

Spacecraft reflectors thermomechanical analysis

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Abstract. In this article, thermo-mechanical analysis results of the composite reflectors for the use on the geostationary Earth orbit possibility studies are described. The behavior of two different space reflector structures manufactured on composite materials is investigated. The estimates of reflecting surfaces RMS deviations for the two extreme cases orbital inclinations are presented.

1. Introduction

Radio frequency communications systems development generates the need for creating space antennas bearing reflective surface with root-mean-square deviation (RMSD) about 10^{-5} meters. Such specifications could be attainable by use of precision reflectors manufactured of composite polymer materials. In addition to high accuracy such reflectors are lightweight and therefore have high dynamic characteristics in comparison with similar reflectors made of metals. The aperture size of precision reflectors is limited by the launch vehicle fairing dimensions.

Stiff precision reflectors have application to spacecraft along with large deployable antenna reflectors [1]. Transformable reflectors with oversized aperture should satisfy mass, stiffness and reflective surface accuracy requirements (approximately RMSD 5^{-3} meters).

Antennas belong to the category of external spacecraft appendages exposed to thermal, radiation and mechanical environments [2]. So besides the surface imperfections due to assembly operations, manufacture processes and specific design features, one of the main factors that influence the reflective surface accuracy of both of these reflectors is temperature deformations of the structures as a result of non-uniform heat distribution during orbital exploitation. Therefore it is necessary to analyse the thermomechanical behavior of each reflector concept for space application.

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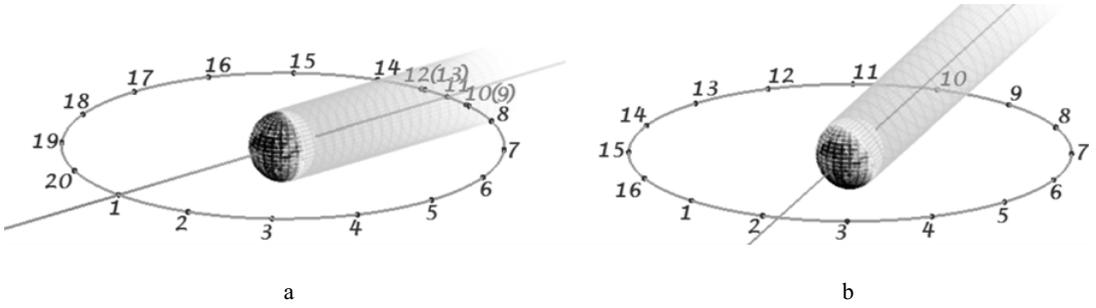


Figure 1. Considered positions of reflectors on GEO: a) March equinox, b) December solstice.

2. Problem formulation and solution method

Thermal mode of reflector is determined mainly by solar radiation, additionally due to solar flux reflected from the Earth, by its own infrared radiation of the Earth, and also due to the solar radiation reflected from the structural elements of the spacecraft [3].

The finite element (FE) method is widely used to solve the problem of finding the temperature distribution in the structure elements. For each FE drawn heat balance equation of the form:

$$(c_m)_i \frac{\partial T_i}{\partial \tau} = Q_i^{ext} + Q_i^{int} + \sum_j \left(\lambda \frac{F}{\delta} \right)_{j-1} (T_j - T_i) + \sum_k \varepsilon_i H_{i-k} \sigma (T_k^4 - T_i^4), \quad (1)$$

where $(c_m)_i$ – heat capacity, Q_i^{ext} – external heat flux on the node i , Q_i^{int} – internal heat generation in the node i , $\lambda \frac{F}{\delta}$ – coefficient determining conductive connection i and j nodes, ε_i – emissivity of node i , H_{i-k} – surface of the mutual radiative heat exchange between i -th and k -th nodes, $\sigma = 5.67 \cdot 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{°C}^4)$ – Stefan-Boltzmann constant.

For each node of the thermal model the heat balance equation is written. The system of equations, supplemented by boundary and initial conditions, completely describes the thermal model. Solar flux Q_{solar} , incident on a unit area design, has the form:

$$Q_{solar} = A_s \cdot S_0, \quad (2)$$

where A_s – the coefficient of absorption of solar radiation, S_0 – solar constant, whose value varies during the year from $1320 \text{ W}/\text{m}^2$ to $1420 \text{ W}/\text{m}^2$. Earth infrared radiative flux is determined by equation:

$$Q_{earth} = Q_{IR} \cdot \varepsilon \cdot \sin^2 \rho, \quad (3)$$

where Q_{IR} – infrared radiation of the Earth ($237 \pm 21 \text{ W}/\text{m}^2$), ε – emissivity, $\sin^2 \rho = R_E / (h + R_E)$, R_E – radius of the Earth, h – the orbit altitude of the object. Heat fluxes Q_{ref} , reflected from Earth

$$Q_{ref} = S_{max} \cdot A_s \cdot a \cdot K_a \cdot \sin^2 \rho. \quad (4)$$

where a – Albedo, K_a – correction coefficient for the solar energy reflection from the Earth sphere.

Thermal math model of the reflector structure includes the finite number of isothermal nodes interconnected by thermal couplings, defined by embodiment of the calculation model node. In the thermal model considered:

- conductive heat transfer between nodes of the antenna structure,
- reradiative heat transfer between nodes of the antenna structure.

To solve the obtained system of equations the available standard or special software, such as specific application for space systems developed by Maya Heat Transfer Technologies Ltd. are used.

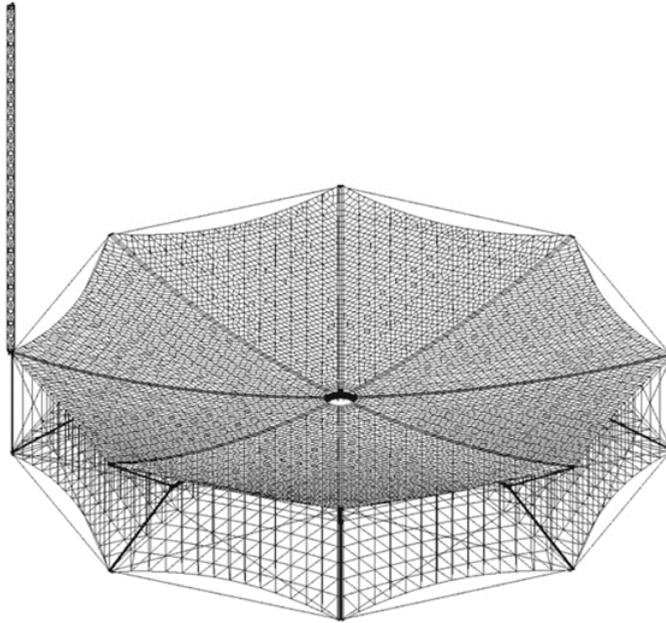


Figure 2. Large deployable reflector FE model.

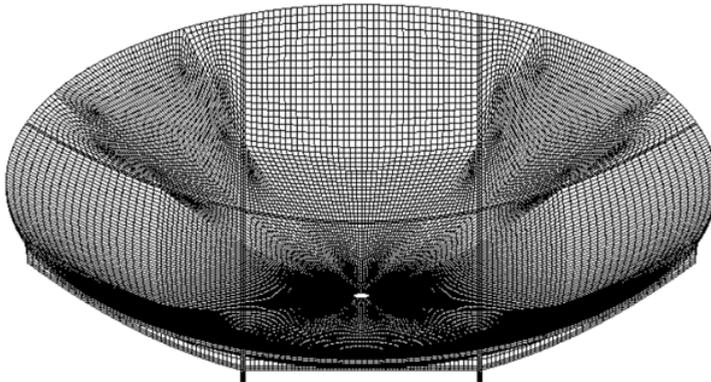


Figure 3. Rigid precise reflector FE model.

Reflectors thermal analysis on the geostationary orbit (GEO) was carried out for the two extreme simulation cases: March equinox ($S_0 = 1380 \text{ W/m}^2$) and the December solstice ($S_0 = 1420 \text{ W/m}^2$). In the March equinox case the shadow of the Earth on the orbital segment duration of 72 minutes is added. All calculations are performed for the period of time in 24-hour with increment on orbital spiral of 10 minutes.

As the results of the thermal mode analysis the arrays of temperature values, which were used as boundary conditions for the stress-strain state (SSS) analysis were obtained.

The thermo-mechanical behavior on the GEO of two reflector structures: precise with aperture diameter of 1.8 m and large deployable reflector on the boom with a diameter of 50 m sizing is investigated. Figures 2, 3 shows the FE model for the SSS analysis of reflectors. Thermal FE models were constructed in accordance with the FE models for SSS simulation and large reflector model was

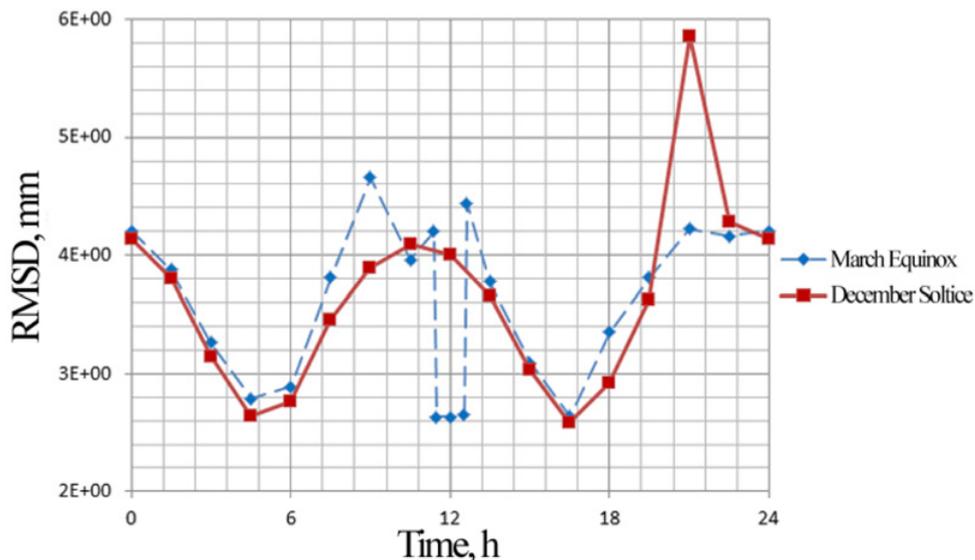


Figure 4. RMSD hourly changes of the large deployable reflector.

adopted by a number of simplifications. The effective thermal characteristics of honeycomb plate was calculated by using approaches and theories described in [4, 5]. Each model has its design features, whose implementation was successfully carried out with the use of possibilities to build and model parameterization in software package ANSYS.

So the model of large deployable reflector contains not only the rigid elements performing the role of load-bearing structure, the metallic net forming the reflective surface, the set of cords, strengthening the rigid structure, the set of rope elements forming the front and back nets and the cords, supporting the parabolic shape of the surface.

The model of precise reflector that is a sandwich structure with the composite skins and aluminum honeycomb core, takes into account orthotropic properties and the material laying.

Following the preliminary calculations, using the possibility of the restart function the stress strain state of each structure under the influence of thermal loads was determined, after that RMSD and radio frequency characteristics on displaced nodes of the reflective surface were calculated.

3. The results of the numerical simulation

For each of the reflector were plotted graphs describing hourly changes of RMSD, presented in Figs. 4, 5. Figure 4 describes RMSD of the large deployable reflector, and Fig. 5 – RMSD of the precise reflector.

From the graphs, positions of reflectors with the highest values of RMSD were determined and using the arrays of reflective surface nodes coordinates of the directivity pattern calculated. Figure 6 shows of the numerical analysis results of the precise reflector behavior on a GEO for the period of time (12.5 h) corresponding to the highest distortions and maximum RMSD (a – temperature distribution, b – total displacement of the nodes).

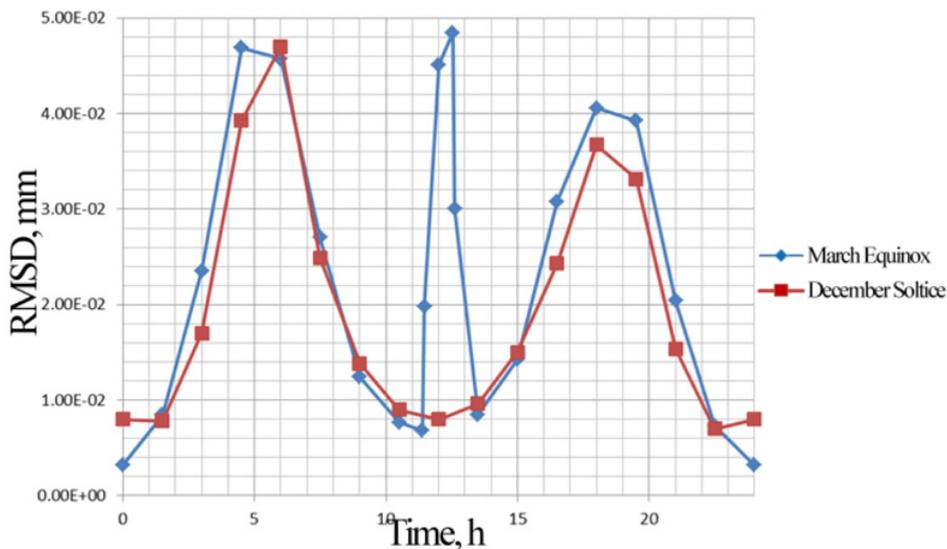


Figure 5. RMSD hourly changes of the rigid precise reflector.

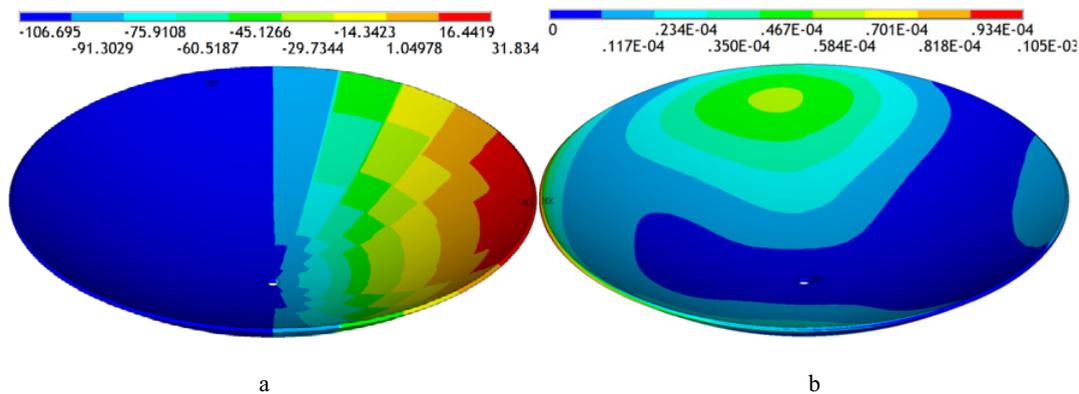


Figure 6. Precise reflector analysis results for the time corresponding to the highest RMSD: a) temperature distribution, K; b) total nodes displacement, m.

4. Conclusion

Using the software complexes facilities and opportunities thermo-mechanical behavior of the composite reflectors for the study of possibility of their use on the GEO was analyzed. The thermal analysis results show the applicability of carbon fiber composites for structural elements of precision reflectors. RMSD magnitudes for reflectors with maximum thermal strains of the reflective surfaces do not exceed the required values for the given structures.

References

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