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Study on the reduction method of the satellite thermal mathematical model

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ABSTRACT

The thermal model reduction method is introduced to condense a huge satellite panel thermal model into a simplified model in order to make efficient calculations in the thermal analysis of a satellite in orbit. The static condensation algorithm with a substitution matrix manipulation is employed to handle the huge matrices without any numerical restriction. The relevant mathematical procedures of reduction are described step-by-step. The thermal model example of a satellite panel is illustrated to demonstrate the developed reduction method and its results are discussed. The influence of generated meshes for the reduced thermal model is reviewed. The calculation times are assessed and comparison between the developed method and the classical block-form LU decomposition method is also performed.

1. Introduction

The electronic components in use these days have more functions and are manufactured to a compact size than expected. Satellites are also required to have a complex mission of high quality and confidence within an optimized weight and size. Therefore, the panel, also known as the structure of a satellite bus, is employing many electronic components, which inevitably induces high heat dissipation. In order to control the temperature of the components and maintain their performance, the panel is occasionally implemented by the thermal control hardware such as heat pipes, radiators, and heaters.

The thermal radiation is the main heat transfer mechanism in satellite thermal analyses. Even a well-made commercial thermal software may fail to analyze the heat transfer in a thermal model that has a large number of nodes (e.g., several tens of thousands of nodes). The reason is apparently caused by the inherent MCRT (Monte Carlo Ray Tracing) method [1]. Since the method is state of the art, MCRT is widely used in commercial software such as Thermal Desktop by Panczak et al. [2] and Thermica by Jacquiqau and Noel [3]. These software can precisely calculate the thermal radiative heat transfer conductors in the space applications. The MCRT method basically requires a long calculation time and numerous computational resources. Moreover, the kinematics of the solar array rotation is included in the model. Due to these characteristics, the thermal model reduction is used quite often.

Simplifying the thermal model is relatively easy if the panel has a small number of components. In this case, a thermal analysis engineer can directly use the RTMM (Reduced Thermal Mathematical Model), which is in the form of easy debugging. However, in cases of a large panel with many components, it is difficult to establish the RTMM directly.

The DTMM (Detailed Thermal Mathematical Model), which includes a honeycomb sandwich panel, electronic components, doublers, heat pipes, and thermal radiation enclosures, nominally requires input values in the form of the dimension, location, thermal resistances / capacities, and optical properties. The input values are used to generate the parameters for thermal solvers such as SINDA/FLUINT (Cullimore and Ring Technology [4]), ESATAN (ITP Engines [5]), and Thermisol (EADS Astrium [6]). The calculation parameters for the solvers can be obtained by hand calculation if the thermal model is relatively simple, but when dealing with a complex thermal model, an automatic model parameter generator such as COMSTAP is utilized occasionally. Jun and Kim [7] have been developing the COMSTAP program since this research was started by Choi and Hwangbo [8] in the Korea Aerospace Research Institute. Fig. 1 shows the COMSTAP software screens running.

In terms of thermal analysis accuracy requirements, it is favorable to consider the linear heat conduction at the contact area between the panel and components due to the local heat dissipation at the interfaces of the nodes. Non-linear heat spreading effects [9] are not recommended to be used as the terms of heat conduction equations. If a non-linear term of heat spreading effect at the

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Nomenclature

A	Area of the node $[m^2]$
a_{jk}	Area-weighted factor (the ratio of the condensed node area to the eliminated node area)
a_{kj}	Area-weighted factor (the ratio of the eliminated node area to the condensed node area)
$\boldsymbol{a}$	A matrix consisting of area-weighted factors
$\boldsymbol{C}$	Linear coupling coefficients matrix
$\boldsymbol{D}$	A set of sub-matrices
$G_{\alpha\beta}$	Conductive heat transfer conductance between node α and node β in the energy equation $[W/K]$
$GL(l, n)$	Linear heat transfer conductance between node l (row l) and node n (column n) in RTMM $[W/K]$
$GR_{\alpha\beta}$	Radiative heat transfer conductance = emissivity × shape factor × area $[W/K^4]$
M	A constituent of matrix $\boldsymbol{M}$
$\boldsymbol{M}$	Linear coupling matrix of the reduced model
N	A set of thermal nodes
P	The power excluding the conduction (the sum of the radiative heat transfer and the heat source terms)
$\boldsymbol{P_l}$	Power vector composed of $\boldsymbol{P_i}$ and $\boldsymbol{P_k}$
Q	Heat source term
T	Temperature $[K]$ or $[°C]$
$\boldsymbol{T_l}$	Temperature vector composed of $\boldsymbol{T_i}$ vector and $\boldsymbol{T_k}$ vector
$\boldsymbol{X_m}$	Temporary matrix composed of $\boldsymbol{T_j}$ vector and $\boldsymbol{P_k}$ vector for replacement
$\boldsymbol{Y_{ml}}$	Substitution matrix
Greek Symbol	
σ	Stefan-Boltzmann constant $(5.67 \times 10^{-8}\ W/m^2K^4)$
Subscript	
α, β	Node index
i	Retained thermal node through the reduction process (the same node present in DTMM)
j	Eliminated thermal node through the reduction process
k	Condensed thermal node that represents the eliminated nodes
l, m, n	Row and column indexes in the matrix or node index

contact interface is used, it may result in an advantage of mesh generation, which can be free from the mesh alignment at that interface, so the total number of thermal nodes are smaller than the mesh aligned case. In non-aligned mesh cases, however, the governing equation becomes complicated and may not be implemented, even by a well-made commercial software. On the other hand, if the user ignores the non-linear term in the heat transfer governing equations for the sake of convenience, then the thermal analysis accuracy is not guaranteed.

In order to maintain the thermal analysis accuracy without any spreading effect, the non-linear heat spreading effect terms in the equations should be eliminated with fully aligned thermal meshes at the contact interfaces. Nevertheless, this method still suffers from the problem of excessive calculation time due to the large number of nodes for the model. Therefore, the thermal model reduction is firstly motivated to avoid the unacceptable computation time for the huge thermal model (more than 40,000 nodes) of a panel and is also inspired by the model debugging inconvenience caused by any modifications in the conductive heat transfer equations. Sometimes, such an additional computation effort such as sensitivity analysis, parametric studies, and stochastic analysis may be necessary, which requires a long computation time. As a consequence, a reduced, but accurate thermal model is very much needed in the development schedule's point of view.

As one of the previous studies done in these research fields, Jouffroy et al. [10] developed the Genassist program to reduce the telecommunication satellite model's accompanying relevant processes. The program employs the Cholesky decomposition for the inverse matrix calculations. Molina and Clemente [11] published the study results of the thermal model automatic reduction targeting the thermal model reduction theory and verification using Matlab software. Bernard et al. [12] created TMRT software capable of reducing the capacitance matrix by virtue of the multi-corporate collaboration.

The first purpose of this work is to propose a thermal model reduction algorithm for handling non-symmetric full matrices in addition to saving computational effort. The second is that the isothermal meshing tolerance in the model reduction is evaluated to acquire more accurate results in terms of the quality of RTMM.

In this paper, a thermal model reduction method from the DTMM of a panel is introduced to enable the satellite level thermal analysis in the orbit environment. Examples of satellite panel reduction procedures and results are described. The method of huge matrix calculation employs static condensation procedures [13] that are not limited by the inverse calculation of huge matrices. Improving the computation time has been attempted through the multi-thread computing architecture by Intel® Math Kernel Library [14] with LAPACK (Linear Algebra Package). The block-form LU decomposition method [15] is employed for the purpose of comparing the computation time with the developed algorithm.

From now on, DTMM is defined as a thermal model of several tens of thousands of nodes that contains the panel, electronic components, heat pipes, and heaters among others. RTMM is defined as a simplified thermal model of several hundreds of nodes optimized from DTMM and keeps as much of the thermo-physical attributes of the DTMM as possible.

2. Procedures and characteristics of thermal model reduction

Examples of the satellite panel DTMM and RTMM are shown in Fig. 2. A total of 1138 nodes and 33 nodes are used for the DTMM and the RTMM, respectively. The reduction ratio is about 1/34. The RTMM is used for thermal radiation, conduction, and convection (if any) calculation in the satellite level thermal analysis.

2.1. Procedures of thermal model reduction

Once the DTMM is constructed, the thermal model reduction procedure begins, which is summarized step-by-step as shown below:

2.1.1. Definition of condensed nodes

- The RTMM nodes can be defined from the corresponding DTMM nodes. When defining the RTMM nodes, the selection of isothermal nodes proceeds by using the DTMM temperature map. Sometimes the user's experience is needed in choosing the isothermal nodes.

2.1.2. RTMM conductor generation

- Afterwards, the calculation of thermal conduction couplings follows, which can be done either manually or automatically. For a large thermal model, an automatic reduction algorithm is necessary to manipulate the huge matrices to accomplish the reduction of coupling data (refer to the next section of the thermal model reduction theory). The thermal radiation couplings for the RTMM shall be generated automatically by means of the MCRT method or view factor method.