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Simon Appel · Jaap Wijker

Simulation of Thermoelastic Behaviour of Spacecraft Structures

Fundamentals and Recommendations

Springer

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The authors dedicate this book to their former boss ir. Marinus P. Nieuwenhuizen of the structural department of Fokker Space and Systems BV, The Netherlands.

Foreword

Thousands of spacecraft have been launched into space since the launch of Sputnik in 1957. We have landed men on the moon, visited planets in our Solar System with robotic probes, stationed scientists on the International Space Station, established global telecommunication and navigation systems, and nowadays, we are setting new goals in exploration, and consequently, despite all the reached accomplished, we are facing new, as well as old, challenges. Among them, the design of spacecraft structures subjected not only to mechanical, vibrational and acoustic loading, but also to extreme thermal conditions, requires new analysis techniques, and the consideration of thermal and structural analyses at the same time.

This book covers the topics necessary to the understanding of the thermoelastic behaviour of spacecraft structures, describing the essential steps of the analysis and verification, without missing important aspects such as handling uncertainties in the thermoelastic analysis process. Each topic is presented in the book with the necessary background, the up-to-date perspective and the essential theory–practical connection, thanks to the extensive industrial experience of both authors.

This book will be of immense help to thermal and mechanical engineers who are looking for concrete answers of their problems and, at the same time, to graduate students who would like to acquire knowledge in the fascinating world of the space structures.

October 2020

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Preface

The authors, Jaap Wijker and Simon Appel, have been working together since October 1986. In that month, Simon Appel arrived as a trainee at the Space division of Fokker Aircraft in the group led by Jaap. In those years, the group was running a technology development activity for ESA-ESTEC of which part of it aimed at developing an interface between the most important lumped parameter thermal analyser of those days, SINDA ("Systems Improved Numerical Differencing Analyser") and the finite element code used in the structures section at ESTEC, which was ASKA ("Automatic System for Kinematic Analysis"). In this activity, the foundation was established of the PAT method, the prescribed average temperature method, that you will find explained in this book and its implementation in the SINAS software: SINda—ASka. The mentioned technology development was initiated by Steve Stavrinidis, and the follow-on developments were run under the supervision of Michel Klein.

Jaap with his team members could be called the founding fathers of the PAT method. In the years after, Simon matured the implementation of the method in the SINAS software and the interface with the commonly used finite element tool MSC Nastran. The tool has been used at ESTEC and at Fokker Space and Systems. These were the years that Jaap and Simon worked on several thermoelastic problems.

In 2001, Simon joined the company that is called today ATG Europe and has been supporting ESA-ESTEC since then. An important part of his time has been, and still is, dedicated to thermoelastic problems and further development of the SINAS software. Jaap kept working for Fokker Space as it was called in the meantime, but also started to lecture at the Delft Technical University. Inspired by his students, he got motivated to write several books on spacecraft structures and related structural dynamics. Despite his retirement in 2009, Jaap continued writing books and managed even to obtain his Ph.D. degree.

The never-ending drive of Jaap to share his knowledge and keep on studying made him to contact Simon to join him writing the book that is now in your hands on the subject of thermoelastic simulations. It is the subject with which the relationship between Jaap and Simon started in the 1980s.

Jaap and Simon enjoyed writing this book. They know there is much more to discuss, and it will never be finished, but at some point, the time is there to share the results with you as reader.

Whether you are a graduate student or an experienced senior thermal or mechanical engineer, Jaap and Simon hope you find some useful information in this book. They also invite you to send feedback and suggestions that they may consider for a potential next edition.

Velserbroek, The Netherlands — Jaap Wijker
Voorhout, The Netherlands — Simon Appel
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- Dick Wijker for facilitating the application of scientific software for the preparation of the numerical examples for this book
- Daniele Stramaccioni for his thorough and critical review of the thermal aspects discussed in the book
- MSC Software and In Summa Innovation for their support on the structural aspects of the numerical examples prepared for this book
- ITP for providing an ESATAN-TMS licence for solving the thermal problems that are part of the examples

and many others who contributed with ideas without realising this.

Perspective

How did the Universe originate, what are its fundamental physical laws and what is it made of? How does the Solar System work? What are the conditions for planet formation and the emergence of life within and outside our Solar System? How can we monitor, understand and preserve the delicate ecosystem of our planet and how can we protect life on Earth? These are some of the fundamental questions we, as human beings, are trying to answer since hundreds of years, and these are the questions the European Space Agency (ESA) is addressing within its world leading space science programmes and Earth observation missions.

With our "time-machine" Planck and his astronomy observer companion Herschel, we changed our view of the Universe, by revealing the relic radiation left by the Big Bang to an unprecedented level of accuracy, measuring fluctuations in temperature of a few millionth of degree, hence tracing the birth of stars and the evolution of galaxies throughout time. Gaia, the billion-star surveyor, has been making precise measurements of the positions, motions and characteristics of stars in order to create a three-dimensional map of our Milky Way and explore the past and future evolution of the Galaxy. PLATO will soon hunt Sun–Earth analogue systems in relatively nearby stars, identifying and studying thousands of exoplanetary systems, with emphasis on discovering and characterising Earth-sized planets in the habitable zone of their parent star. Closer to us, the Copernicus Earth observation programme is taking the pulse of our planet and is providing decision-makers with indisputable data in order to understand global changes and intervene effectively to resolve them.

These are some of the most recent missions ESA has developed in an attempt to shed light in the understanding of the Universe and our home, the Earth. They have posed exceptional challenges to the thousands of European engineers and scientists working in industry, academia and in the agency for the development, the verification and the operation of these scientific jewels. Space is probably the most demanding and hostile operational environment in which human engineering products are required to function. Without any repair or maintenance option, space structures shall guarantee years of performances reaching incomparable levels of accuracy and stability of the telescopes and optical instruments on-board. And, this shall be ensured despite the very demanding mechanical loading during launch and separation and the prohibitive temperature environment and fluctuations encountered in-service.

Although more and more the design of our space and Earth exploring satellites is driven by thermomechanical performances, hardly any textbooks or university classes are devoted to this fundamental discipline. Many good references exist addressing spacecraft thermal analysis and control, and also, a vast amount of literature can be found on the different satellite structural engineering subjects. However, these sources only cover the relevant topics within the context of the respective disciplines. In some cases, the interaction with the other subject is briefly discussed, but mainly from the perspective of their own domains. Moreover, the thermal and structural disciplines for the development of spacecraft structures and payloads have been traditionally supported by two distinct entities in most space engineering organisations, and in addition, both disciplines are using different analysis methodologies and associated numerical tools.

Thermomechanical and thermoelastics analyses aim to predict the deformations and the stresses affecting a structure or a component due to temperature fields and variations. In order to have a complete understanding of the problem, the two above-mentioned disciplines need to be addressed in a synergistic and cross-sectorial manner. A structural finite element model for thermoelastic predictions of a structure under a given thermal environment cannot be precisely established without a detailed knowledge of the temperature fields described by the thermal model. Conversely, a thermal engineer needs to have an adequate understanding of what are the temperature results and the resolution required by the structural model for reliable analysis.

The present book aims at capitalising the vast experience of the authors in the field of thermoelastic predictions applied to spacecraft structures and provides a coherent approach to solve practical and real-life problems. While analysing the different modelling and verification objectives of the thermal and structural domains, the authors address the current state-of-the-art approaches and limitations for both analyses and provide a suitable and verified method for addressing both disciplines in a synergistic fashion. This also includes specific numerical tools for transferring results from the structural to the thermal numerical environment and vice versa.

The book is most welcome in the space community and will provide a unique guidance to senior and the younger generation of engineers involved in the structural and thermal analyses of sophisticated spacecraft structures and instruments. It can constitute a sound basis for the building of a dedicated European Cooperation for Space Standardisation (ECSS) standard related to thermoelastic analysis and verification, ultimately leading to more performing space missions, improving our understanding of the Universe and contributing to a better life on our planet.

May 2021

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Contents

Acronyms and Abbreviations

Abbreviations

ASM	Aerospace Specification Metals
AU	Astronomical unit
CNES	Centre National d'Etudes Spatiales
CPPT	Centre-Point Prescribed Temperature method
CSA	Canadian Space Agency
CTE	Coefficient of thermal expansion
DOF	Degree of freedom
ECSS	European Cooperation for Space Standardisation
ESA	European Space Agency
ESTEC	European Space Technology Center
FE	Finite element
FEA	Finite element analysis method
FEM	Finite element model
FoS	Factor of safety
GMM	Geometric mathematical model
HST	Hubble Space Telescope
IDW	Inverse distance weighting
IR	Infrared
JAXA	Japan Aerospace Exploration Agency
KARI	The Korean Aerospace Research Institute
KSASS	Korean Society Aeronautical Space Science
LEOP	Launch early orbit phase
LHS	Latin hypercube sampling
LoS	Line of sight
LPM	Lumped parameter method
MCRT	Monte Carlo ray tracing
MCS	Monte Carlo sampling
MoS	Margin of safety
MPC	Multipoint constraint

NAFEMS	National Agency for Finite Element Methods and Standards
NASA	National Aeronautical and Space Administration
PAT	Prescribed average temperature
PCB	Printed circuit board
PCL	MSC.Patran Command Language
PEM	Point estimates moments
RBE	Rigid body element
RF	Radio frequency
SM	Service mission
SRC	Standardised regression coefficient
STOP	Structural, thermal and optical performance
SWOT	Surface Water Ocean Topography
TMM	Thermal mathematical model
TN	Thermal node
TRP	Temperature reference point

Symbols

A	Area, cross-section (m^2)
a	Radius (m), constant, coefficient, [A]-matrix term
$[B]$	Interpolation matrix
b	Radius (m), width (m)
C	Heat capacitance
$[C]$	Conduction matrix
CTE	Coefficient of thermal expansion (n/m/°C, m/m/K)
c_p	Specific heat (J/kg/°C, J/kg/K)
^{o}C	Centigrade (degree Celsius)
E	Energy (W)
$[E]$	Unitary diagonal matrix
$[D]$	Elasticity tensor
E	Young's modulus (Pa)
F	Force (N), view factor
(F_T)	Equivalent thermal load vector
$F(x)$	Function of x
$F(x,\ y)$	Function of $x,\ y$
$\mathcal{F}$	Hottel's total view
f	Frequency (Hz)
G	Shear modulus (Pa), conductance (W/°C,K)
G_{sc}	Solar constant (W/m^2)
G_{ss}	Transformation matrix
GL	Conductor, thermal conductance coefficient (W/°C,K)
GR	Radiative conductor
h	Height, thickness (m), convective heat transfer coefficient (W/m/°CK)

H	Panel height
I	Second moment of area (m^4), integral
J	Joules, Jacobian, thermal functional
K	Kelvin
K	Stiffness matrix
K_c	Conduction matrix
k	Conductivity coefficient (W/m/K, W/m/°C)
$\mathcal{N}$	Normal distribution
l, L	Length (m)
L_{ref}	Reference length (m)
$\mathcal{LN}$	Log normal distribution
m	Discrete mass (kg)
M_T	Equivalent thermal moment (NM)
M	Mass matrix
M_{eff}	Modal effective mass (kg)
N	Number of samples
P	Pressure (Pa)
P_T	Thermal force (N)
q	heat transfer rate
Q_s	Solar constant (W)
Q	Heat flux (W/m^2)
$\left(R_Q\right)$	Heat flow vector
r	Radius (m)
R	Distance (m), resistance (°C/W, K/W), residual, Rayleigh quotient
T	Temperature (°C, K)
T_{ref}	Reference temperature (°C, K)
t	Time (s), thickness (m)
r	Radius (m)
u	Displacement m, stochastic variable
$\mathcal{U}$	Uniform distribution
U	Strain energy
U_m	Matrix of coefficients (MPC equations)
v	Displacement (m)
V	Volume (m^3), coefficient of variation
W	Watts
w	Deflection (m)
x	Coordinate, variable
y	Coordinate, variable
Y	Stochastic variable

Greek Symbols

α	Absorption coefficient (-), absorptivity

α	Coefficient of thermal expansion (m/m/K, m/m/°C)
β	(Thermal) Expandability (m/m/°C), thermal stress modulus (Pa), constant
β_x	Sensitivity index
ε	(Thermal) Emittance (-), emissivity, (engineering) strain (m/m)
δ_{ij}	Kronecker delta
δ	Displacement (m), differential operator, virtual (displacement)
Δ	Difference, evaluated (temperature), prescribed displacement
ζ	Isoparametric coordinate, dummy variable
μ	(Ensemble) average value
η	Bond thickness (m), isoparametric coordinate, dummy variable
λ	Lamé modulus (Pa), constant
Λ	Lagrange multiplier
ν	Poisson's ratio (-)
Π	Potential energy
σ_{ii}	Component stress tensor (Pa)
σ	Boltzmann constant ($W/m^2/K^4$), standard deviation, constant
θ	Angle
τ	Shear stress (Pa)
ϕ_R	Rigid body mode
Φ	Probability function
Ψ	Trial function, (nodal) shape function
ω^2	Eigenvalue