Conclusion
In this paper, a novel re-entrant honeycomb metamaterial with negative thermal expansion effect is designed. Through the calculation of CTE, Young’s modulus and Poisson’s ratio by FEM, it is proved that the metamaterial has negative CTE and negative Poisson's ratio. CTE and Young's modulus can be effectively improved by optimization. It is an effective method to apply the optimized metamaterial to the honeycomb core of the satellite reflector. The maximum deformation of the reflector was reduced by 31.47% and the RMS of the total thermal deformation is reduced by 39.48%.

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References
[1] Zhang C H 2004 Study of large double reflected antenna surface *Fiber Reinforced Plastics/


Composites (01) 38-9

[2] Wang X H 2006 Development status and trend of microsatellite technology Digital Communication World (06) 44-6

[3] Ma W C, Zhu M B, Ye H Y and Lian P Y 2014 Method for predicting extreme temperature conditions of satellite control antennas with solar heating Chinese Space Science and Technology 34(04) 59-65

[4] A Florio F. and T Josloff A. 1968 Thermo/structural analysis of a large flexible paraboloid antenna Journal of Spacecraft and Rockets 5(12) 1417-24

[5] Liu Y H and Du P 2013 Research process of metal honeycomb sandwich boards Machine Building & Automation 42(01) 9-11+15

[6] Evans Ken 1990 Tailoring the negative Poisson ratio Chemistry and Industry 654-7

[7] Ren X, Zhang X Y and Xie Y M 2019 Research progress in auxetic materials and structures Chinese Journal of Theoretical and Applied Mechanics 51(03) 656-87

[8] Mu X F, Yao W X, Yu X Q, Liu K L and Xue F 2005 A survey of surrogate models used in MDO Chinese Journal of Computational Mechanics (05) 608-12