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Abstract

As a typical deployable satellite antenna structure, the hoop truss antenna possesses broad application prospects in high-power spaceborne antennas due to its advantages of large aperture, light weight, high packaging efficiency, good stiffness, and the fact that its total mass does not increase proportionally with the deployed aperture. The alternation of space thermal environments and non-uniform temperature distribution can easily cause severe thermally induced vibration problems for large-scale, highly flexible hoop truss antenna structures, potentially leading to spacecraft failure. To address this issue, an orbital thermal radiation model for a certain type of large-aperture hoop truss antenna in its deployed state is first proposed. This model can calculate the shadowing factors among internal structural components of the antenna, particularly the shadowing of truss elements by the antenna reflector, thereby obtaining the effective solar incident heat flux received by each truss element of the antenna under the combined effects of internal structural shadowing and Earth shadow effects. Based on this, a thermal conduction analysis model for the hoop truss antenna is established. The effective solar incident heat flux received by the antenna, calculated by the orbital thermal radiation model, is input into this thermal conduction model to obtain the temperature field variations of the hoop truss antenna during on-orbit operation. The research results indicate that due to mutual shadowing among internal structural components of the antenna, significant temperature differences exist across various parts of the antenna truss structure, with a maximum value reaching nearly 270 ℃. Coupled with orbital shadowing effects, the antenna experiences rapid transient temperature changes during moments such as entering and exiting the Earth shadow region. It should be noted that such drastic temperature variations and temperature distribution non-uniformity may cause large deformations and thermally induced vibration problems in the hoop truss antenna, requiring further in-depth investigation.

Full Text

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Orbital Thermal Analysis of a Circular Truss Antenna Considering Structural Occlusion and Earth Shadow Effect

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Abstract: As a typical deployable satellite antenna structure, circular truss antennas have broad application prospects in high-power spaceborne antennas because of their large aperture, low mass, high stowage ratio, good stiffness, and the advantage that the total mass does not increase exponentially with increasing deployed aperture. The alternating hot and cold environment in space and the nonuniformity of the temperature distribution can readily induce severe thermally induced vibration problems in large, highly flexible circular truss antenna structures, and may even lead to spacecraft failure. To address this problem, an orbital thermal-radiation model for a large-aperture circular truss antenna after deployment is first proposed. This model can calculate the occlusion coefficients among internal structural members of the antenna, especially the occlusion of truss elements by the antenna reflector. On this basis, the effective solar incident heat flux received by each truss element of the antenna under the combined effects of structural occlusion within the antenna and the Earth shadow effect is obtained. A heat-conduction analysis model for the circular truss antenna is then established, and the effective solar incident heat flux received by the antenna, calculated using the orbital thermal-radiation model, is introduced into this heat-conduction model to obtain the variation of the temperature field of the circular truss antenna during orbital operation. The results show that, owing to mutual occlusion among internal structural components of the antenna, the temperature differences among different parts of the antenna truss structure are large, with a maximum value reaching nearly 270 °C. In addition, because of the orbital shadowing effect, at moments such as entry into and exit from the Earth shadow region, the antenna undergoes rapid instantaneous temperature changes. It should be noted that such drastic temperature variations and nonuniform temperature distributions may trigger large deformation and thermally induced vibration problems in circular truss antennas, requiring further in-depth investigation.

Keywords: circular truss antenna; orbital thermal-radiation model; structural occlusion; Earth shadow effect; occlusion coefficient; effective heat-flux density; temperature field

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Thermal analysis of a circular truss antenna considering structural shading and ground shadow effect

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Abstract: As one of the deployable satellite antenna structures, the circular-truss antenna has a wide application prospect in high power satellite-borne antenna due to its advantages of large aperture, light weight, high capacity, good stiffness, and the fact that the total mass does not increase exponentially with the ex-

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panding aperture. The alternation of hot and cold environment in space and the inhomogeneity of temperature distribution can easily cause serious thermal vibration problems and even lead to the failure of a spacecraft. In this paper, an orbital solar radiation model is presented instead of the traditional ray projection method for calculating the shielding coefficient between the internal components of a circular truss antenna. By this model, we obtained the effective solar incident heat flux received by each truss element of the antenna under the combined action of the shielding effect between the antenna' s internal components and the earth shadow effect. On this basis, the thermal radiation-conduction model of the circular truss antenna is established. Variations of the temperature field of the circular-truss antenna in orbit can be calculated through the thermal radiation-conduction model by submitting the effective solar incident heat flux received by each truss element of the antenna obtained from the orbital solar radiation model. A numerical test is performed on a 40 m-aperture circular-truss antenna. The results show that the temperature difference of each part of the antenna truss structure is large due to the mutual shielding effect between the internal components of the antenna, and the maximum value reaches about 270 ℃. What is more, the antenna will have a rapid change in temperature when it enters or exits the earth shadow region. It should be noted that the large deformation and thermal vibration of the circular truss antenna may be caused by the drastic temperature change and the inhomogeneity of the temperature distribution.

Key words: circular truss antenna; orbital solar radiation model; structural shielding; earth shadow effect; shielding coefficient; effective heat flux; temperature field

Because circular truss antennas have many advantages, such as the ability to achieve apertures in the range of 6–150 m, low mass, high packaging efficiency, good stiffness, and a total mass that does not increase exponentially with increasing deployed aperture, they are currently one of the most promising types of large space-deployable antennas and have attracted great attention from specialized researchers.

Large flexible antennas operate in special thermal-radiation environments. When periodically entering and exiting the Earth' s shadow region, the severe temperature changes can lead to thermally induced vibration of flexible antennas. In 1956, BOLEY[^1] first studied the problem of thermally induced vibration of thin beams and plates under uniform heat flux. By introducing a time-varying thermal bending moment as a load into the structural dynamics equation, he proposed the BOLEY coefficient for judging whether thermally induced vibration occurs in a structure. However, the BOLEY coefficient can only reveal the mechanism of thermally induced vibration of simple structures under uniform heat flux; for large complex antenna structures in thermal alternating environments, the mechanism of thermally induced vibration is still unclear. Large flexible antenna structures are complex, have many degrees of freedom, and exhibit significant nonlinearities such as motion gaps. They are usually modeled by the finite element method, and temperature is applied to the model as a load for thermally induced vibration analysis. The temperature-field calculation of large flexible antenna structures mainly adopts geometric methods: according to the orbital position and attitude of the structure, the relative geometric position with respect to the sunlight is determined, the radiative heat flux is calculated, and the temperature-field distribution is then obtained. FARMER et al.[^2] analyzed the temperature field of an antenna support truss structure in geosynchronous orbit; the temperature range of the truss entering and exiting the Earth' s shadow was −180–150 ℃. Flexible structures expand or contract with temperature changes. Under nonuniform heating and deformation constraints, thermal stresses are generated within the structure, thereby affecting the structural stiffness. SHEN Zhenxing et al.[^3] considered a large space circular truss antenna, assumed the connection joints to be ideal connections and ignored the joint mass, established a thermally induced vibration model of the truss antenna, and analyzed the transient thermally induced vibration response of the truss structure under impulsive solar-radiation loading in a fixed direction. XUE et al.[^4–^5], on the basis of previous work, proposed a Fourier thermal element for nonlinear transient temperature-field calculation, which can efficiently and accurately simulate the transient temperature field, thermal deformation, and thermal stress of complex space structures. On this basis, a Fourier thermal tube element was used to extend BOLEY' s theory to complex structures[^6], considering the coupling influence of spacecraft attitude angle and flexible appendage motion on the input heat flux, and thermal-structural uncoupled and coupled analyses of spacecraft structures were carried out, respectively[^7]. This type of Fourier thermal tube element was later adopted by SU Xinming et al.[^8-^9] for thermally induced vibration and thermal-stability analysis of space truss structures. ZHENG Shikun et al.[^10] introduced thermally elastically coupled linear time-varying stiffness, established thermo-elastically coupled dynamic equations for a cable-net/frame combined structure of a circular truss antenna, and analyzed the influence law of temperature changes during entry into and exit from the Earth-shadow period on thermally induced vibration of the spacecraft structure.

At present, most studies on thermo-structural coupling analysis of antenna structures do not consider the influence of shielding effects between antenna structures on antenna temperature variation. Although a small number of studies consider shielding between internal antenna components, the calculation methods are relatively complex. In response to this problem, this study proposes a method for calculating the structural shielding coefficient of an antenna. On this basis, a thermal radiation-conduction model is established separately, and the calculation considers the antenna ⋯

Under the structural occlusion effect and the Earth-shadow effect, the heat-flux density and temperature field are analyzed, and the influence law of the structural occlusion effect on the antenna temperature-field distribution is studied.

1 Thermal Analysis Model for the Circular Truss Antenna Structure

1.1 Calculation of Heat-Flux Density Considering Occlusion among Internal Antenna Structures and the Earth-Shadow Effect

1.1.1 Calculation of the Occlusion Coefficient among Internal Antenna Structures

Because the geometric dimensions of the circular truss antenna are far smaller than the distances from the Sun and the Earth, it may be considered that the solar-radiation intensity received by the antenna structure at different orbital altitudes is the same. Meanwhile, in practical engineering calculations, fluctuations in the solar constant caused by changes in the distance between the Sun and the Earth can be neglected. Therefore, the Sun can be approximately regarded as a point light source, and the solar rays incident on the surfaces of the antenna elements can be regarded as parallel light.

Establish the global coordinate system *o-xyz* shown in Fig. 1. Then the paraboloid equation of the antenna reflector is

Schematic of the coordinates of the antenna

Figure 1: Schematic of the coordinates of the antenna

$$x^2 + y^2 = 4fz \qquad (1)$$

where f is the focal length of the antenna reflector.

Fig. 1 Schematic of the coordinates of the antenna

Assume that the solar ray always rotates about point o in the yoz plane. When the solar incidence angle is θ, the coordinates of the tangent point with the antenna reflector are (a, b, c). Then the normal vector at this point can be expressed as $(2a, 2b, -4f)$, and the tangent plane of the antenna reflector at this point is

$$2a(x - a) + 2b(y - b) - 4f(z - c) = 0 \qquad (2)$$

and the solar incidence angle satisfies

$$k = \tan\left(\frac{\pi}{2} - \theta\right) = \frac{b}{2f} \qquad (3)$$

Substituting the tangent point (a, b, c) into Eq. (1), and combining Eqs. (2) and (3), the tangent-plane equation can be obtained as

$$2ax + \frac{2f}{\tan\theta}y - 4fz - a^2 = 0 \qquad (4)$$

Considering that the tangent point (a, b, c) should lie within the antenna range, i.e., $0 \leq c \leq h$, one can obtain

$$-\sqrt{4f\left(h - \frac{f}{\tan^2\theta}\right)} \leq a \leq \sqrt{4f\left(h - \frac{f}{\tan^2\theta}\right)} \qquad (5)$$

If the tangent point (a, b, c) lies outside the region, considering the overall symmetry of the paraboloid, the point (a, b, c) must be scaled as a whole to obtain

$$\left(\frac{a}{k}, \frac{b}{k}, h\right)$$

Substituting this into the tangent-plane equation and translating it to the position that has just intersected the regional boundary gives the critical tangent plane, satisfying

$$\frac{2a^2}{k} + \frac{2fb}{k\tan\theta} - 4fh + d = 0 \qquad (6)$$

where d is the undetermined translation coefficient associated with the translation amount.

Because the critical tangent point $\left(\frac{a}{k}, \frac{b}{k}, h\right)$ is likewise on the reflector surface, it satisfies

$$\left(\frac{a}{k}\right)^2 + \left(\frac{b}{k}\right)^2 = 4fh \qquad (7)$$

The undetermined translation coefficient d can be determined from Eqs. (6) and (7).

The calculation procedure for the member occlusion coefficient is as follows:

Because the occlusion effect of the antenna reflector on the truss differs for sunlight at different angular ranges, the solar incidence angle is divided into three regions: $0 \leq \theta \leq \pi - \theta_0$; $\pi - \theta_0 < \theta < \pi + \theta_0$; $\pi + \theta_0 \leq \theta \leq 2\pi$.

1) When the solar incidence angle θ lies in region , calculate the occlusion coefficient of truss element l_i: let x be traversed from $-x_{\max}$ to $x_{\max}$ with a step size of $\frac{1}{x_{\max}}$. Denote

$$x_c = \sqrt{4f\left(h - \frac{f}{\tan^2\theta}\right)}$$

If

$$4f\left(h - \frac{f}{\tan^2\theta}\right) \leq 0$$

then set $x_c = -1$, in which case $x_c \leq x_{\max}$.

a) When $|x| \leq x_c$,

substituting the focal-point coordinates $(0, 0, f)$ gives $d_{l_i} = -4f^2 - x^2$. Substituting the coordinates of truss element nodes x_1 and x_2 into the tangent-plane equation, respectively, yields

$$d_s = 2xx_1(1) + 4fx_1(2)\cot\theta - 4fx_1(3) - x^2 \qquad (8)$$

$$d_e = 2xx_2(1) + 4fx_2(2)\cot\theta - 4fx_2(3) - x^2 \qquad (9)$$

where $x_1(1)$, $x_1(2)$, and $x_1(3)$ denote the x-, y-, and z-axis coordinates corresponding to element node 1, respectively; $x_2(1)$, $x_2(2)$, and $x_3(3)$ denote the x-, y-, and z-axis coordinates corresponding to element node 2, respectively.

If $d_l d_s \geq 0$, then the starting point of the member element is occluded and $c_1 = 1$; otherwise $c_1 = 0$. If $d_l d_e \geq 0$, then the terminal point of the member element is occluded and $c_2 = 1$; otherwise $c_2 = 0$.

At this time, the occlusion on the back side of the antenna truss is further considered. If

$$x_1(2) \geq 4fh - x^2$$

then the starting point of the member element is not occluded, and $c_1 = 0$. If

$$x_2(2) \geq 4fh - x^2$$

then the terminal point of the truss element is not occluded, and ···

occluded, $c_2 = 0$.

The distances from the starting and ending points of the truss element to the plane are calculated as follows:

$$d_{si} = \frac{|d_s|}{\sqrt{(2x)^2 + (4f\cot\theta)^2 + (-4f)^2}} \qquad (10)$$

$$d_{ei} = \frac{|d_e|}{\sqrt{(2x)^2 + (4f\cot\theta)^2 + (-4f)^2}} \qquad (11)$$

Thus, the occlusion coefficient at this time can be expressed as

$$f_s = \frac{d_{si}c_1 + d_{ei}c_2}{d_{si} + d_{ei}} \qquad (12)$$

b) When $|x| > x_c$

From Eqs. (7) and (8), the scaling coefficient and the planar translation coefficient are calculated respectively as

$$k = \sqrt{\frac{x^2 + 4f^2\cot^2\theta}{4fh}} \qquad (13)$$

$$d = 4fh - \frac{2x^2}{k} - \frac{4f^2\cot^2\theta}{k} \qquad (14)$$

Substituting the focus $(0, 0, f)$ gives $d_i = -4f^2 + d$. Substituting the element nodes x_1 and x_2, respectively, into Eq. (6) yields

$$d_s = 2xx_1(1) + 4fx_1(2)\cot\theta - 4fx_1(3) + d \qquad (15)$$

$$d_e = 2xx_2(1) + 4fx_2(2)\cot\theta - 4fx_2(3) + d \qquad (16)$$

Similarly, if $d_i d_s \geq 0$, the starting point of the member is occluded, and $c_1 = 1$; otherwise $c_1 = 0$. If $d_i d_e \geq 0$, the ending point of the member is occluded, and $c_2 = 1$; otherwise $c_2 = 0$.

At this point, the occlusion on the rear side of the antenna truss is considered again. If $x_1(2) \geq 4fh - x^2$, then the starting point is not occluded, and $c_1 = 0$. If $x_2(2) \geq 4fh - x^2$, then the ending point is not occluded, and $c_2 = 0$.

Then, according to Eqs. (10) and (11), the distances d_{si} and d_{ei} from the starting and ending points of the truss element to the tangent plane are calculated, respectively. The occlusion coefficient f_s of this truss element can then be obtained from Eq. (12).

After the traversal calculation is completed, $f_s = \min\{f_s\}$ is taken as the final occlusion coefficient of the truss element.

2) When the solar incidence angle is located in interval , the Sun is incident from below the antenna. Considering that the structure has no part satisfying $x_1(2) > h$ or $x_2(2) > h$, the occlusion coefficient can be directly taken as $f_s = 0$.

3) When the solar incidence angle is located in interval , the occlusion coefficient of the truss element is calculated using a method and steps similar to those used when the solar incidence angle is located in interval .

1.1.2 Calculation of the Earth-occlusion coefficient

When a spacecraft passes through the Earth's shadow region, it is not irradiated by the Sun. Between the shadow region and the fully illuminated region there is a penumbral region, where the spacecraft receives only partial solar irradiation. Therefore, the solar heat flux density received by the satellite at any time satisfies

$$S(t) = g(t)S_0 \qquad (17)$$

where S_0 is the solar incident heat-flux constant; $g(t)$ is the equivalent heat-flux receiving coefficient, which can be calculated by

$$g(t) = 1 - \xi(t) \qquad (18)$$

where $\xi(t)$ is the Earth-occlusion coefficient, satisfying [11]

$$\xi(t)=\begin{cases}0, & \varepsilon>\gamma+\delta\\ \dfrac{\left(\dfrac{\gamma}{\delta}\right)^2\left[\alpha-\dfrac{\sin(2\alpha)}{2}\right]+\left[\beta-\dfrac{\sin(2\beta)}{2}\right]}{\pi}, & \gamma-\delta\le\varepsilon\le\gamma+\delta\\ 1, & \varepsilon<\gamma-\delta\end{cases} \tag{19}$$

where

$$\alpha=\cos^{-1}\left(\frac{\varepsilon^2+\gamma^2-\delta^2}{2\varepsilon\lambda}\right) \tag{20}$$

$$\beta=\cos^{-1}\left(\frac{\varepsilon^2-\gamma^2+\delta^2}{2\varepsilon\delta}\right) \tag{21}$$

$$\gamma=\sin^{-1}\left(\frac{R_{\mathrm{E}}}{R_{\mathrm{P}}}\right) \tag{22}$$

$$\delta=\sin^{-1}\left(\frac{R_{\mathrm{S}}}{r_{\mathrm{sp}}}\right) \tag{23}$$

$$\varepsilon=\cos^{-1}\left(\frac{r_{\mathrm{sp}}\cdot r_{\mathrm{sp}}}{|r_{\mathrm{sp}}|\,|r_{\mathrm{EP}}|}\right) \tag{24}$$

where: r_{sp} denotes the vector from the center of the Sun to the satellite; r_{EP} denotes the vector from the center of the Earth to the satellite; $\alpha_0=\omega t$ denotes the angle through which the spacecraft (antenna) moves in its orbit; R_{E} denotes the radius of the Earth; R_{P} denotes the distance from the satellite to the center of the Earth; R_{S} denotes the radius of the Sun; and R_{SE} denotes the distance from the center of the Sun to the center of the Earth.

1.1.3 Calculation of heat-flux density

According to the preceding analysis, when the occlusion effect among antenna structures and the Earth-shadow effect are considered, the actual heat-flux density received by each truss element of the antenna is

$$S(t)=[1-f_s(t)]g(t)S_0\cos\varphi \tag{25}$$

where φ is the included angle between the solar incident ray and the normal direction of the truss element.

1.2 Temperature-field calculation model

Assume that the annular antenna operates in a synchronous orbit, the orbital altitude is high, and the air is rarefied; therefore, the influence of heat generated by atmospheric friction is neglected. The thermal equilibrium equation of the large space truss is given by

$$c\rho A\frac{dT}{dt} - \lambda A\frac{\partial^2 T}{\partial x^2} + P\sigma\varepsilon T^4 - D_c\sigma\sum_{n=1}^{N}\varepsilon_n B_n T_n^4 = p_0(q_s + q_r + q_e) \qquad (26)$$

where: λ is the thermal conductivity of the material; c is the specific heat capacity per unit mass of the material; A is the unit cross-sectional area; T is the absolute temperature of the element; D_c is the perimeter of the cross section; σ is the blackbody radiation constant; ε is the surface emissivity of the element; ε_n is the surface emissivity of the other nth element; B_n is the absorptivity of the element for radiation from the other nth element; T_n is the absolute temperature of the other nth element; p_0 is the area factor of the spatial heat source received by the element; and q_s, q_r, and q_e are, respectively, the solar radiant energy, Earth-reflected energy, and Earth-radiated energy per unit area.

By assembling the heat-conduction equations for all antenna elements, the iterative equation for the transient temperature field of the ring truss antenna can be obtained as follows[^12]:

$$K_1T^n + K_2T^n + K_3T^n = Q_1 + Q_2 + K_3T^{n-1} \qquad (27)$$

where: K_1 denotes the heat-conduction matrix; K_2 denotes the thermal-radiation matrix; K_3 denotes the heat-capacity matrix; Q_1 is the space-radiation heat-load matrix; Q_2 is the radiation-boundary-term matrix; and T^n and T^{n-1} denote the thermodynamic temperature matrices at the nth step and the $(n-1)$th step, respectively.

2 Calculation Results and Analysis

2.1 Calculation of Shading Coefficient and Heat-Flux Density

As shown in Fig. 2, assume that the orbit of the antenna is a geosynchronous orbit, with an orbital altitude of 35 786 km and an orbital period of 86 062 s. The Earth is at the vernal equinox, and the corresponding solar heat-flux constant is $S_0 = 1\ 377.8\ \mathrm{W/m^2}$. The initial position of the antenna is in the Earth' s shadow region, and $\theta(0) = 0$.

图 2 天线与太阳光相对位置示意图

Fig. 2 Schematic of the orbital position of the antenna relative to the sunlight

Fig. 2

Figure 2: Fig. 2

Fig. 3

Figure 3: Fig. 3

The satellite rotates counterclockwise around the Earth. For the large ring truss antenna shown in Fig. 3, its structural parameters are listed in Table 1, where I_{xx}, I_{yy}, and I_{zz} are used to calculate the shading coefficient of the antenna at different orbital positions by the method in Section 1.1. The antenna aperture is 60 m, the antenna height (vertical strut length) is 3 m, and the antenna focal length is 150 m. The shading coefficients of the antenna were calculated for $\theta = 20^\circ$, 45°, 80°, 200°, and 275°, respectively. Without considering the shading of the antenna by the Earth, and considering only the mutual shading between the antenna and the truss, the cloud maps of the shading coefficient are plotted as shown in Figs. 4-8, where light yellow denotes the illuminated region and black denotes the unilluminated region.

表 1　天线关键几何参数

Tab. 1　Key geometric parameters of the antenna

Parameter	Value
Aperture/m	40
Wall thickness/mm	10
Number of transverse rods	40
Joint mass/kg	0.01
Number of vertical rods	20
$(I_{xx}, I_{yy}, I_{zz})/(\mathrm{kg}\cdot\mathrm{m}^{-2})$	0.01, 0.01, 0.01
Number of diagonal rods	20
Outer diameter of rod/mm	50

The heat-flux density received by each element of the antenna truss members was calculated. The calculation time step was 1 min. Four key positions in the antenna truss structure, including points A, B, C, and D (Fig. 3), were selected, and the heat-flux-density curves received at these four positions were plotted, as shown in Fig. 9. It can be seen that, due to the shielding effect among the antenna elements, the four curves differ significantly. When the antenna leaves the Earth' s shadow region at about 2 084.5 s, the heat-flux density received by the antenna truss members at positions A and B rapidly increases to the maximum value, whereas the heat-flux density received at positions C and D remains 0 at 16 080 s and 20 340 s.

图 3　天线桁架结构关键点位置示意图

Fig. 3　Schematic of key points of antenna truss structure

Because the antenna is initially in the backlit region, the shading coefficient is entirely 1. As the incidence angle increases, the area of the antenna truss

Fig. 4

Figure 4: Fig. 4

Fig. 5

Figure 5: Fig. 5

receiving solar illumination continuously increases. When the solar incidence angle is greater than the right critical [[unclear: text continues on next page]]

angle $\theta_r = 95.710\,6°$ and left critical angle $\theta_l = 275.710\,6°$. If occlusion between members is not considered, all members are irradiated by sunlight at this time; among them, at the special position $\theta = 180°$, the bottom of the antenna is fully irradiated, while all other locations are fully occluded.

图 4 天线绕地球旋转 20° 下光线遮挡

Fig. 4 Distributions of the shielding coefficient of the antenna when it rotates 20° around the Earth

图 5 天线绕地球旋转 45° 下光线遮挡

Fig. 5 Distributions of the shielding coefficient of the antenna when it rotates 45° around the Earth

图 6 天线绕地球旋转 80° 下光线遮挡

Fig. 6 Distributions of the shielding coefficient of the antenna when it rotates 80° around the Earth

图 7 天线绕地球旋转 200° 下光线遮挡

Fig. 7 Distributions of the shielding coefficient of the antenna when it rotates 200° around the Earth

图 8 天线绕地球旋转 275° 下光线遮挡

Fig. 8 Distributions of the shielding coefficient of the antenna when it rotates 275° around the Earth

图 9 不同关键点处太阳入射热流密度时间历程曲线

Fig. 9 Time-history of the effective solar heat flux at different key points

Fig. 6

Figure 6: Fig. 6

Fig. 7

Figure 7: Fig. 7

Fig. 8

Figure 8: Fig. 8

2.2 Temperature-field calculation

The initial temperature of the antenna is set to 20 °C, and it is in the vernal equinox condition. The antenna material is carbon fiber, and the material parameters are shown in Table 2. According to the calculations in Section 2.1, the solar incident heat flux at various locations of the antenna is obtained, and the variation of the antenna temperature field during orbital operation is calculated. Figure 10 gives the antenna temperature-field cloud maps at operating times of 7 200, 21 600, 32 400, and 64 800 s, respectively. It can be seen from Fig. 10 that, because the occlusion effect is considered, the temperature distribution over the antenna is extremely nonuniform, and the maximum temperature difference in the antenna temperature distribution can reach about 270 °C. Meanwhile, the time-history curves of temperature at the four key nodes A, B, C, and D shown in Fig. 11 are plotted. It can be seen that, during orbital operation, owing to the antenna entering and leaving the shadow region and the occlusion effect of the antenna reflecting surface, the temperature at various positions of the antenna truss fluctuates greatly, and the maximum range of temperature variation can reach 300 °C.

表 2 天线关键材料参数

Tab. 2 Key material parameters of the antenna

参数	值
Elastic modulus / Pa	1.75×10^{11}
Density / $(\mathrm{kg} \cdot \mathrm{m}^{-3})$	1 600
Thermal expansion coefficient / (K^{-1})	8×10^{-7}
Solar absorptivity	0.81
Emissivity	0.6
Poisson’ s ratio	0.3
Thermal conductivity / $(\mathrm{W} \cdot \mathrm{m}^{-1} \cdot \mathrm{K}^{-1})$	400

Fig. 9

Figure 9: Fig. 9

参数	值
Specific heat capacity / ($J \cdot kg^{-1} \cdot K^{-1}$)	800

(a) time = 7 200 s (c) time = 21 600 s

(b) time = 32 400 s (d) time = 64 800 s

Fig. 10 Temperature distribution cloud maps of the antenna truss structure at different times (unit: °C)

Fig. 11 Time-history curves of the temperature at key positions

3 Conclusion

For the circular truss antenna structure, a new method for calculating the occlusion coefficient of antenna components is proposed. This method also accounts for the influence of the Earth-shadow effect on the incident solar heat flux. Based on this method, the effective incident solar heat-flux density received by each part of the antenna components during orbital operation is obtained. Meanwhile, a thermal radiation–conduction analysis model of the circular truss antenna structure is established. Using the calculated effective incident heat flux as input, temperature-field analysis and thermally induced vibration analysis are carried out respectively.

The calculation results show that occlusion among the internal structures of the truss has a relatively large influence on the temperature-field distribution of the antenna, with the maximum temperature difference reaching nearly 300 °C. In addition, under the influence of the orbital Earth-shadow effect, at times such as entering and leaving the Earth-shadow region, the antenna undergoes instantaneous rapid temperature changes, which may further produce relatively large thermal deformation and thermally induced vibration, thereby affecting the surface accuracy of the antenna.

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Figure 1

Figure 10: Figure 1

Figure 2

Figure 11: Figure 2

Figures

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