THERMAL MODELING TECHNIQUE FOR A SATELLITE IMAGER

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인공위성 영상기의 열모델링 방법

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Conductive and radiative thermal model configurations of an imager of a geostationary satellite are presented. A two-plane method is introduced for three dimensional conductive coupling which is not able to be treated by thin shell plate thermal modeling technique. Especially the two-plane method is applied to massive matters and PIP(Payload Interface Plate) in the imager model. Some massive matters in the thermal model are modified by adequate correction factors or equivalent thickness in order to obtain the numerical results of thermal modeling to be consistent with the analytic model. More detailed nodal breakdown is specially employed to the object which has the rapid temperature gradient expected by a rule of thumb. This detailed thermal model of the imager is supposed to be used for detailed analyses and test predictions, and be correlated with the thermal vacuum test results before final in-flight predictions.

Key Words : Thermal Modeling, Two-plane Method, Interface Conductance, FEM, FDM, GOCI, COMS

1. INTRODUCTION

This paper shows the detailed thermal model description of the GOCI(Geostationary Ocean Color Imager) main unit installed onto COMS(Communication, Ocean, and Meteorological Satellite) of Korea[1]. GOCI is the first ocean color imager operated on the geostationary orbit. Conductive and radiative configurations of the GOCI thermal model are presented. As an old fashioned manner since 1960's, thin shell plate modeling is prefered in the spacecraft thermal engineering because of its heritage and well-established numerical and/or experimental database[2]. Therefore the basic method for thermal modeling recalls two-dimensional thin shell plate modeling technique. Hereafter a newly devised, called, two-plane method is introduced for three dimensional conductive coupling adapted to the general thin shell plate thermal modeling. Some massive matters in the thermal model are modified by adequate correction factors or equivalent thicknesses in order to obtain the numerical results of thermal modeling to be consistent with the analytic model. More detailed nodal breakdown is specially employed to the FPA(Focal Plane Array), PIP(Payload Interface Plate) bipods, entrance baffle, pupil and the pointing mirror of the GOCI[3]. Thermica v3.2[4] is basically used to build up the thermal models by using thin shell plates thermal meshing. As a result, the mathematical thermal model of GOCI includes 3674 lumped capacity nodes[5]. The GOCI elements names used in this paper are given in the Fig. 1 and Fig. 2. GOCI is extensively composed of the telescope, FPA, mechanisms, and secondary structure enveloping the former elements. In order to analyze the accurate thermal behavior of GOCI, detailed radiative and conductive thermal models representative of the physical characteristics are necessary.

2. THERMAL MODELING OF MIRRORS

2.1 GENERAL

Thin shell plates are basically used in thermal modeling

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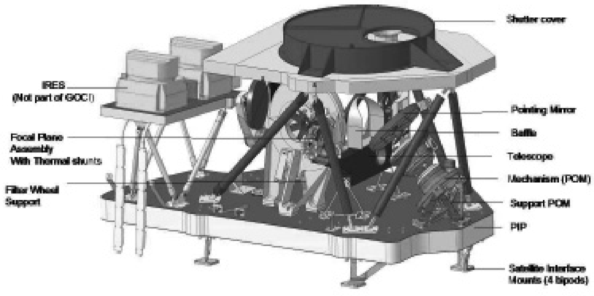


Fig. 1 Overview of GOCI without radiators and MLI

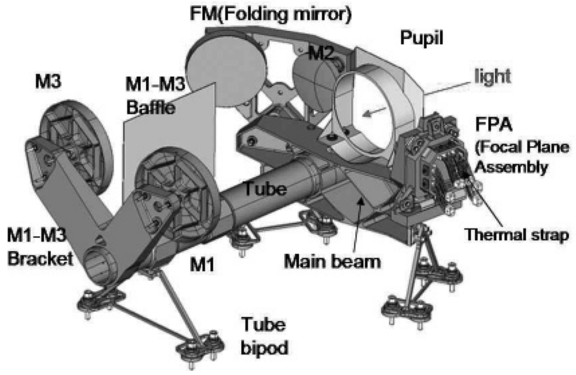


Fig. 2 GOCI Telescope

for all mirrors.

Two-dimensional heat conduction can be only considered when thin shell plates are totally used in the thermal model. All the faces of thin shell plates are both active in thermal radiation except for the mounting feet which are modeled as non-active radiative surfaces on their contact area. Masks are included in the model when necessary. All the optical faces of the mirrors are modeled with triangular thermal nodes in order to avoid the surface warping which would be appeared in quadrangle thermal nodes. At least two thermal nodes in the height (axial direction) are modeled for all stiffeners in order to get the axial temperature gradient of the mirrors. The conductive coupling calculation is made by using FEM method. Edge nodes are used to simulate the conductive heat transfer and are included not in the other sub-models but in the main thermal model.

2.2 THERMAL MODEL THICKNESS CORRECTION

Most of the mirror components are based on thin shell plate modeling except for massive matters such as a mast which connects the mounting feet and the optical face.

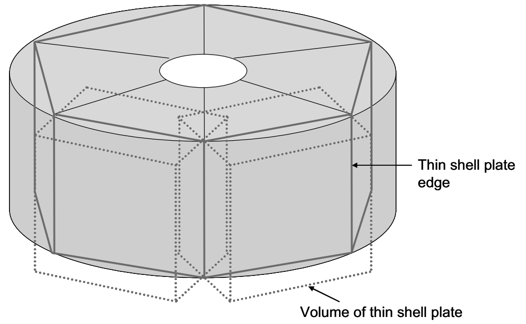


Fig. 3 Heat capacity difference between the analytic and numerical model

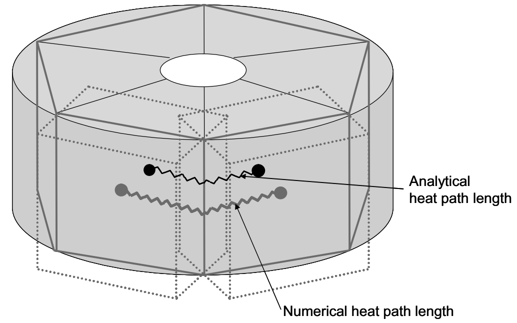


Fig. 4 Conductive coupling difference between the analytic and numerical model

Mirrors are divided into several components. For example, the components are the outer/radial/circumferential stiffeners (inner and outer); lower/middle/upper mast, mounting feet, and the optical face. Sometimes high thicknesses, for example, more than 0.01m induce the overestimation and/or underestimation in heat capacity and conductive coupling calculation for curved shapes. In Fig. 3 and Fig. 4, differences are illustrated between the analytic model and the numerical model when the models are divided into six nodes. The thick solid line is a numerical thin shell plate edge in the geometrical model, and the dashed line is the volume of each thin shell plate. The heat capacity of numerical model is generally larger than that of the analytic model because the thickness of the numerical model is a constant with radius direction by thin shell plate modeling. Therefore, some additional volumes should be included in heat capacity calculation. On the other side, in the numerical model, the conductive thermal path length between adjacent nodes is longer than that of the analytic model, which means that the conductance of the nodes would be smaller one. Numerical correction factors which are equivalent to the

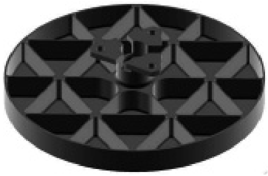


Fig. 5 Solid model of PM

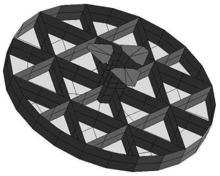


Fig. 6 Thermal model of PM

Fig. 7 Solid model of the M2 mirror

results from the analytic model are obtained in the calculation of heat capacity and conductive coupling.

In M1, M3, FM and PM mirrors thermal modeling, there are lower and/or middle mast components having high thicknesses with curved shapes. It is needed to check if there is the compatibility between the analytic calculation and the numerical calculation. The numerical radiative area always shown as flat surfaces in thin shell plate modeling is smaller than the analytic one since the numerical radiative area does not take the real outer curved shape into consideration. These radiative area corrections are not considered in this modeling.

2.3 POINTING MIRROR MODELING

The solid model of the GOCI pointing mirror is shown in Fig. 5. SiC is used for the mirror material. The radiative and conductive thermal model configuration of the pointing mirror is shown in Fig. 6. The radiative thermal model exactly uses as the same shown in the Fig. 6. However each quadrangle, rectangle, or triangle node has different thicknesses corresponding the solid model illustrated in Fig. 5. There are two components, lower and middle mast, to be considered by correction factors in the pointing mirror thermal modeling. The calculated results for the heat capacity and conductive coupling correction of the mirror are shown in Table 1 accompanying their correction factors. The correction of each component thickness for the mirror is shown in Table 2.

2.4 M2 MIRROR MODELING AND TWO-PLANE METHOD

The solid model of the GOCI M2 mirror is shown in Fig. 7. The mirror material is also SiC.

Three-dimensional conduction heat transfer simulation is impossible in the thin shell plate thermal model which is made in Thermica version 3.2. So, a method is developed that is enabled to simulate the three-dimensional conduction heat transfer using a thin shell plate thermal model and called “Two-plane method”. The two-plane method uses:

Table 1. Numerical correction factor in heat capacity and conductive coupling

Component	Heat capacity			Conductive coupling		
	Analytic(J/K)	Numerical(J/K)	Correction factor	Analytic(W/K)	Numerical(W/K)	Correction factor
Lower mast	49.654	63.581	0.781	5.500	4.296	1.280
Middle mast	10.387	16.257	0.639	1.719	1.098	1.565

Table 2. Correction of each component thicknesses

Mirror	Description	Thickness before correction(m)	Thickness after correction(m)	Note
Pointing mirror	Outer stiffener	0.002	0.002	
	Radial stiffener	0.0015	0.0015	
	Circum.(Inner) stiffener	0.0015	0.0015	
	Circum.(Outer) stiffener	0.0015	0.0015	
	Lower mast	0.016	0.0205	1)
	Middle mast	0.012	0.0188	1)
	Upper mast	0.003	0.003	
	Feet	0.005	0.005	
	Optical face	0.0022	0.0022	

1) Thicknesses are not acceptable in thin shell plate modeling for cylindrical shapes. Correction is inevitable.

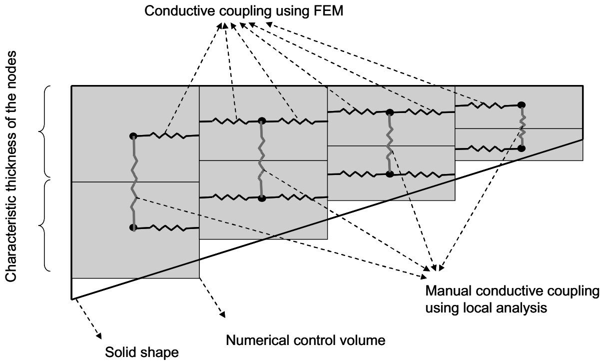
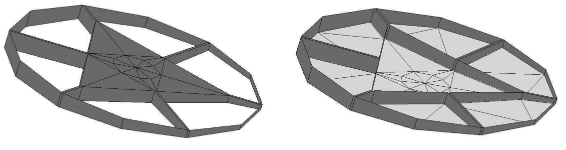


Fig. 8 Schematic of two-plane method

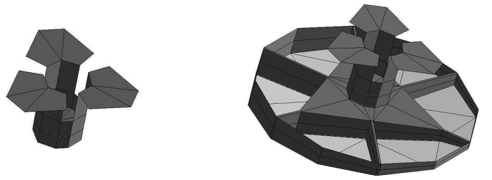
— Two thin shell plate thermal mesh
— Each thin shell plate mesh has the conductive coupling inside its internal mesh(using FEM / local analysis)
— The third direction of heat path between the two thin shell plate meshes is modeled by using the local analysis method(GL=kA/L)

In the case that the thin shell plate mesh has a variable cross-sectional area along to the heat path, the characteristic thicknesses of the thin shell plate mesh are determined by choosing the arithmetic average thickness of the minimum and maximum thicknesses for a given mesh. The schematic that describes the two-plane method is shown in Fig. 8. For the M2 mirror, total three massive matters are considered for the three-dimensional heat conduction simulation. Two massive matters are generated from each of the half of the outer stiffener and the massive triangle which supports the optical face.

Another massive matter is the middle mast which connects the massive triangle to the mounting feet. These three massive matters are represented by a thin shell plate having high thickness. Each thin shell plate is thermally coupled by the conductive conductance manually. The M2 mirror thermal model configurations are shown in Fig. 9.A ~ Fig. 9.D. In the figures the three thin shell plates representing massive matters are described and the heat capacity model of the M2 mirror. Conductive couplings of each of the planes are automatically calculated by FEM method in Thermica, and then the local analysis method is manually used in order to make conductive couplings between the planes. Especially all side walls of the radial stiffeners and the massive triangle which are not involved in the conductive model have the thickness of zero that is applicable only to the radiative geometry model. The M2 mirror thermal model configurations are shown in Fig. 9.(a) - Fig. 9.(d).



(a) 1st plane model (b) 2nd plane model



(c) Middle plane and upper mast (d) Entire model

Fig. 9 Conductive thermal model configurations of M2 mirror

In the figures the three thin shell plates representing massive matters are described and the heat capacity model of the M2 mirror. Conductive couplings of each of the planes are automatically calculated by FEM method in Thermica, and then the local analysis method is manually used in order to make conductive couplings between the planes. Especially all side walls of the radial stiffeners and the massive triangle which are not involved in the conductive model have the thickness of zero that is applicable only to the radiative geometry model.

3. THERMAL MODELING OF FPA

The FPA(Focal Plane Array) of GOCI consists of the following components: detector, detector window, detector package, PCB, flexible leads, radiation shield, thermal shunt, radiator, FPA MLI(Multi-Layer Insultation), FPA bracket and its baffle. For conductive coupling calculation, the local analysis method is used for rectangular shape nodes. Otherwise the FEM analysis method using edge nodes is used for the complex meshes of the nodes such as triangle or quadrangle nodes. Thin shell plates which ignore their heat conduction along thickness direction are used in the FPA thermal modeling. A different configuration for every component is used to make its conductive model. Then interface conductances are modeled to consider the contact heat transfer between these configurations. The calculation method of these interface conductances is described in more detail in section 3.1. The thermal shunts which are anticipated to have high temperature gradient are split into five thermal nodes. Fig. 10 shows the radiative model of FPA.

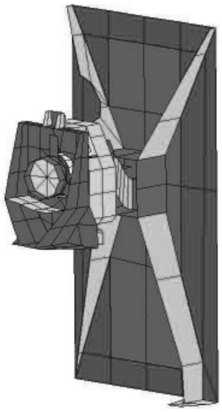


Fig. 10 Radiative configuration of FPA

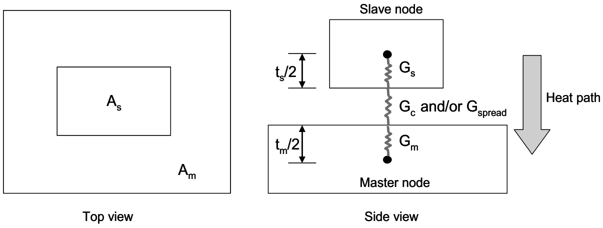


Fig. 11 Schematic of interface conductance

3.1 INTERFACE CONDUCTANCE CALCULATION METHOD

Each component of the FPA is linked by gluing and/or screwing or a part of the other component. So an interface model is necessary to connect one component to the other one. The interface conductance between two components is generally determined by the serial thermal conductance circuit theory. Considering the two nodes which are in contact with each other one node is named "master node" and the other node is named "slave node" for convenience's sake. Once the thermal path through the interface surface is determined, the length of thermal path and the surface area normal to the path can be found. The schematic for the interface conductance is illustrated in Fig. 11. This method is useful when the contact areas of the nodes are not identical between adjacent two nodes which have a physical contact. The internal conductance of a slave node itself is[6]

$$G_s = \frac{k_s A_s}{t_s/2} \tag{1}$$

where k_s is the thermal conductivity of the slave node,

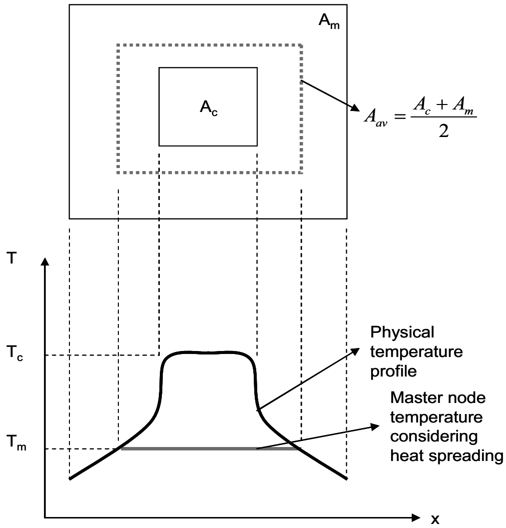


Fig. 12 Schematic of spreading conductance concept

A_s is the surface area normal to the heat path, and t_s is the thickness of the slave node. For the same way the internal conductance of a master node itself is

$$G_m = \frac{k_m A_m}{t_m/2} \tag{2}$$

where the subscription of m means the master node.

Either gluing or screwing for the contact method, the contact conductance can be represented by

$$G_c = h_c A_c \tag{3}$$

where h_c is the surface conductance(W/m2K) and A_c is the contact area.

3.2 SPREADING CONDUCTANCE

Spreading effect on the contact area should be considered if the slave node has some heat dissipation itself. The cases are not only that the power dissipation of the slave node is more than some amounts (but depending on configurations) but also that the contact area(A_c) is less than $0.6A_m$. If there is a contact area(A_c) dissipating heat on the master node area(A_m) the representative temperature of the master node can be assumed as the temperature at the arithmetic average area between A_c and A_m. When the spreading conductance can be ignored the temperature of the master node will be the same of T_c. The spreading conductance can be expressed by a

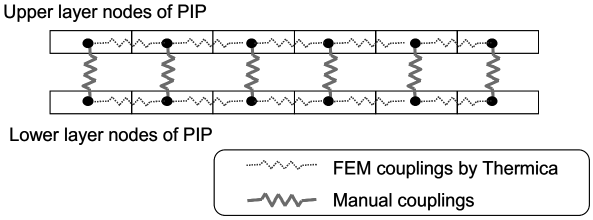


Fig. 13 Conductive couplings in the PIP thermal model

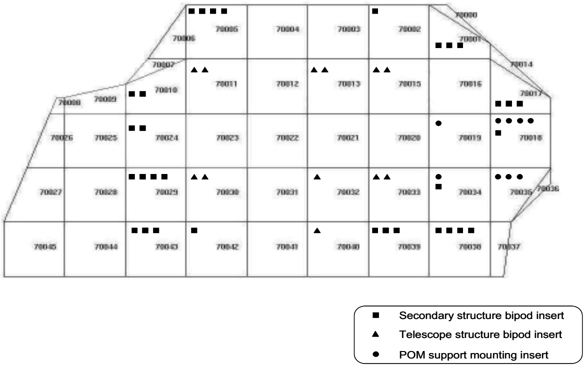


Fig. 14 Location of inserts considered in the PIP thermal model

non-linear formula as the equation below, and refer to Fig. 12 for the concept.

$$G_{spread} = \frac{4\pi k_m t_m}{\ln\left(\frac{A_c + A_m}{2A_c}\right)} \tag{4}$$

The total conductance between nodes at the interface is defined by:

$$G_{total} = \frac{1}{\frac{1}{G_s} + \frac{1}{G_c} + \frac{1}{G_{spread}} + \frac{1}{G_m}} \tag{5}$$

4. THERMAL MODELING OF PIP

For the conductive model of the PIP, two thin shell plate layers are considered(upper and lower PIP nodes). The conductive couplings for each layer of the PIP nodes are calculated by the FEM coupling calculation module of Thermica (see Fig. 13). However the couplings between upper and lower layer of the PIP are calculated by the local analysis method manually(two-plane method).

It is necessary to consider the inserts in the heat capacity budget. Some inserts are considered at its location(when inserts are heavy); other inserts' capacities are spread on the all PIP area(on both layers of the PIP). All of the massive inserts(the inserts for the telescope bipods, POM support and PIP bipods) used in the PIP are considered in the heat capacity model:

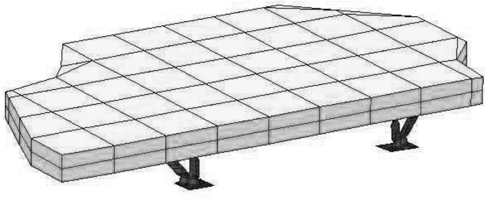


Fig. 15 Overall thermal model of PIP

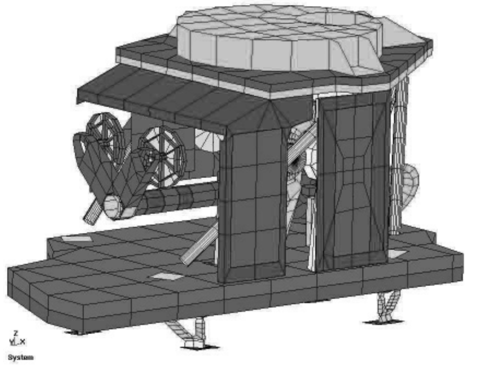


Fig. 16 Integrated GOCI model internal(without MLI covering)

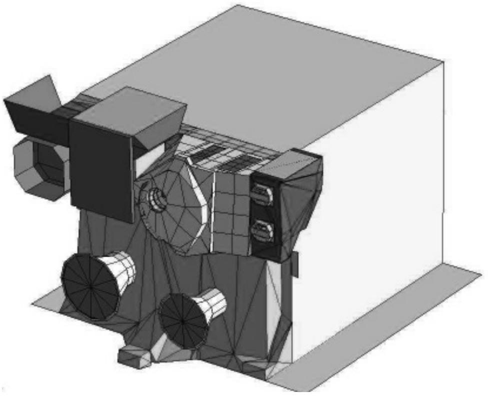


Fig. 17 COMS spacecraft with GOCI payload

— For the telescope bipods interface : 6 interfaces on the PIP
— For the POM support interface : 3 interfaces on the PIP

— For the PIP bipods : 8 interfaces on the PIP

Fig. 14 shows the upper layer nodes of the PIP and corresponding massive inserts considered in the heat capacity model. These additional heat capacities of locally massive inserts are added to the corresponding PIP nodes. The overall configuration of PIP and its bipods is shown in Fig. 15.

5. CONCATENATED GOCI MODEL

The integrated GOCI detailed thermal model is shown in Fig. 16. In Fig. 17 the COMS spacecraft installing GOCI payload is illustrated with other payloads in order to take into account the radiative environment by the external spacecraft geometry influencing GOCI thermal behavior.

6. CONCLUDING REMARK

Detailed thermal modeling has been performed for an ocean color imager of a geostationary satellite. An efficient modeling technique, called two-plane method, is introduced to be compatible with the analytic model of massive matters by using thin shell plate modeling. A correction factor is contributed to compensate the volume loss resulted from sparse numerical meshing. T

his detailed thermal model of the imager is supposed to be used for detailed analyses and test predictions, and be correlated with the thermal vacuum test results before final in-flight predictions.

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