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Research on Optimal Design Method of Carbon Fiber Composite Antenna Reflection Surface Based on Finite Element Analysis

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Abstract: Aiming at the deformation of carbon fiber composite antennas(CFCA) in sub-millimeter wave and even higher frequency bands under extremely environment, the research on the optimal design method of CFCAs has been proposed. Based on the laminate theory and the properties of carbon fiber composite materials, the simulation model of carbon fiber composite antenna sample has been established, which is verified by designing the sample and experiment. Then, CFCA deformation simulation model has been established and the influence of the parameters including the fiber angle, fiber layups numbers on the reflector deformation has been studied. Based on the above research, the reflector design method and deformation analysis method for carbon fiber antenna based on physical simulation are proposed to provide theoretical guidance for the research of the CFCA.

1. Introduction

With the development of space technology, parabolic antenna systems with high frequency and high band (20 GHz-60GHz) and higher frequency band (100 GHz-200GHz) are used in all kinds of communication satellites. It is very sensitive to the deformation caused by temperature change[1].Antennas usually work in the rarefied area of field air, and the working environment usually has the characteristics of extremely low temperature and large variation of temperature difference, which causes the antenna reflector to deform and causes the error between the actual and the theoretical paraboloid[2]. This error directly affects the electrical performance of the antenna and further affects the working performance of the antenna. A part of the antenna reflector is made of carbon fiber composites with high strength, high modulus and high temperature resistance to ensure the performance of the antenna in the sub-millimeter wave or even higher frequency band[3].

Carbon fiber composites (CFRP) are anisotropic materials with distinct differences in electrical, magnetic, thermal, and mechanical properties along the fiber axis and perpendicular to the fiber axis. anisotropy brings more selectivity to the design, which can meet the strength, stiffness and other special requirements by changing the parameters such as the appropriate laying direction and the number of layers, and also provide a huge design space for the optimal design of the structure[4].At the same time, because of the characteristics of anisotropy, the deformation mechanism of external load is not clear under different working conditions. In order to increase stiffness, the reflector of carbon fiber composite antenna will adopt the structure of aluminum honeycomb and upper and lower skin, which will affect the uniformity and thermal deformation of antenna reflector.

Scholars at home and abroad focus more on the specific properties of carbon fiber composites. There is no detailed and systematic study on the application of carbon fiber materials for surface reflector antennas. Gao Hongcheng et al. compared the properties of carbon fiber reinforced composite reflector antenna and metal reflector antenna under three kinds of beams. It is concluded that the difference between the reflector antenna and the metal reflector antenna in the directional diagram is small. The reflector antenna of carbon fiber composite material has light weight and has much less influence on the servo system than the metal reflector antenna, which can completely replace the metal reflector antenna[5]. Zhou Xingchi and others designed the surface error of all carbon fiber antenna due to thermal deformation is about 1/6 of that of all aluminum reflector and 1/3 of the skin reflector of aluminum core carbon fiber material. It is proved that the reflector of all carbon fiber antenna has a better advantage in reducing thermal deformation[6]. The above studies have obtained that the carbon fiber reflector is less deformed than the aluminum alloy reflector, but the influence mechanism on the accuracy of the antenna reflector is not studied from the specific parameters of the carbon fiber material.

Goutham P et al. compared the RMS value and quality of the reflector made of epoxy carbon composite and the traditional aluminum reflector, and found that the minimum RMS value of the top and bottom panel of the reflector with a carbon fiber angle of 0/45/45/90/0/45/45/0 is 0.065 mm, compared with the reflector antenna with aluminum structure, the RMS value decreased and the weight decreased by 8%[7]. By using the MSC.PATRAN/NASTRAN for secondary development, Rong ji et al. simulated the thermal deformation of the main reflector of a large-caliber composite antenna at a uniform temperature field, and selected a reasonable layer laying method. The results of deformation value, parabolic fitting parameters and shape accuracy meet the design requirements (composed of 0/45/45/90)[8]. Wu nan have reconstructed the antenna based on the the simulation structure optimization[9]. However, because the carbon fiber reflector does not replace the aluminum alloy reflector in a wide range, and there is no detailed and systematic study on the deformation mechanism of the carbon fiber reflector, it can not provide theoretical guidance for the research and development of the carbon fiber reflector[10]. However, because the carbon fiber reflector does not replace the aluminum alloy reflector in a wide range, and there is no detailed and systematic study on the deformation mechanism of the carbon fiber reflector, it can not provide theoretical guidance for the research and development of the carbon fiber reflector. In practical engineering, the research and development period of carbon fiber reflector antenna is long, and it takes a long time to determine the reflector fiber laying scheme, which results in the long time and high cost of the previous theoretical demonstration[11,12]. In order to improve the deformation of antenna under large temperature difference, the existing methods reduce the sensitivity of antenna reflection to temperature change to a certain extent and ensure the accuracy of antenna surface, but the pertinence and limitation are too strong and lack of generality.

Compared with metal reflector antenna, carbon fiber composite reflector antenna can effectively reduce the thermal deformation of the surface, but the influence mechanism of the coating angle and thickness of carbon fiber on the thermal deformation of the reflector is not clear. At present, the manufacturing technology of large carbon fiber composite reflector antenna is not mature, which leads to the lack of application of carbon fiber composite reflector antenna in large high stability reflector. Therefore, in view of the unclear thermal deformation of the reflector antenna of carbon fiber composites, the thermal deformation law of the reflector is studied when the number of layers, the sequence of layers and the temperature change. Firstly, the carbon fiber composite aluminum honeycomb sample is designed according to the reflector of carbon fiber antenna, and the thermal deformation finite element simulation and the sample heating experiment are carried out. By comparing the simulation results with the experimental results, the accuracy of the finite element model of carbon fiber composites and the correctness of the finite element analysis method are verified. Secondly, the finite element model of carbon fiber aluminum honeycomb sandwich reflector is established by using the verified method, and the thermal deformation and variation trend of the model under different temperature conditions are analyzed. The influence of temperature, the angle of carbon fiber and the number of layers on the thermal deformation of the reflector is further analyzed and summarized. According to the structural parameters obtained by this law, the carbon fiber reflector is designed and compared with the original model. The results not only provide a method for finite element simulation of carbon fiber reflector antenna, but also provide some theoretical guidance and reference for its design and optimization.

2. Simulation Analysis of Thermal Deformation of Carbon Fiber Composites

The structural characteristics of antenna reflector is sandwich and consisted of carbon fiber composite skin (symmetrical layers) and aluminum honeycomb (Figure 1 and Figure 2). It is difficult to establish the finite element model of composite materials directly and to verify directly on the antenna reflector. So we design a sandwich panel as sample according to the reflector structure for further study.

As the special character properties of carbon fiber composites, the finite element model of CFCA is different from that of other isotropic materials in finite element analysis. So it is necessary to set up material model that is suitable for this case and the experiment to verify the accuracy of the proposed FEA model.

Several key parameters, including numbers of layers, laminated fiber angle should be explained first. According to the carbon fiber composite production process, the carbon fiber composite material is produced by laying layer by layer of carbon fiber cloth and the number of fiber layers is generally 6~16. The laminated fiber angle in this case is explained as follows: Taking the layer-a as the base layer, the angle between layer-b and a fiber is 90 degree; the angle between layer-c and a is 45 degree, and so on. Theoretically, the laminated fiber angle is from -90 to 90. Considering engineering experience and fabrication technology of carbon fiber composites, the 0, ±45 and 90 degree are often used, which will be considered in this theory.

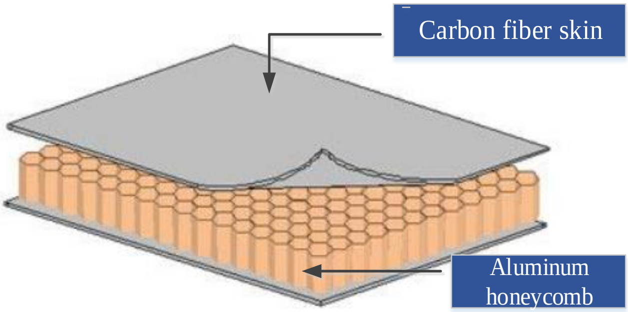

Figure 1: The sandwich structure of carbon fiber composite and aluminum honeycomb

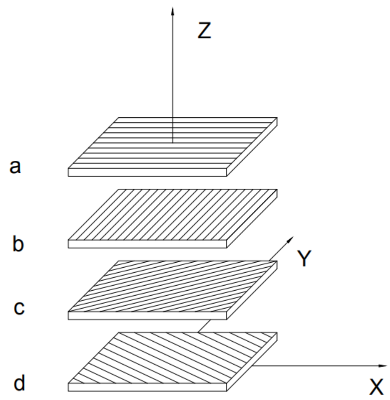

Figure 2: Schematic diagram of the angle of carbon fiber layup

The sample is as follows: the panel is consisted of 16 layers of CFRP skins with an angle of 45 °of each two adjacent layers and aluminum honeycomb sandwich. The shape size of the sample is 100×200×30.8 mm, the layer thickness of CFRP is 0.13 mm, the height of aluminum honeycomb is 10 mm. The finite element model of sample is shown in Figure 3. The upper and lower layers are symmetrical laminated carbon fiber composites, defined as skin-1 and skin-2 respectively and the middle layer is aluminum honeycomb. The laminated angle of carbon fiber is shown in Figure 4.

Based on the classic laminate theory, the skin structure of the sample is established, and the layer-to-layer coupling is set to simulate the layer-to-layer adhesion. The influence of the honeycomb on the properties of sample is solved by the equivalent mechanical parameters of honeycomb by energy method and calculated by radiative heat transfer coefficient calculation of radiant heat conduction in honeycomb core. Thus, the material parameters are shown in Table 1.

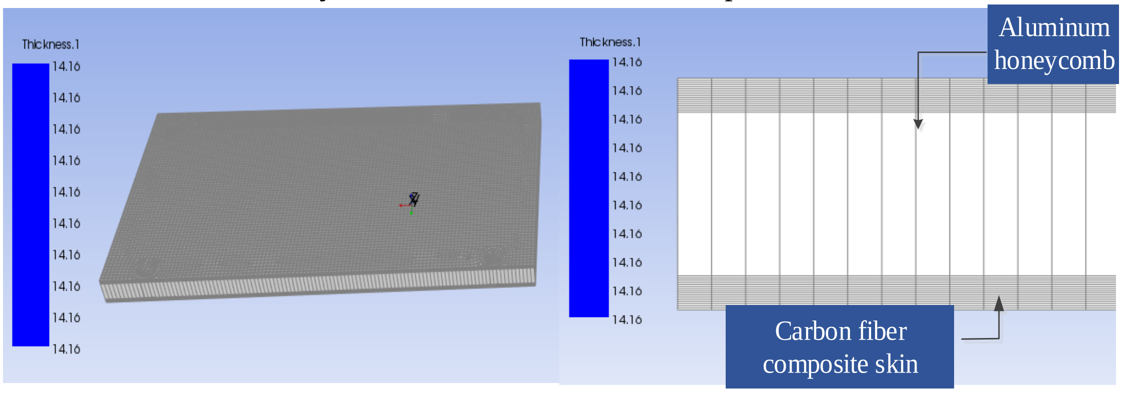

Figure 3: Interface diagram of finite element model of CFRP

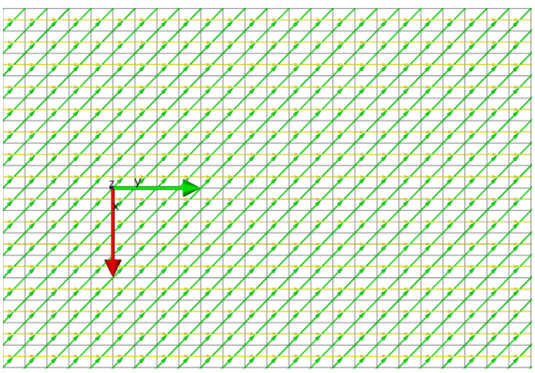

Figure 4: Modeling of carbon fiber composite laminate

Table 1: Performance parameters of skin and core material

Properties		Aluminum honeycomb	CFRP
Elastic modulus	E_{11}/MPa	1	1.136×10^5
	E_{22}/MPa	1	1.136×10^5
	E_{33}/MPa	255	1.136×10^5
Shear modulus	G_{12}/MPa	1×10^{-6}	16470
	G_{23}/MPa	37	8000
	G_{13}/MPa	70	8000
Poisson's ration	μ_{12}	0.49	0.11
	μ_{23}	0.001	0.01
	μ_{13}	0.01	0.01
CTE	$a_1/10^{-6}.°C^{-1}$	23.2	0.2
	$a_2/10^{-6}.°C^{-1}$	23.2	0.2
	$a_3/10^{-6}.°C^{-1}$	23.2	0.48

A uniform temperature field is used in finite element simulation, and the setting temperature is 60℃. The thermal deformation cloud diagram under 60℃ is obtained as shown in Figure 5. The maximum deformation value is denoted as Max-Y, the minimum value is denoted as Min-Y. Max-Y is 0.038mm, Min-Y is -0.127 mm, and the RMS value of the heated surface is 0.022mm.

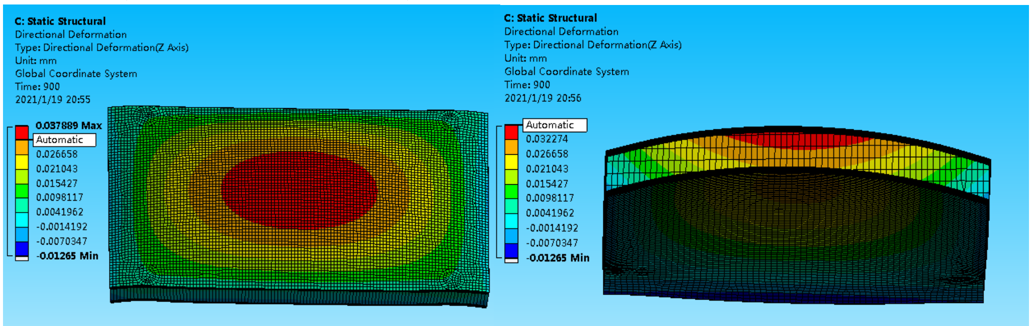

Figure 5: Thermal deformation cloud map of finite element model

Then the experiment sample has been produced, shown in Figure 6, to verify the correctness of the finite element model of the sample and the accuracy of the above method. The thermal deformation measuring equipment is consisted of displacement sensor, digital instrument and power amplifier. The heating device is consisted of an electric heater and a thermostat. By setting the temperature of the thermostat, the heater is at the specified temperature and remains floating near the specified temperature. During the experiment, the displacement sensor (motion detector) is in contact with the upper surface of sample, and the temperature sensor is used to measure the temperature of the contact surface of sample and the displacement sensor. The vertical displacement of the experimental sample is recorded when it reaches the specified temperature. The experimental device is shown in Figure 7, the sample is fixed at four corners. Measuring point-1 upper and measuring point-2 upper are measuring point of the upper surface of sample, and Measuring point-1 lower and measuring point-2 lower are measuring point of the upper surface of sample.

Figure 6: Sandwich structure of carbon fiber composite and aluminum honeycomb

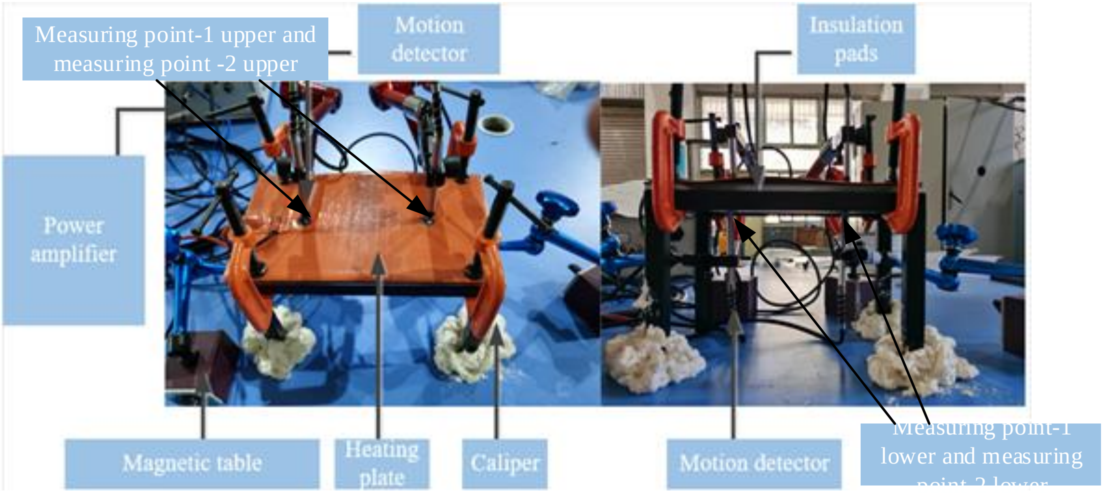

Figure 7: Carbon fiber composite material experimental device

In order to ensure the accuracy of measurement data, we took the average value of the 5 times measurement at each temperature. After each measurement, the thermostat was turned off and the next measurement was performed after waiting for it to cool down and reset.

The experimental environment temperature is 16℃, and the thermostat is set to 25℃ at the first time. When the surface temperature of the heating plate is stable, the voltage data collected by the data acquisition instrument is obtained, shown in Figure 8, which could reflect the surface displacement. According to the characteristics of the displacement sensor, the displacement sensor probe is squeezed and contracted when the voltage increases, and the displacement sensor probe is released when the voltage decreases, so the deformation direction of the carbon fiber board points upward.

After the experiment completed, the thermal deformation data shown in Figure 9 is obtained through calculation and arrangement.. According to the data, the following conclusions can be drawn:

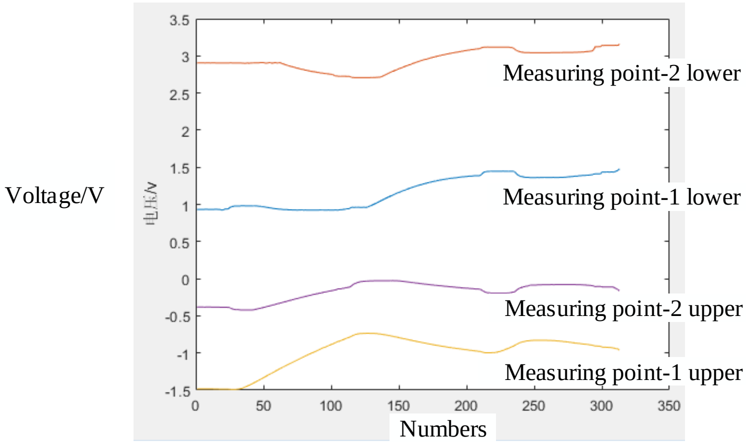

Figure 8: The collected voltage curve with time

(1) When the upper surface is heated, the carbon fiber panel has a bow-shaped change trend, that is, the upper and lower surfaces bulging upward, which is close to the thermal deformation distribution in the simulation.

(2) The simulation data is close to the data of the measuring point in the experiment, the maximum difference is 0.0136mm; the errors are all within the allowable range.

It can be seen that the FEA results is unanimous to the experiment results, which can verify the above finite element model of the carbon fiber and honeycomb sandwich panel is correct, and the thermal deformation simulation analysis method can truly reflect the deformation of the carbon fiber composite sandwich panel after heating. This method can be further used for the carbon fiber composite reflector antenna research on thermal deformation.

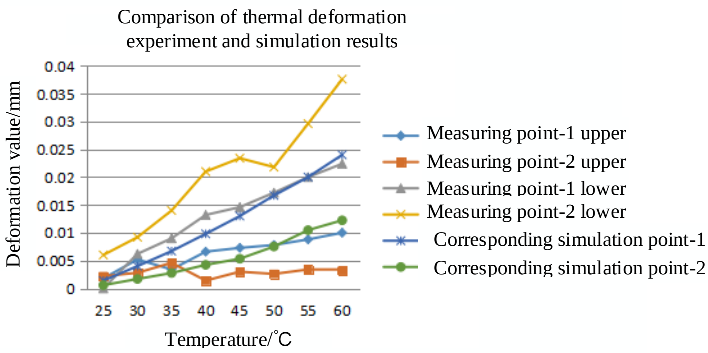

Figure 9: Thermal deformation experiment and simulation data of carbon fiber sandwich panel

3. Finite Element Analysis of Thermal Deformation on Carbon Fiber Composites Antenna

3.1 Finite Element Model of the Carbon Fiber Composite Antenna

The structure of the reflector antenna usually includes the reflector, the back frame and the center body. This paper takes the parabolic antenna with 9m caliber as an example. The reflector is a sandwich structure composed of carbon fiber composite and aluminum honeycomb, which is consisted with the previous sample structure. The reflector skin was preloaded at 60℃ before curing to ensure the thickness uniformity of the skin. The aluminum honeycomb is treated with glass fiber / epoxy before the whole bonding curing to prevent the contact corrosion between aluminum honeycomb and carbon fiber, and the adhesive surface of the skin and aluminum honeycomb is polished to improve the bonding strength. Back frame structure is composed of hollow steel pipe welding with diameter of 15 mm, and adjacent radiation beam and ring beam increase steel degree through diagonal cross welded steel pipe. The back frame structure consists of a hollow steel tube welded with a diameter of 15 mm. the adjacent radiation beam and the ring beam increase the stiffness of the steel tube welded by diagonal cross welding.

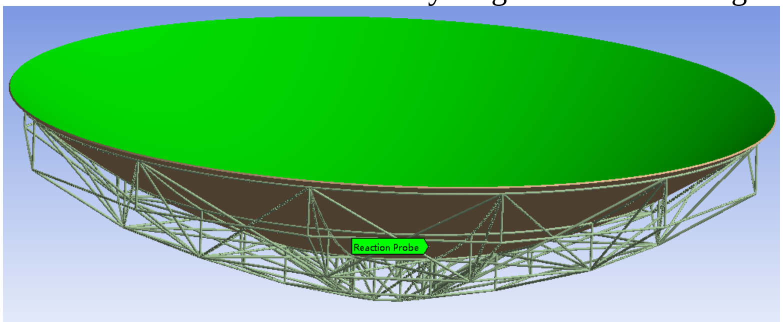

Figure 10: The finite element simulation model of antenna

Based on the above structural details, the finite element model of reflector antenna is established, as shown in Figure 10. The actual antenna structure has a large number of welding and bolt connection structures, which are ignored in the finite element model. The model of carbon fiber reflector is set as solid element, and the back frame is beam element. Finally, the spot weld function is used in the steady-state thermal analysis module to simulate the bolt connection function in practical engineering. The external load includes gravity and temperature. The antenna is affected by solar radiation and ground thermal radiation. With the change of solar incident angle with time and region, and the transformation of antenna attitude, the temperature environment of antenna surface is extremely complex. In this paper, the temperature is simplified into uniform temperature field. At the same time, the temperature is applied to the surface of the reflector (the surface pointing in the direction of the sky). The upper surface temperature is transferred to the lower surface by the heat conduction coefficient, and the heating of the reflector in the actual working condition is simulated as far as possible. The RMS value of thermal deformation of reflector is the main basis to measure the design of antenna structure. The accuracy of antenna surface is evaluated by the RMS value and the maximum value of axial deformation.

3.2 Effect of Laying Number on the Accuracy of Shape Surface

Combined with the working environment of the antenna in this paper, the influence of changing the number of layers of carbon fiber on the thermal deformation of the reflector antenna is studied by selecting the determined temperature environment and the fiber angle. Usually, the antenna working environment is outdoor and the temperature changes greatly. According to the literature, the temperature range of extreme environment is -55℃~70℃, and some extreme temperatures can reach 80℃[10]. The minimum temperature and the maximum temperature are -60℃ and 80℃ respectively (slightly larger than the extreme temperature range recorded in the literature), and the angle of carbon fiber composites is 45 and 90 respectively. Then, the thermal deformation of reflector antenna is analyzed by changing the number of layers of carbon fiber composites. The thermal deformation of reflector antenna is analyzed by changing the number of layers of carbon fiber composites. The deformation cloud diagram is obtained as shown in Figure 11, and the number of layers of carbon fiber composites-thermal deformation curve is shown in Figure 12. To facilitate description, the maximum deformation value of reflector calculated by simulation is recorded as Max-Y, RMS value of reflector deformation is recorded as δ_Y. In this paper, the high precision antenna is mainly used. All the calculated effective bits are reserved to three decimal places to reach micron level.

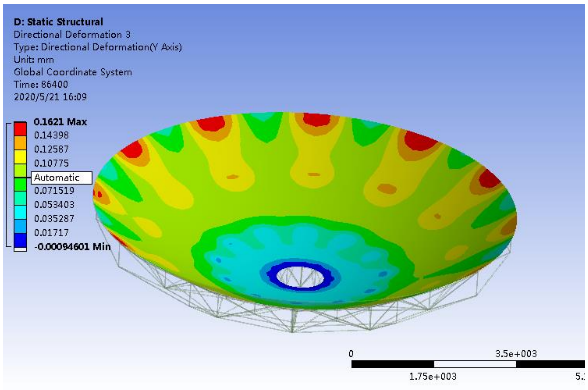

Figure 11: Y-direction thermal deformation cloud image of the reflecting surface at 60℃

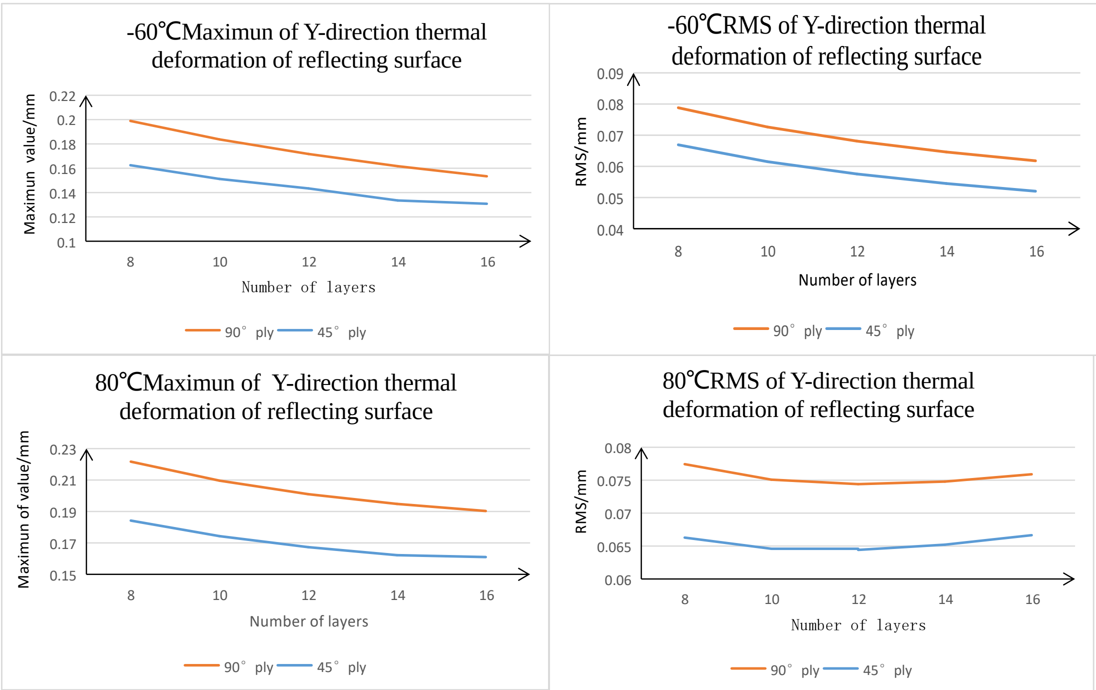

Figure 12: Relationship between number of layers and thermal deformation of reflector

Based on the simulation results, the following conclusions can be drawn:

(1) It can be seen that the maximum value of Max-Y appears when the fiber laying angle is 90 and the number of layers is 8 at each temperature. The possibility of local large deformation is the greatest under this condition.

(2) Max-Y gradually decreases with the increase of the number of layers. When the number of layers reaches the maximum number of 16 layers, the trend of decreasing becomes slowest.

(3) Under the same number of layers and temperature, the δ_Y value at the angle of 45 degrees is smaller than that at the angle of 90 degrees.

(4) From the above results, it can be further concluded that when other conditions are the same, the deformation of the reflector decreases with the increase of the number of layers, but the decreasing trend decreases with the increase of the number of layers. In the actual design process, gravity and manufacturing cost are increasing for each additional layer of carbon fiber reflector. The appropriate number of layers should be selected according to the actual situation, and the balance

between the accuracy of the surface and the economic cost should be selected.

(5) It can also be observed that the reflector deformation under the angle of 90 degrees is slightly larger than that under the angle of 45 degrees, and the possibility of local large deformation is higher. When the number of pawnshop layers is the same, the fiber angle of 45 is better than the angle of 90. The results can provide the basis for selecting the fiber angle below.

3.3 The Influence of Temperature on the Deformation of the Carbon Fiber Composite Reflector Antenna

According to the results of Section 3.2, the fiber layering angle is to be 45 degrees, and the temperature range of -20~60℃ is set (usually the temperature range of the antenna working). The thermal deformation of antenna is studied when the temperature (discrete) and the number of fiber layers change. The simulation results are shown in Figure 13.

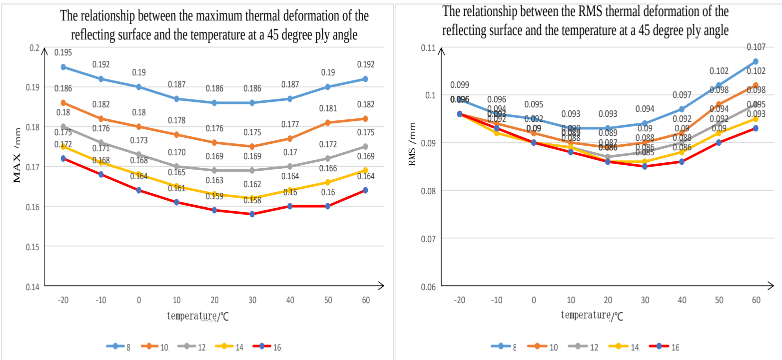

Figure 13: Effect of temperature on thermal deformation of reflector

According to the simulation results, the following conclusions can be drawn:

(1) a maximum of Max-Y (0.195 mm) occurs when -20℃ and 8 layers of carbon fiber composites. a minimum of Max-Y (0.158 mm) appears at 30℃ and 16 layers of carbon fiber composites. When the maximum of δ_Y (0.107mm) appears at 60℃ and 8 layers of carbon fiber composites, the minimum of δ_Y (0.085mm) appears at 30℃and 16 layers of carbon fiber composites.

(2) When the number of layers is determined, the minimum Max-Y appears at 30℃.At the same time, the large deformation at low temperature and high temperature indicates that the low temperature deformation of carbon fiber composites is obvious.

(3) At 60 ℃, the δ_Y varies significantly with the amount of carbon fiber, And the Max-Y difference of reflector is obvious, but it decreases with the increase of layer number. It shows that the possibility of local large deformation with the increase of the number of layers at high temperature does not decrease significantly.

(4) The δ_Y of reflector antenna with different number of layers at -20℃ is close, but the Max-Y changes obviously with the number of layers and decreases with the increase of the number of layers. It shows that at low temperature, the possibility of local large deformation decreases with the increase of the number of layers. At the same time, it shows that the low temperature deformation of carbon fiber composites can not be ignored, which should be one of the key points in subsequent research.

(5) With the increase of temperature, the influence of the number of layers on the RMS value of reflector antenna deformation increases. With the increase of the number of layers, the difference between the maximum value and the RMS value of thermal deformation of reflector antenna becomes smaller and smaller. Therefore, in practical engineering, the number of fiber layers that

meet the requirements should be selected according to the actual situation. This conclusion can guide the manufacture and process design of carbon fiber reflector.

4. Conclusion

Based on the analysis of the properties of carbon fiber composites and the study of carbon fiber reflector antennas, the thermal deformation mechanism of the reflector of carbon fiber composites is studied by taking a 9-meter antenna as an example. The deformation law of reflector under variable temperature affected fiber interlayer angle and number of layers is obtained. It is found that when the number of fiber layers reaches 16 layers, the influence of the angle between the layers can be ignored to a certain extent (the accuracy of the reflector is within the micron level). The above results not only provide theoretical basis for the design of carbon fiber reflector, but also provide a finite element analysis method for thermal deformation of carbon fiber reflector based on physical simulation. In the following work, the thermal deformation and the thermal deformation mechanism of reflector closer to the actual temperature gradient will be calculated. And combined with ANSYS to write software to further realize the rapid design and deformation prediction of carbon fiber reflector antenna.

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