Thermal distortion compensation of a high precision umbrella antenna

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Abstract. Ribs of umbrella antennas act as cantilever beams, which make it difficult for the holding of reflector shape, and especially in thermal environment, thermo-elastic distortion of the ribs would largely degenerate the system performance. Combined with development of a high precision umbrella antenna, thermal distortion compensation under in-orbit temperature field is conducted. Distortion compensation of a single rib model is carried out firstly by temperature field optimization of the fixed end, and distortion compensation of the whole antenna is accomplished by genetic algorithm. Simulation results show very good compensation effect on reflector thermal distortion, while root mean square of the reflector thermal distortion reduces from 0.37mm to 0.27mm.

1. Introduction
Umbrella Antennas also named radial rib antennas are widely used in tracking and data relay satellites and deep space exploration spacecraft’s, such as the TDRS, the Galileo Jupiter Probe of the USA and the Louche satellite of Russia [1, 2]. Main reflectors of umbrella antennas are composed of deployable composite ribs and metal mesh. While design frequency is low as in S and UHF band, the antenna could perform well without much mesh adjustment work, however, as the design frequency comes to Ku band or above, distortion of the reflector is no longer tolerable, and tensile cable networks are introduced in the mesh reflector. By tension of the front and back cables, connect points of the mesh reflector are pulled to the ideal reflector surface. Compared with other types of deployable antennas, umbrella antennas are simple in structure configuration, reliable in deployment, and are very suitable for center feed layout. However, as ribs of umbrella antennas act as cantilever beams, which make it difficult for the holding of reflector shape, and especially in thermal environment, thermo-elastic distortion of the ribs would largely degenerate the system performance.

To control thermal distortion of the reflectors, there are two commonly used methods. The first one is to limit temperature range of the antenna by thermal controls such as SLI (single layer insulation), MLI (multilayer insulation) and heaters. The second one is by shape control strategies in orbit, which modifies shapes of the reflector by piezoelectric ceramics, shape memory alloys or other smart actuators. Active shape controls have more direct control effects, but measurement of reflector distortion in outer space, actuators suitable for aerospace environment and high efficient control algorithm design are blocks waiting to be removed. So far, active shape controls are mainly conducted at simulation or laboratory level, no applications in aerospace have reported yet [3-6].
Combined with development of a high precision umbrella antenna, thermal distortion compensation under in-orbit temperature field is conducted. Distortion compensation of a single rib model is carried out firstly by temperature field optimization of the fixed end, and distortion compensation of the whole antenna is accomplished by genetic algorithm. Simulation results show very good compensation effect on reflector thermal distortion, while root mean square of the reflector thermal distortion reduces from 0.37mm to 0.27mm.

2. Thermal distortion of high precision umbrella antenna
As the antenna be launched into orbit with satellite and deployed, the most important influence factor of outer environment on antenna thermal distribution is the solar irradiation. As a result of earth self-rotation, temperature of the antenna will change from high to low daily. Besides, as the solar incident angle changes periodically, there are three typical solar days, the first one is summer solstice, the date the sun radiates vertically at the Tropic of Cancer. The second one is winter solstice, the date the sun radiates vertically at the Tropic of Capricorn. And the last one is Autumnal Equinox or Spring Equinox, the date the sun radiates vertically at the equator. Also considering degeneration of thermal control materials, there are six typical days for antenna thermal analysis, these are BOLSS, BOLWS, BOLEQ, EOLSS, EOLWS and EOLEQ, in which BOL and EOL refer to begin of life and end of life respectively.

For thermal analysis of the umbrella antenna, 24 simulation steps are set each day with an interval of an hour. Figure 1 shows temperature distribution of the reflector main structure at EOLSS twenty four o’clock satellite time, at which the satellite is in shadow of the earth, and temperature of the reflector reaches its minimum, while temperature of the tensile cables come to -157°C. Figure 2 is the corresponding reflector distortion map, as the tensile cables shrink at low temperature, the reflector deforms as a trend of close up, and far end deformation of the ribs are nearly 1mm.

![Figure 1. Thermal map of the reflector](image)
Figure 2. Thermal distortion map of the reflector

Thermal distortion of the reflector expressed in RMS is summarized in Figure 3, as a result of thermal control degeneration, thermal distortion RMS in EOL cases are generally greater than that of BOL cases, and the maximum thermal distortion RMS of the reflector is 0.37mm. Thermal distortion of the reflector has already exceeded the thermal distortion budget, and further thermal distortion optimization has to be done to meet the thermal distortion requirement.

Figure 3. Thermal distortion RMS curve of the reflector

3. Thermal distortion compensation of a single rib model

As shown in Figure 4a, temperature distribution is the same at the front and back side of the rib under uniform temperature field, and the inner force induced by thermal load can be given as:

\[ F_1 = EA\alpha \Delta T \quad F_2 = EA\alpha \Delta T \quad M = 0 \]  

Where \( F_1 \) and \( F_2 \) are axial tension or compression forces at the front and back side of the rib, \( EA \) is the tensile stiffness coefficient of the rib, \( \alpha \) and \( \Delta T \) refer to thermal expansion coefficient and temperature rise of the rib respectively, \( M \) is the bending moment induced, but as axial tensile forces are the same at the front and back side of the rib, \( M \) should be zero.

If by external temperature rising, temperature at the front and back side of the rib is modified to be different, the inner force induced by thermal load can be given again as:

\[ F_1 = EA\alpha \Delta T_1 \quad F_2 = EA\alpha \Delta T_2 \quad M = Ea.\alpha (\Delta T_1 - \Delta T_2) h \]
Where \( h \) is distance between the front and back side of the rib to bending neutral surface. As axial tensile forces at the front and back side of the rib are no longer the same, the bending moment \( M \) will result in rotation of the rib, as shown in Figure 4b. So by changing temperature at the front and back side of the rib, thermal distortion of the rib could be compensated.

\[
\begin{align*}
F_1 &= E\alpha \Delta T \\
F_2 &= E\alpha \Delta T \\
M &= E\alpha (\Delta T_1 - \Delta T_2) h
\end{align*}
\]

(a) Uniform temperature (b) Non-uniform temperature

**Figure 4.** Sketch of rib deformation under thermal load

Thermal distortion compensation of a single rib model under the uniform temperature filed of +60°C is conducted, and the simulation results are shown in Figure 5. In Figure 5a, without thermal distortion compensation, the maximum deformation at far end of the rib is 0.12mm. However, as shown in Figure 5b, after thermal distortion compensation, the maximum deformation at far end of the rib reduces to 0.01mm while temperature at the front side of the rib rises +20°C.

\[
\begin{align*}
Z_{\text{mm}} & \quad Y_{\text{mm}} \\
0 & \quad 0 \\
0.12 & \quad 400 \\
0.01 & \quad 0.05
\end{align*}
\]

(a) Without compensation (b) With compensation

**Figure 5.** Thermal distortion compensation of a single rib model

Figure 6 shows relationship curve between far end thermal deformation and the temperature rise, the deformation and temperature rise show very well linear relationship. Far end of the rib could deform 0.0054mm while the temperature raises 1°C. And for further application, Calibration of the deformation and temperature rise should be done firstly by test to get the exact mechanical-thermal coupling coefficient.
4. Thermal distortion compensation of the antenna

Sketch of a rib mounting on the antenna is shown in Figure 7, the high precision umbrella antenna consists of 18 composite material ribs, after be launched into orbit, drive motor will operate and drive the deploy arm to rotate with the rib until the antenna is fully deployed, then the deploy arm will be locked by the lock unit. The deploy arm, the rib and the lock unit could be simplified to be a one-dimension rotation system, length changes of the lock unit will induce rigid rotation of the deploy arm about its rotate axis, and result in further close up or close down of the reflector. As the rib is relatively long, small rotation angle at the near end would result in large deformation at the far end. By former simulation and test, the amplification factor is 35.7, which means that if length of the lock unit changes 1μm, far end displacement of the rib would be 35.7μm.

Displacement amplification of the rib increases difficulties to design the lock unit, which requires it to be dimension stable. However, it also supports a new approach for thermal distortion compensation of the reflector, and by exact length control of the lock unit, a higher level displacement control could be achieve at the antenna level.

The focal point of the reflector thermal distortion compensation in orbit is how to find the corresponding temperature rises of the 18 lock units. As a commonly used intelligent algorithm, the genetic algorithm could find a relatively best solution in a short time, and is very suitable for multiple solution problems just as the thermal distortion compensation. By binary encoding, each chromosome includes 18 genes, and each gene corresponds to a lock unit with the digits of 7, which mean that the temperature rise could change from 0℃ to 127℃.

By predefinition of the design space, the reflector thermal distortion compensation problem could be simplified as a non-constraint optimization as below [7,8]:

\[
\text{find Min}\{\text{RMS}\} \quad (3)
\]
The equilibrium equation of thermal distortion analysis is:

$$KX = F_T$$

(4)

While $K$ refers to the global stiffness matrix, $FT$ is the node equivalent thermal load matrix, and $X$ is the node displacement matrix.

Thermal distortion of the reflector can be finished by the following steps:

Finite element modeling of the antenna to obtain the global stiffness matrix $K$;

Apply a uniform temperature field $T_0$ on the antenna finite element model and get the node displacement matrix $XT_0$ by linear static analysis;

The node equivalent thermal load matrix $FT_0$ can be determined by

$$T_0 = KX$$

and the corresponding node equivalent thermal load vector $FT_0k$ (k=1~18) of the kth lock unit can be separated from $FT_0$ according to the node id, so mechanical-thermal coupling coefficient $D_k$ of the kth lock unit can be defined as:

$$D_k = \frac{FT_{0k}}{T_0 - T_{ref}}$$

(5)

Suppose the thermal case needs to be distortion compensated is $Ts$, and by the same process of step 2 and 3, the corresponding node displacement matrix $XTs$ and node equivalent thermal load matrix $FTs$ can be obtained, and thermal distortion RMS of the reflector without compensation is:

$$RMS_{Ts} = \sqrt{\frac{\sum_{n}^{m} X_{Tsk}^2}{n-m+1}}$$

(6)

Where number of the reflector nodes is $n-m+1$.

By genetic algorithm, set temperature rises of the 18 lock units to be design variables $Tn=\{T1, T2, ..., T18\}$, then the added node equivalent thermal load matrix of the kth lock unit result from temperature rise $Tn$ is:

$$P_{Tnk} = D_k (T_n - T_{ref}) = \frac{T_n - T_{ref}}{T_0 - T_{ref}} F_{T0k}$$

(7)

The overall added node equivalent thermal load matrix is:

$$P_n = \{P_{Tn1}, P_{Tn2}, ..., P_{Tn18}\}$$

(8)

Then the thermal-mechanical equilibrium equation with distortion compensation is:

$$KX_{Ts} = F_{Ts} + P_n$$

(9)

The node displacement matrix $XTs$ and the corresponding thermal distortion RMSTs can be updated by equation 6.

Repeat steps 5 N times for genetic iteration to get a relatively minimum of RMS.

During genetic algorithm iteration, population at each generation is set to be 40, the number of generation is 30, probability of crossover is 0.8, and the probability of migration is 0.005. Relationship curve between thermal distortion RMS of the reflector and generations is shown in Figure 8, thermal
distortion RMS of the reflector reduces as the generation increases, and thermal distortion RMS reaches its minimum at 0.27mm after 30 generations, the thermal distortion RMS has reduced about 27% compared with the former result. And the final temperature rises of the 18 lock units are summarized in Table 1.

![Figure 8. Relationship curve between thermal distortion RMS and generation](image)

| No | Temperature rise /°C |
|----|----------------------|
| 1  | 88                   |
| 2  | 82                   |
| 3  | 48                   |
| 4  | 73                   |
| 5  | 65                   |
| 6  | 117                  |

| No | Temperature rise /°C |
|----|----------------------|
| 7  | 117                  |
| 8  | 101                  |
| 9  | 113                  |
| 10 | 43                   |
| 11 | 45                   |
| 12 | 61                   |

| No | Temperature rise /°C |
|----|----------------------|
| 13 | 31                   |
| 14 | 87                   |
| 15 | 24                   |
| 16 | 18                   |
| 17 | 103                  |
| 18 | 109                  |

5. Conclusion
Combined with development of a high precision umbrella antenna, thermal distortion compensation under in-orbit temperature field is conducted. Based on thermal compensation simulation of a single rib model, thermal distortion compensation of the whole antenna is carried out. The proposed thermal distortion compensation method has the following merits: Firstly, thermal control method is mature in aerospace engineering, thin-film heaters and sheathed heaters are widely used before and could supply good source of thermal energy. Secondly, the control algorithm is robustness in nature, and could find a relatively best solution in a short time. And finally, local control of the rib and lock unit could realize the exact and rough control of reflector respectively.

However, there are still several aspects need to be further researched before the thermal compensation method to be used in aerospace environment, such as: The thermal compensation depends on thermal expansion of the lock units, and temperature rises mean that the compensation can only makes the reflector to be close up. Thermal isolation of the thermal expansion units from surrounding units and reflector thermal distortion measurement in space environment still need further investigation and validation.

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