Thermal design and analysis of high power star sensors

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\textbf{Abstract}

The requirement for the temperature stability is very high in the star sensors as the high precision needs for the altitude information. Thermal design and analysis thus is important for the high power star sensors and their supporters. CCD, normally with Peltier thermoelectric cooler (PTC), is the most important sensor component in the star sensors, which is also the main heat source in the star sensors suite. The major objective for the thermal design in this paper is to design a radiator to optimize the heat diffusion for CCD and PTC. The structural configuration of star sensors, the heat sources and orbit parameters were firstly introduced in this paper. The influences of the geometrical parameters and coating material characteristics of radiators on the heat diffusion were investigated by heat flux analysis. Carbon–carbon composites were then chosen to improve the thermal conductivity for the sensor supporters by studying the heat transfer path. The design is validated by simulation analysis and experiments on orbit. The satellite data show that the temperatures of three star sensors are from 17.8\degree C to 19.6\degree C, while the simulation results are from 18.1\degree C to 20.1\degree C. The temperatures of radiator are from 16.1\degree C to 16.8\degree C and the corresponding simulation results are from 16.0\degree C to 16.5\degree C. The temperature variety of each star sensor is less than 2\degree C, which satisfies the design objectives.

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1. Introduction

The attitude accuracy of star sensors has great influence on the precision of the earth observation from the space. With the development of the optical technology, the objects on the earth under 10 m could be distinguished from the space and the attitude accuracy of the star sensors must be higher than 5\degree in this situation [1,2]. The requirement for the attitude accuracy of the star sensors is thus much higher, and the thermal deformation cannot be ignored. The data from the satellites on orbits show that thermal deformations especially deformation of the mounting surface has become the most important factor affecting the altitude accuracy of star sensor [3–5]. The temperature variety of the star sensors are affected by the space heat flux and the internal power consumption. The effect of space heat flux could be reduced through optimizing the distribution of sensors [6]. Thus the heat diffusion design of internal heat has become significant in the thermal design of CCD star sensors for the high-resolution optical remote sensors. Peltier thermoelectric cooler (PTC), which is a typical cooler for CCD star sensors and operates through the satellite’s life, turns to be more important for CCD star sensors. The major objective for the thermal design thus is to diffuse the heat generated by the Peltier thermoelectric coolers.
ASTRO™ 10 star sensors, which are the thermal design objectives of this paper, are installed at a high-resolution optical remote sensor. There are three star sensors and each star sensor consists of an optical head and electrical units. The optical heads are mounted on the pedestal of optical remote sensor. The electrical units are located in the instrument cabin of the satellite and attached to the optical heads with cables. The rated accuracy of ASTRO™ 10 star sensor is not larger than $2''$ and the actual attitude accuracy of the satellite on orbit could be smaller than $5''$ if the temperature of star sensors are controlled within $\pm 3^\circ C$ [8,9]. The product instruction of ASTRO™ 10 shows that the power consumption of each optical head is 2 W with PTC off. The power consumption of the optical head could be more than 2 W and even be 5.5 W if the PTC operates at the target temperature of the CCD set as $-20^\circ C$, $-10^\circ C$, $-5^\circ C$ and $0^\circ C$.

In order to guarantee the attitude accuracy of the star sensors, thermal design is carried out for ASTRO™ 10 star sensors and their mounting supporter. A heat radiator is designed on the sensor supporter to dissipate the heat from PTC. The structure of the paper is as follows. Section 2 introduces the structure configuration of star sensor suite. The thermal design of the radiator is then presented in Section 3. The simulation of thermal analysis is in Section 4 and the experiment validations are presented in Section 5. At the end of the paper is the Conclusions.

2. Structural configuration of star sensors suite

The structural configuration of star sensors suite is shown in Fig. 1, which is composed of three star sensors and a mounting supporter. Each star sensor includes a baffle, optical components, a CCD with PTC and a mounting flange. The flange and the baffle are made of AlZnMgCu1.5, while the mounting supporter is made of cast titanium alloy. Star sensors are mounted on the supporter by flanges and the supporter is mounted on the pedestal of optical remote sensor through mounting surfaces.

3. Design of the radiator

3.1. The problem to be solved

The power consumption of each optical head with PTC off was 2 W in a previous satellite and the average diffused heat is about 3 W on orbit through baffle in an orbit period [5].

If the PTC turns on, the power consumption of optical head is more than 2 W. The temperature of star sensor on orbit
would be out of control with the previous thermal design pattern in this situation. A heat radiator thus needs to be designed and this radiator should absorb as little heat flux as possible. Otherwise, the temperature of star sensor would be higher than the requirements.

3.2. Orbit parameters

The orbit of the satellite is a Sun synchronous circular orbit with inclination of 97° and altitude of 480 km. The local time of descending node is 1:00 P.M. The Z direction of the satellite always points to the Earth and the satellite flights along X direction. According to the satellite reference frame, the star sensors suite is located on X direction of the satellite.

3.3. Thermodynamic equilibrium equations

The thermodynamic equilibrium equation of the star sensors suite on the satellite could be described as below,

\[ \sigma T^4 S = Q_{\text{inner}} + \left[ q_{\text{solar}} \left(1 + k_{a\text{albedo}}\right) \right] \cos \beta S_{\text{sensor}} + q_{\text{earth}} \epsilon_{\text{h}} S_{\text{radiator}}. \]  

(1)

The parameters \( q_{\text{earth}} \), \( k_{a} \), \( F \) and \( \rho_{\text{albedo}} \) are defined with the orbit and structure parameters. Six parameters to cause the temperature variety are listed as below.

\( Q_{\text{inner}} \), inner power of star sensors;  
\( q_{\text{solar}} \), solar constant;  
\( \beta \), beta angle;  
\( \alpha_{s} \), solar absorptivity;  
\( \epsilon_{h} \), infrared emissivity;  
\( S \), area of the radiator.

In order to control the temperature in the requirement range, the power of the internal heat sources should be controlled and the ratio of solar absorptivity to infrared emissivity should be small and the infrared emissivity should be high.

3.4. Internal heat sources of star sensors

According to the data from previous satellite, the actual power consumption of optical head is much more than 5.5 W when the target temperature of CCD is set as –20 °C. In order to identify the internal heat sources and certify the power consumption of the optical head, ground tests were carried out. The interface temperature in the ground tests are 18 °C and the power consumptions of different CCD target temperatures are shown in Table 1.

3.5. Heat flux analysis

The star sensors suite is located on X direction of the satellite. The heat flux absorbed by the suite is directly related to the absolute value of beta angle, which is the angle between solar and orbit plane. The higher the absolute value of beta angle is, the less sun energy the star sensors absorb. Beta angle of the satellite changed from 1st Jun 2012 to 1st Jun 2013 as shown in Fig. 2. The maximum of beta angle in a year is –15.9°, on 21st Jan 2013. The minimum of beta angle in a year is –25.1°, on 15th May 2013. Combined with variety of solar flux, 15th May 2013 with solar flux of 1322 W/m² is set to be cold case and 21st Jan 2013 with solar flux of 1412 W/m² is set to be hot case.

The exposed faces of the sensors suite are mainly on the baffles and the supporter. There are thus two radiator designs. One is to choose baffles as the radiator and the other one is to choose part of the supporter as the radiator. The choice of the radiator is decided by the value of the heat flux, which is the reason of heat flux analysis. The average incident heat flux densities of star sensors and their supporter in an orbit period in hot case are calculated and shown in Fig. 3.

As shown in Fig. 3, the highest incident heat flux density is located on the baffles. The higher incident heat flux means the higher heat absorbed from space as discussed before. Thus the baffles cannot be chosen as radiators in this case. The area on the supporter between sensor B and sensor C is chosen to be the radiator since its incident heat flux density is lowest.

<table>
<thead>
<tr>
<th>Temperature target of CCD (°C)</th>
<th>0</th>
<th>−5</th>
<th>−10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption (W)</td>
<td>5.1</td>
<td>7.8</td>
<td>8.4</td>
</tr>
</tbody>
</table>

Table 1  
Power consumptions of different CCD target temperatures.
3.6. The radiator coating

Because of the ultraviolet and particle (electron, proton) irradiation, atomic oxygen and etc., the thermal control materials coated in the radiator may degrade in space [10,11]. The degradation of the materials in thermal control ability is mainly demonstrated as the ascent of solar absorptivity. The changes of the solar absorptivity and emissivity of materials in LEO orbit for three years are listed in Table 2. ITO coated silverized F46 film is chosen to cover the radiator since its ratio of solar absorptivity to infrared emissivity is lowest after three years operation. It is worthy to point out that the emissivity of the F46 film is positive relevant to film thickness. The emissivity of the film with 127 μm is 0.78 [10] and the one with 50 μm is 0.69. However, in this paper, the film of 50 μm is the only choice in our institute. The absorbed heat flux density of the radiator was calculated out after the coating, which is not higher than 34.2 W/m². The amplified figure of the area is shown in Fig. 4.

<table>
<thead>
<tr>
<th>Material</th>
<th>Solar absorptivity (Initial)</th>
<th>Emissivity (3 years later)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITO coated alumi-nized polyimide</td>
<td>0.36</td>
<td>0.56 [12]</td>
</tr>
<tr>
<td>ITO coated silverized F46</td>
<td>0.13</td>
<td>0.32 [13]</td>
</tr>
<tr>
<td>5781 white paint</td>
<td>0.23</td>
<td>0.46 [13]</td>
</tr>
</tbody>
</table>
3.7. Heat transfer path

The internal heat is generated by the electronic components including CCD and PTC, which are located in the circuit box under the mounting flange. The heat transfer path is shown in Fig. 5. The heat generated from CCD and PTC diffuses through circuit box and mounting flanges to the radiator. The heat diffusion efficiency is thus improved by optimizing the heat resistance from the mounting flanges to the radiator in this paper.

In order to reduce the heat resistance, carbon–carbon composites with high thermal conductivity (about 350 W/m/K) were adhered to both sides of the supporter with silicon rubber. The composites used on both sides had the same thickness of 0.5 mm. The thermal conductivity of the supporter is improved from 8.8 W/m/K to 45 W/m/K by adhere the composites [14].

3.8. Radiating ability

The optimized maximum area of radiator is 0.025 m². Since it mainly orients to –Y direction, the radiator nearly could not be illuminated directly by the sunlight. There is no object to block the view from radiator to the space, so the view factor could be set to 1. According to formula followed:

\[ Q = \sigma \cdot \varepsilon \cdot F \cdot T^4 \cdot S, \]

The power radiated out is 6.83 W when the temperature of the radiator surface is 16 °C.

In hot case, the range of absorbed heat flux of radiator is shown in Fig. 6. The average power in an orbit period is about 0.53 W and the peak value is 0.81 W.

The actual power radiated out is about 6.3 W considering the average absorbed heat flux. To maintain the temperature of radiator, the power of active heater is ultimately set to 8 W according to the margin principle in thermal design.

The power diffused with the baffles is about 9 W. The total power radiated out by the sensors suite is about 15.3 W if ignoring the heat exchange of multilayer insulation (MLI). The target temperature of CCD could be set to 0 °C on which the amount of power consumptions is 15.3 W.

4. Thermal analysis

4.1. Model

In order to validate the design, simulations were carried out by Thermal Desktop. The hot case and cold case were set as shown in Table 3. The transient thermal analyses were accomplished considering the orbit parameters, the distribution of internal power consumptions, the optical properties of MLI and covered film.

![Fig. 4. Absorbed heat flux density of radiator in hot case.](image)

**Fig. 4.** Absorbed heat flux density of radiator in hot case.

**Fig. 5.** Heat transfer path.
4.2. Results of hot case

The highest temperatures of mounting flanges and the supporter in hot case are shown in Fig. 7. The temperature range of mounting flanges is from 18.3 °C to 20.1 °C and the range of radiator is from 16.0 °C to 16.5 °C.

Temperature variety of the star sensors suite is shown in Fig. 8. The temperature changes periodically with time. Sensor A has the highest PV value of 1.6 °C and sensor B has the lowest PV value of 0.5 °C.

4.3. Results of cold case

Space heat flux in cold case is lower than that in hot case and the power consumptions of star sensors also decrease. The temperature ranges of star sensors and radiator are thus narrower compared with the ones in hot case.

The periodic variety of temperatures in cold case is shown in Fig. 9. The temperature range of mounting flanges is from 18.1 °C to 19.5 °C and the range of radiator is from 16.0 °C to 16.4 °C.
4.4. Result statistics

Table 4 contains temperatures of components in cases. The lowest temperature of star sensors is 18.1 °C and the highest value is 20.1 °C. Temperature differences among star sensors are not more than 2 °C and range of each star sensor is less than 2 °C.

5. Test on orbit

The satellite was launched into orbit in 2012. Temperature targets of CCD of star sensors were all set at 0 °C. Temperatures on 21st Jan 2013 are shown in Fig. 10. Temperatures on 15th May 2013 are shown in Fig. 11. As shown in Table 5, temperature variety among star sensors on orbit is smaller than 1.8 °C and the range of either star sensor is in 1.8 °C. The temperature range of the star sensors is from 17.8 °C to 19.6 °C and the temperature range of the radiator is from 16.1 °C to 16.8 °C. Considering numerical error of acquisition system, difference between analysis and data on orbit could be accepted.

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Temperatures in transient cases (°C).</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Radiator</td>
</tr>
<tr>
<td>Hot case</td>
<td>16.0–16.5</td>
</tr>
<tr>
<td>Cold Case</td>
<td>16.0–16.4</td>
</tr>
</tbody>
</table>

Fig. 8. Temperature variety in hot case.

Fig. 9. Temperature variety in cold case.
6. Conclusions

In order to realize the temperature stability of the star sensors ASTRO™ 10, a radiator is designed through thermal analysis in this paper. The location, the coating thermal control material and the heat transfer path of the radiator are analyzed. The optimized area of the radiator is 0.025 m², which located on the supporter between sensor B and sensor C. The thermal conductivity of the supporter is improved from 8.8 W/m/K to 45 W/m/K with adhering carbon–carbon composites.

The simulation results show that the temperature variety of each star sensor is less than 2 °C. The maximum variety of star sensors on orbit is less than 1.8 °C, which validates the thermal design of the radiator. The attitude accuracy of star sensors with this design can be smaller than 5″ which guarantees the earth observation accuracy within 12 m from orbit in 480 km high.

References


