



Lecture Notes in Mechanical Engineering

P. Pradeep Pratapa
G. Saravana Kumar
Palaniappan Ramu
R. K. Amit *Editors*

Advances in Multidisciplinary Analysis and Optimization


Proceedings of the 4th National
Conference on Multidisciplinary Analysis
and Optimization



Springer

Lecture Notes in Mechanical Engineering

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Preface

This book contains selected papers from the 4th National Conference on Multidisciplinary Design, Analysis and Optimization (NCMDAO-4) which was held at Chennai between October 7 and 9, 2021. The virtual conference was organized by the Department of Engineering Design, the Indian Institute of Technology Madras (IITM), in collaboration with the mechanical engineering department at the Indian Institute of Science, Bengaluru (IISc), and the Design Division of the Aeronautical Society of India (AeSI). This conference was the fourth in an annually planned event to create a platform for researchers in academia, government labs and industry professionals working in the areas of multidisciplinary design, analysis and optimization to share their current work.

Optimization is imperative in today's multidisciplinary R&D environment to push the envelope in design. Several domains such as aerospace, automotive, manufacturing and biomedical among others significantly benefit from optimization and gain a competitive edge. Advances in optimization theory, algorithms and the ecosystem for large computations have made it possible to improve the performance and economy of components, devices, processes and entire systems. Efficient analysis and design are possible even for those complex problems where analytical and computational models are not typically available. Design under uncertainty, emerging techniques that use machine learning and quantum computing to accelerate optimization are also pursued vigorously. The conference was organized with these goals in mind.

The response from various government laboratories, academic institutions and private companies was overwhelming with roughly 145 registered participants attending the two-day conference. Over 25% of the contributed papers were from the manufacturing and consulting industries, while the rest of them were from academic institutions and government research laboratories such as ISRO, ADA and NAL. Over the two days of the conference, about 79 papers were presented out of which over 71 full papers were contributed. These papers were peer-reviewed by the papers committee, and a total of 48 high-quality papers are included in this proceedings.

The conference was held over two days with a pre-conference masterclass. Masterclass included a talk and hand-on session on polynomial chaos expansions (PCE) and UQLab by Prof. Bruno Sudret and Ms. Nora Luthen, ETH Zürich. The second

masterclass was on graphs and physics-informed neural networks (PINN) for hybrid modeling and uncertainty quantification by Prof. Felipe A. C. Viana, University of Central Florida.

A student design competition on the optimal design of heat exchangers for solar still application was also conducted. The main conference included two keynotes, three invited talks, two impact talks and three sponsor presentations. The keynotes were delivered by Dr. William Baker of Skidmore, Owings and Merrill on Maxwell, Rankine, Airy and Modern Structural Engineering Design, and by Prof. Wei Chen of Northwestern University on Interdisciplinary Data-driven Design of Engineered Materials Systems. Invited talks were delivered by Dr. Arvind Kumar of Optym on using Optimization for Managing Electric Vehicle (EV) Loads on Power Grid, by Dr. S. A. Ilangoan from ISRO on Batteries for Space: Design and Challenges, and by Dr. N. R. Srinivasa Raghavan of Tarxya Limited on Industrial Applications of AI/ML/Optimization. Impact talks were delivered by Mr. Suresh Kumar of Pepul on Process Innovation in HR Policies—a Systems Perspective in Building a Million-dollar Company and by Mr. Ramasubramanian of VillageRES on Decentralising and Demystifying Renewable Energy Technologies for the Remote Rural Population.

The conference agenda was divided into six parallel sessions. Each session had roughly five papers. Each paper was scheduled based on a session theme. The following were the themes of the conference:

S1T1 Data-Driven Decision/AI/ML
 S1T2 Aerodynamics/CFD
 S1T3 Aircraft Design 1
 S1T4 Space
 S2T1 Structures 1 and Space
 S2T2 3DP
 S2T3 Fluids 1
 S2T4 TO 1
 S3T1 Structures 2
 S3T2 UQ/Statistics 1
 S3T3 TO 2
 S3T4 Manufacturing 1
 S4T1 UQ/Statistics 2
 S4T2 Surrogates
 S4T3 Structures 3
 S4T4 MDO 1
 S5T1 Materials
 S5T2 TO 3
 S5T3 SC
 S5T4 MDO 2
 S6T1 Aircraft Design 2
 S6T2 Fluids 2
 S6T3 Structures 4
 S6T4 Manufacturing 2

The conference was sponsored by leading industries in the field of optimization such as AUTODESK, ANSYS and BETA simulation solutions besides strong support from SAEINDIA and Springer.

The papers included in this proceedings were selected based on a rigorous review considering the theme of the conference in mind. We hope that this collection of work would ignite further interest in this field in the country and elsewhere and will continue to be active for years to come with an increased contribution.

Chennai, India

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Optimization Applications: Aerospace

Optimization of Blunt Nose Semi-spherical Heat-Shield in Hypersonic Flow at Mach 7.99



Chandan Kumar and Akshay Prakash

1 Introduction

A flow is stated as hypersonic flow if its Mach number is five or above. Such flows are generally encountered during atmospheric entry or in the case of hypersonic missiles. There is intense shear and thermal loads to the surface at such a high speed. In order to protect the vehicle from this extreme heat, Thermal Protection System (TPS) is used. There are different ways to protect the vehicle thermally, commonly using a heat-shield or active and passive cooling. It is not possible to employ the active and passive cooling system due to limited energy resources and geometrical constraints at hypersonic speed [1]. Hence, the only way left to dissipate the extreme thermal energy on the surface of the vehicles is to use a heat-shield. In general, heat-shields are made up of ablative or non-ablative materials [2]. Ablative materials work by ablation; that is, part of it melts, vaporizes, and breaks off to carry away heat harmlessly, as illustrated by Niehaus [2]. In contrast, non-ablative materials undergo pure conduction till failure or deformation in some cases prior to failure depending on the materials' properties. Curry [3] performed the thermal analysis of a one-dimensional ablative heat-shield with the backup structures at the inner cabin. The backup structures were considered to be made up of non-ablative materials. The time-dependent heat flux was applied as a boundary condition at the outer surface of the heat-shield rather than using any fluid solver to compute the heat flux. Balakrishnan et al. [4] presented a detailed analysis of the heat-shield of Galileo probe, which was designed to study the Jovian atmosphere. The heat-shield was made up of carbon-phenolic. The forebody, except the nose, was divided into frustums. At an off-stagnation location, peak heating was observed near a reattachment point. The final mass of the heat-shield was reduced by 89 kg. The forebody contributed 90% to the reduction in the final mass, while the aft section of the heat-shield con-

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tributed 10%. Mazzaracchio and Marchetti [5] performed the thermal analysis of a one-dimensional ablative heat-shield. The uncertainty and sensitivity analysis was performed to estimate the probability of maintaining the specified temperature of the underlying material. Three different cases with different materials and missions were considered: Stardust return capsule, Mars rover capsule, and aerocapture mission for Neptune. Their study showed 17% reduction in the overall weight of the TPS when the input uncertainty values were halved. In 2013, Ewing et al. [6] developed a numerical tool for 1D ablation problem based on a control volume approach with the variable grid to include the effect of surface movement. Other non-traditional complexities were considered, such as material swelling and mechanical erosion (spallation). It was claimed that their approach provides stable results even in case of extreme heat flux and ablation conditions, unlike the CMA (Charring Material Ablation) program [7] which suffers solution instabilities and fails to converge due to grid refinement issues. A combined computational and experimental study of an ablative heat-shield was conducted on a scaled model of NASA's Orion Multi-Purpose Crew Vehicle by Combs et al. [8] in 2017. The ablative heat-shield was made up of naphthalene, and the study was mainly focused on the visualization of ablation products using laser-induced fluorescence technique. The visualization process showed that the boundary layer carried the ablating naphthalene product into the different regions: over the capsule shoulder, separated shear layer, and back-shell re-circulation zone. It was found that the separated flow region has a higher naphthalene concentration than any other location.

The ablative heat-shield undergoes pyrolysis when subjected to the thermal loads, and as a result, gaseous products release through its surface into the boundary layer. The outgoing gaseous products affect the boundary-layer profile and incoming heat fluxes through the surface. The properties of the ablative materials are largely experiment-dependent. Due to lack of access to such experimental facilities and experimental data, which generally falls under classified research, a non-ablative heat-shield is considered, which works by pure conduction. The objective of the present work is to perform a thermal analysis of a blunt nose semi-spherical non-ablative heat-shield coupled with a hypersonic fluid flow solver. The thermal load at the surface is computed using the fluid solver, which uses a shock-fitting technique to solve the hypersonic flow-field. Based on the inner cabin temperature predicted within the specified limit by the solid solver, the thickness of the heat-shield is optimized using the Newton-Raphson method at different locations in the body curvature direction and hence reduces its overall weight.

2 Mathematical Formulation

The governing equation for a perfect gas, laminar flow, is given by the Navier-Stokes equation in vector form as

$$\frac{\partial U}{\partial t} + \frac{\partial F_j}{\partial x_j} + \frac{\partial G_j}{\partial x_j} = 0 \quad (1)$$

$$U = \begin{bmatrix} \rho \\ \rho u_1 \\ \rho u_2 \\ \rho u_3 \\ E \end{bmatrix} \quad F_j = \begin{bmatrix} \rho u_j \\ \rho u_1 u_j + p \delta_{1j} \\ \rho u_2 u_j + p \delta_{2j} \\ \rho u_3 u_j + p \delta_{3j} \\ (E + p) u_j \end{bmatrix} \quad G_j = \begin{bmatrix} 0 \\ \tau_{j1} \\ \tau_{j2} \\ \tau_{j3} \\ \tau_{ji} u_j + k \frac{\partial T}{\partial x_j} \end{bmatrix} \quad (2)$$

$$\tau_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu \frac{\partial u_k}{\partial x_k} \delta_{ij} \quad (3)$$

where U is a conservative variable vector. The flux vector is symbolically broken into inviscid and viscous flux denoted by F_j and G_j , respectively. The subscript j represents a direction and has the value $j = 1, 2, 3$ which corresponds to the x , y , and z directions, respectively. The equation of state for a perfect gas is used to relate the pressure and temperature. In U , F , and G vectors, the first row represents continuity equation, the next three rows represent momentum equation, and the last row represents energy equation. The total energy E in the last row is given by

$$E = \rho \left(C_v T + \frac{1}{2} \sum_i u_i u_i \right) \quad (4)$$

The unsteady Navier-Stokes equations are solved in the region between shock and the semi-spherical blunt body (shock-fitting technique) and solved numerically. The convective terms are collected as inviscid terms and solved using the flux-splitting method [9], while the diffusion terms are collected as viscous terms and solved using a high-order central difference scheme [9]. The governing equations are transformed into the body-fitted curvilinear coordinates (ξ, η, ζ) as

$$\begin{cases} \xi = \xi(x, y, z) \\ \eta = \eta(x, y, z, t) \\ \zeta = \zeta(x, y, z) \\ \tau = t \end{cases} \iff \begin{cases} x = x(\xi, \eta, \zeta, \tau) \\ y = y(\xi, \eta, \zeta, \tau) \\ z = z(\xi, \eta, \zeta, \tau) \\ t = \tau \end{cases} \quad (5)$$

$$\frac{1}{J} \frac{\partial U}{\partial \tau} + \left(\frac{\partial E'}{\partial \xi} + \frac{\partial F'}{\partial \eta} + \frac{\partial G'}{\partial \zeta} \right) + \left(\frac{\partial E'_v}{\partial \xi} + \frac{\partial F'_v}{\partial \eta} + \frac{\partial G'_v}{\partial \zeta} \right) + U \frac{\partial \frac{1}{J}}{\partial \tau} = 0 \quad (6)$$

where

$$E' = \frac{F_1 \xi_x + F_2 \xi_y + F_3 \xi_z}{J} \quad (7)$$

$$F' = \frac{F_1 \eta_x + F_2 \eta_y + F_3 \eta_z}{J} \quad (8)$$

$$G' = \frac{F_1 \zeta_x + F_2 \zeta_y + F_3 \zeta_z}{J} \quad (9)$$

$$E'_v = \frac{G_1 \xi_x + G_2 \xi_y + G_3 \xi_z}{J} \quad (10)$$

$$F'_v = \frac{G_1 \eta_x + G_2 \eta_y + G_3 \eta_z}{J} \quad (11)$$

$$G'_v = \frac{G_1 \zeta_x + G_2 \zeta_y + G_3 \zeta_z}{J} \quad (12)$$

The superscript $'$ represents the transformed fluxes. J is a Jacobian of the transformation. F and G with subscript 1, 2, and 3 are inviscid and viscous fluxes in x , y , and z direction, respectively. E' , F' , and G' are the transformed fluxes in ξ , η , and ζ direction, respectively, and their corresponding viscous part is represented by subscript v . τ is the transformed time and should not be confused with viscous dissipation τ_{ij} in Eq. (2). The inviscid fluxes are split into two terms based on positive and negative eigenvalue as follow

$$\begin{aligned} F' &= F'_+ + F'_- \\ F'_\pm &= \frac{1}{2} (F' \pm \Lambda U) \\ A &= R \Lambda L \end{aligned} \quad (13)$$

R and L consist of right and left eigenvector arranged column-wise, respectively. Λ is a diagonal matrix holding eigenvalues as its diagonal. The spatial discretization of the flux derivative is given as

$$\frac{\partial F'}{\partial \eta} = \frac{\partial F'_+}{\partial \eta} + \frac{\partial F'_-}{\partial \eta} \quad (14)$$

The flux corresponding to positive eigenvalue is discretized using an upwind scheme, whereas the flux corresponding to negative eigenvalue is discretized using a downwind scheme. A fifth-order explicit scheme [9] is used for the discretization given as

$$u'_i = \sum_{k=-3}^3 \tilde{\alpha}_{i+k} u_{i+k} - \frac{\tilde{\alpha}}{6! b_i} \left(\frac{\partial u^6}{\partial x^6} \right)_i + \dots \quad (15)$$

This scheme has an adjustable parameter $\tilde{\alpha}$ which makes it upwind, downwind, or central. The scheme is upwind when $\tilde{\alpha} < 0$ and downwind when $\tilde{\alpha} > 0$. When $\tilde{\alpha}$ is zero, it becomes sixth-order central difference scheme. The dissipative nature of scheme is controlled by $\tilde{\alpha}$, and it is less dissipative when $\tilde{\alpha}$ closer to zero. In the present shock-fitting formulation, shock is located at

$$\eta(x, y, z, t) = \eta_{\max} = \text{constant}$$

and treated as a computational boundary. The grid points at η_{\max} are assumed to be immediately downstream of the shock. The condition behind the shock is calculated using Rankine-Hugoniot equation [9] given as

$$(\mathbf{F}_s - \mathbf{F}_\infty) \cdot l_s + (U_s - U_\infty) l_t = 0 \quad (16)$$

where,

$$\begin{aligned} \mathbf{F} &= F_1 \hat{i} + F_2 \hat{j} + F_3 \hat{k} \\ l_s &= \frac{\eta_x}{J} \hat{i} + \frac{\eta_y}{J} \hat{j} + \frac{\eta_z}{J} \hat{k} \\ l_t &= \frac{\eta_t}{J} \end{aligned}$$

The subscripts ∞ and s represent the variables ahead and behind of the shock, respectively. \mathbf{F} and U are flux and conservative variables vectors. l_s and l_t are the unit normal vectors to the shock for space and time, respectively. The above equation requires shock velocity which is computed using compatibility relation immediately behind the shock. The compatibility relation [9] is obtained by taking a derivative of Rankine-Hugoniot equation with respect to the computational time given as

$$\begin{aligned} (\mathbf{A}_s \cdot l_s) \frac{\partial U_s}{\partial \tau} - (\mathbf{A}_\infty \cdot l_s) \frac{\partial U_\infty}{\partial \tau} + (\mathbf{F}_s - \mathbf{F}_\infty) \cdot \frac{\partial l_s}{\partial \tau} \\ + \left(\frac{\partial U_s}{\partial \tau} - \frac{\partial U_\infty}{\partial \tau} \right) \cdot \frac{\partial l_t}{\partial \tau} \\ + (U_s - U_\infty) \cdot \frac{\partial l_t}{\partial \tau} = 0 \end{aligned} \quad (17)$$

where A is the flux Jacobean. Readers are advised to go through Zhong's work [9] for further details on shock-fitting formulation. The convective heat flux at the surface is computed using the temperature difference between solid and adjacent fluid as

$$q = h(T_f - T_s) \quad (18)$$