A Methodology for Aerothermodynamic Shape Optimization of Hypersonic Entry Aeroshells

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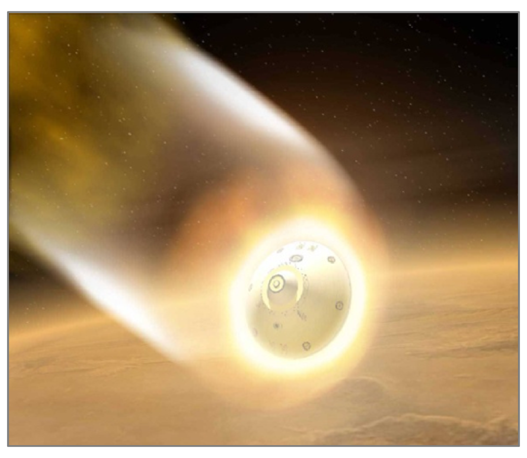
Introduction



Aeroshell shape design represents a tradeoff among multiple, competing objectives related to drag, stability, heating, packaging and overall system mass. Previous work by the authors [1] focused on the optimization of entry aeroshell shapes based on objectives related to aeroshell geometry and hypersonic aerodynamic performance. That multi-objective optimization framework is being extending to include the impact of hypersonic aerothermodynamics – that is, aerodynamic heating will be considered alongside the previously-developed objectives.

The method incorporated to approximate surface heat flux allows for multiple levels of aerothermodynamic fidelity to be introduced into the optimization process. Thus, the framework being developed supports a multi-fidelity exploration of the trade-offs between multiple conflicting design objectives.

Methodology

This work is divided into three main components: aeroshell shape parameterization, hypersonic aerothermodynamic analysis, and optimization.

Shape Parameterization

Non-uniform rational B-spline (NURBS) surfaces are used to represent aeroshell shapes, allowing for the generation of both traditional quadric and arbitrary free-form surfaces. An example NURBS aeroshell is shown in Fig. 1. Red dots correspond to the NURBS control points, which serve as the design variables during optimization.

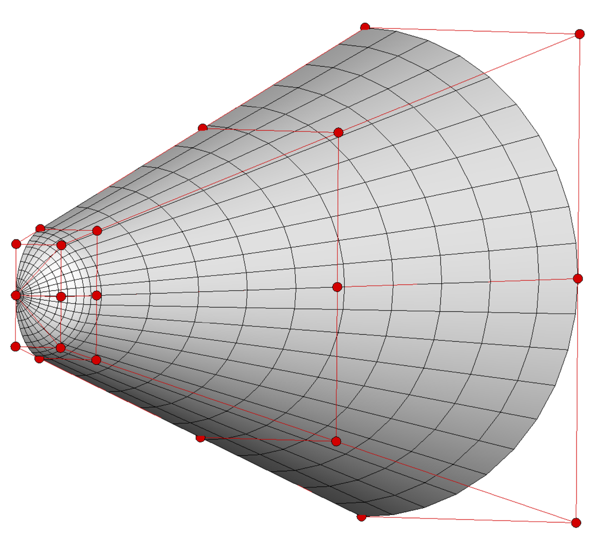


Fig. 1. Example NURBS aeroshell surface.

Aerothermodynamic Analysis

As described in [1], estimates for hypersonic aerodynamic forces are made using Newtonian flow theory. The methodology used to perform aerothermodynamic analyses has been adapted from research [2] that demonstrated the ability to obtain approximate 3D heating distributions from a series of axisymmetric analyses.

Based on thin shock layer theory, Brykina [2] found that the heat flux distribution depended primarily on two parameters:

(1) inclination of the local surface to the freestream flow: θ
(2) ratio of Reynolds number to the local surface mean curvature: Re/H

Thus, bodies with matching parameters will have approximately equal heat flux distributions. In particular, axisymmetric bodies can be generated which have similarity parameters that match those of lines along the surface of the original 3D body originating from the geometric stagnation point. Analyzing multiple such equivalent axisymmetric bodies (EABs) then provides an estimate for the heat flux distribution on the original 3D surface.

Following the approach in [3], EABs are generated from meridians along the 3D surface. These meridians are defined as the intersection of the surface and a plane that passes through the geometric stagnation point and that is parallel to the freestream velocity (see Fig. 2).

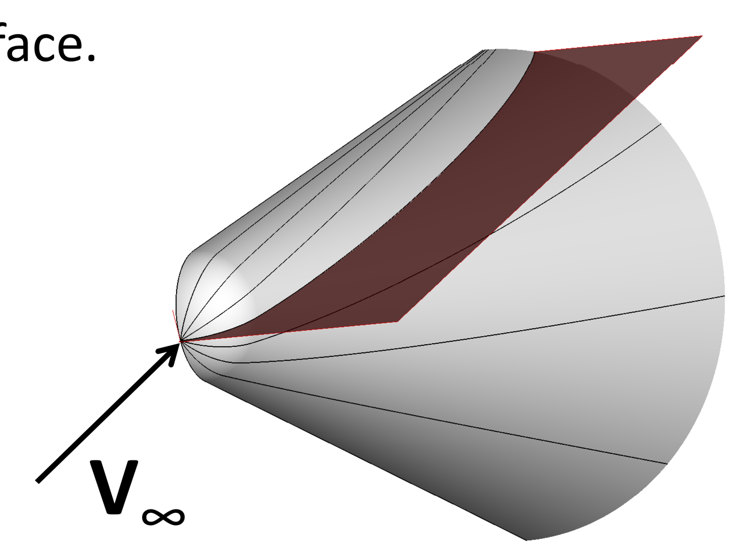


Fig. 2. 3D aeroshell with example meridians and meridian plane.

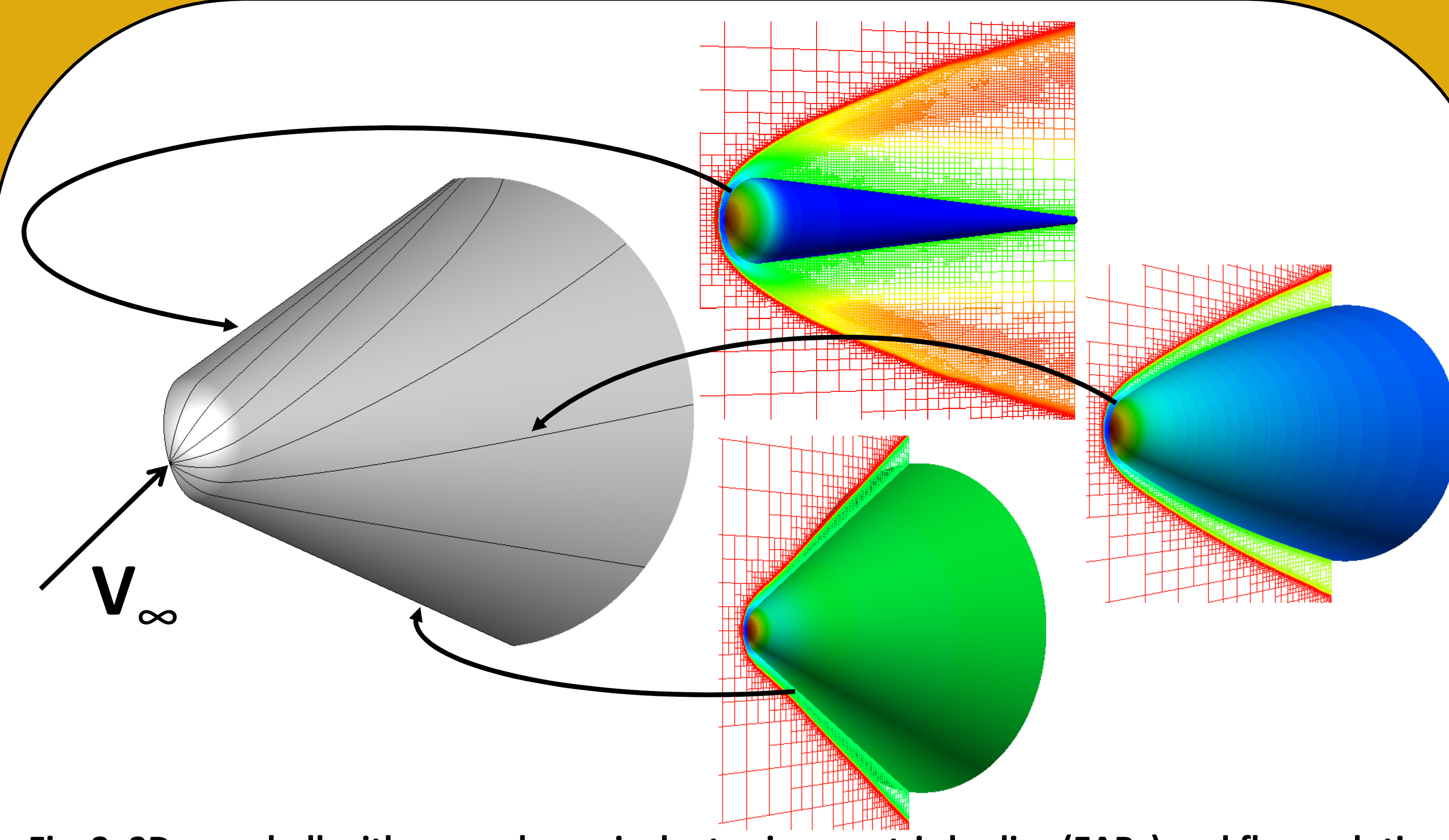


Fig. 3. 3D aeroshell with example equivalent axisymmetric bodies (EABs) and flow solutions.

Once surface meridians have been identified along the 3D surface, corresponding EAB geometries are generated based on the first similarity criterion that specifies the distribution in θ. Next, axisymmetric aerothermodynamic analyses are performed on these EABs and the second similarity criterion is satisfied by multiplying the resulting heat flux by the scale factor $(H_{3D}/H_{EAB})^{½}$. The resulting scaled heat flux is then taken to be the estimate of the heat flux along the corresponding meridians on the original 3D surface.

Aerothermodynamic analysis of EABs can be performed using any level of fidelity. At the low-fidelity level, a Newtonian inviscid solution is coupled with an approximate boundary-layer technique that provides an estimate of heat flux. Higher-fidelity solutions can be obtained either by replacing the Newtonian inviscid solution with an Euler solution or by applying Navier-Stokes analyses to the EABs. Furthermore, these analyses can be carried out in parallel. These options enable a multi-fidelity approach that exploits the speed of the low-fidelity analyses and leverages with higher-fidelity analyses where needed. When applied to optimization, this approach provides a computationally efficient means of exploring the design space.

Optimization

Optimization is performed using single- and multi-objective genetic algorithms (GAs). Multi-objective GAs are a computationally efficient means of obtaining an entire set of tradeoff, or Pareto, solutions in a single execution of the optimizer.

Continuing Work

Near-term efforts involve extending the Mars Science Laboratory test case from [1] to include heating objectives. Additionally, further verification and validation of the approximate aerothermodynamic method will be performed to quantify its range of applicability.

References

1. Theisinger, J. E. and Braun, R. D., "Multi-Objective Hypersonic Entry Aeroshell Shape Optimization," *Journal of Spacecraft and Rockets*, Vol. 46, No. 5, 2009, pp. 957-966.

2. Brykina, I. G., Rusakov, V. V., and Shcherbak, V. G., "A Method of Determining the Heat Fluxes and Friction in Three-Dimensional Problems of Hypersonic Streamline Flow Using Two-Dimensional Solutions," Dokl. Akad. Nauk. SSSR, Vol. 316, 1991, pp. 62-66.

3. Brykina, I. G. and Scott, C. D., "An Approximate Axisymmetric Viscous Shock Layer Aeroheating Method for Three-Dimensional Bodies," NASA TM-98-207890, May 1998.

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