Applied Thermal Engineering 105 (2016) 456–466

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Quasi-autonomous thermal model reduction for steady-state problems in space systems

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HIGHLIGHTS

- Manual reduction of spacecraft thermal models is time consuming and error-prone.
- The physical characteristics of the model are respected.
- A matrix method has been developed. It performs the reduction in an automatic way.
- The method is limited for now to steady-state problems.
- The method is universal, not dependent on a particular software tool.

ARTICLE INFO

Article history:
Received 31 July 2015
Accepted 5 March 2016
Available online 21 March 2016

Keywords:
Thermal model reduction
ESATAN-TMS
Spacecraft thermal control

ABSTRACT

A matrix method is developed to reduce the number of elements of spacecraft thermal mathematical models based on the lumped parameter method. The aim of this method is to achieve a satisfactory thermal model reduction for steady-state problems, in an automatic way, while preserving the physical meaning of the system and the main characteristics of the model. The simplicity of the method, and the computational cost, are also taken into account. The reduction process is based on the manipulation of the conductive coupling matrix, which is treated as a sparse graph adjacency matrix. Then, a depth-first search algorithm is used to find the strongly connected components, which define the condensed nodes. Finally, all the thermal entities are reduced, and the results from the condensed model are compared to those from the detailed one. The entire reduction process is tested on a real thermal model, showing a good performance. In the conclusions section the characteristics and limitations of this method are shown.

1. Introduction and state of the art

Spacecraft thermal control addresses the problem of keeping space vehicles and their components temperatures within the appropriate range [1–3]. Tests and analyses are used together for the study and the design of a thermal control subsystem. In the earliest stages of the design, the preliminary studies can be performed using analytical calculations [4–9]. But as the system becomes more complex and detailed, it is necessary to rely on other tools. While the tests allow the design to be verified, they are very complex and expensive. Therefore, in recent years, thermal simulation has become more and more relevant. In Europe, the standard tool for thermal analysis in the space industry is ESATAN-TMS [10].

When working with thermal models, it is very usual to have very detailed models (for typical lumped parameter solvers, it is in the range of 10^3–10^4 nodes) for the element/unit which is being studied. Then, this element might have to be included in a higher hierarchy model, or it could be necessary to carry out extensive simulations (*e.g.* transient and sensitivity analysis). To keep the size of the model under reasonable limits ($<10^5$ nodes) and save analysis time, in all the aforementioned cases it is highly recommendable to reduce the number of nodes of the thermal model under study. The reduced thermal model must behave as the detailed one (in terms of temperatures and heat fluxes through the boundaries), while having a smaller number of nodes, so-called "size".

The classical approach to deal with this situation is to set up a reduced geometrical mathematical model (RGMM). The reduced thermal mathematical model (RTMM) is built on a user-definition basis. This means the modeler builds the RGMM, and

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http://dx.doi.org/10.1016/j.applthermaleng.2016.03.017
1359-4311/

Nomenclature

A	adjacency matrix, $n_d \times n_d$
B	change of basis matrix, $n_d \times n_d$
C	thermal capacity vector, $n \times 1$ (J/K)
c_p	specific heat capacity (J/(kg K))
D	distance matrix, $n_d \times n_d$ (m)
G	thermal capacity matrix, $n_d \times n_d$ (J/K)
H	heat flux vector, $n_b \times 1$ (W)
I	identity matrix, $n \times n$
K	conductive coupling matrix, $n \times n$ (W/K)
L	distance between node center and interface (m)
n	number of nodes
P	restriction matrix, $n_d \times n_c$
p_f	dimensionless filtering threshold
q	heat flux difference vector between detailed and reduced model results, $n_b \times 1$ (% or W)
q_{max}	maximum allowable heat flux difference (% or W)
q_{lim}	heat flux limit for separation between relative and absolute values of heat flux difference (W)
Q	thermal loads vector, $n \times 1$ (W)
r_r	reduction ratio
R	radiative coupling matrix, $n \times n$ (m^2)
S	node cross-section (m^2)
$\mathbf{S_{cn}}$	connected components label array, $n_d \times 1$
t	thickness (m)
T	temperature vector, $n \times 1$ (K)
v	node volume (m^3)
w	node width (m)
X	node spatial coordinates (x, y, z), $n_d \times 3$ (m)

Greek symbols

$\boldsymbol{\delta}$	vector of temperature differences between derived and calculated values (K), $n_c \times 1$
δ_{max}	maximum allowable temperature difference (K)
ΔT_{max}	temperature difference threshold (K)
λ	thermal conductivity (W/(m K))
μ	parameter (m^2/s)
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant (W/(m^2 K^4))
$\boldsymbol{\Theta}$	temperature difference matrix, $n \times n$ (K)

Accents

–	derived values
^	calculated values
~	dimensionless values

Subscripts

b	boundary node
c	condensed model
cb	conductive to boundary nodes
d	detailed model
rb	radiative to boundary nodes
sort	sorted

Superscripts

B	including marked boundary nodes
D	detailed model
F	filtered
I	including marked internal boundary nodes
R	reduced model
S	sizing
T	transposed
*	linearized

Abbreviations

CSR	Compressed Storage by Rows
GMM	Geometrical Mathematical Model
ESA	European Space Agency
FPA	Focal Plane Assembly
MLI	Multi-Layer Insulation
PHI	Polarimetric Helioseismic Imager
RGMM	Reduced Geometrical Mathematical Model
RTMM	Reduced Thermal Mathematical Model
SCC	Strongly Connected Components
TMD	Thermal Model Data
TMM	Thermal Mathematical Model

according to its definition, the nodes from the detailed thermal mathematical model (DTMM) are condensed into RTMM nodes. Then, the general practice is to get two snapshots of the DTMM (usually hot and cold operational worst cases) and, by tuning the conductive couplings and the heat loads, try to match the results from the RTMM and the DTMM. This process is time consuming, and tends to be error-prone.

Some authors and companies have developed a number of algorithms and computer codes to automatize this reduction process. For instance, Bernard et al. [11–13] have developed the TMRT (thermal model reduction tool) software. This software is intended to reduce large mathematical models. The program is based on a Guyan–Irons reduction, and it seems to work well, but it needs the reduction to be pre-defined by the engineer. This approach requires essentially defining the reduction scheme *a priori*. A very similar approach can be found in [14–16]. Deiml et al. [17] have carried out a wide analysis of the different techniques that could be applied to spacecraft thermal model reduction. They focus on nonlinear methods, which can achieve reductions with very good correlation, at the expense of losing part of the physical interpretation of the problem. They are also the only ones that also deal with the reduction of the geometrical mathematical model (GMM).

The main goals and points of the quasi-autonomous thermal reduction process presented here are:

a. Reduce the thermal model taking into account the different quasi-isothermal zones. By grouping similar-temperature nodes, it is possible to reduce the error produced by reducing the matrices. It can be supposed that parts which are strongly connected (larger conductive couplings) will be more isothermal than other parts which are weakly connected.
b. The model reduction should be done in a quasi-automatic way. This means, the only parameters that need to be defined are the maximum allowable temperature and heat fluxes differences, as well as the desired reduction ratio.
c. The reduction process will depend on the temperatures and boundary conditions. Having more scenarios (*e.g.* hot and cold operational cases) will constrain the problem more.
d. In engineering applications, it is essential to preserve the physical interpretation of the model elements, as well as the physical characteristics, to be able to take design decisions changing physically achievable parameters. This implies having positive thermal couplings, to preserve the boundary nodes, the heat loads, the symmetry in the coupling matrices, and the conductive physical paths.

The work presented hereafter is partially inspired by the large resistor networks reduction methods [18,19].