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Multi-Objective Hypersonic Entry Aeroshell Shape Optimization

John E. Theisinger* and Robert D. Braun†
Georgia Institute of Technology, Atlanta, Georgia 30332-0150

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A framework has been developed to identify hypersonic entry aeroshell shapes that are Pareto-optimal with respect to multiple conflicting objectives. The objectives and constraints are derived from the aeroshell geometry and aerodynamic performance. Shapes are parameterized using nonuniform rational B-splines for maximum design flexibility. Hypersonic aerodynamic objectives and constraints are based on rapid predictions obtained from Newtonian flow theory. Single- and multi-objective genetic algorithms are employed for optimization. This framework has been applied to the Mars Science Laboratory mission to quantify tradeoffs inherent to blunt-body aeroshells. Lift-to-drag ratio, volume, and size constraints were derived from the 70-degree sphere-cone aeroshell for this mission, and aeroshell shapes were optimized based on three conflicting objectives: drag area, longitudinal static stability, and volumetric efficiency. First, single-objective optimization revealed the extreme designs for this objective space. Next, two-objective optimization produced Pareto fronts of compromise designs that illustrate the tradeoffs among each pair of objectives. Finally, a three-objective optimization provided Pareto-optimal designs that offer simultaneous improvement in all three objectives relative to the baseline 70-degree sphere-cone aeroshell.

Nomenclature

A = reference area, m^2
A = axial force, N
$C_D A$ = drag area (D/q_∞), m^2
$C_L A$ = lift area (L/q_∞), m^2
$C_M A l$ = pitching moment per unit freestream dynamic pressure (M/q_∞), m^3
C_p = pressure coefficient, $(p - p_\infty)/q_\infty$
D = drag force, N
L = lift force, N
L/D = lift-to-drag ratio
l = reference length, m
M = pitching moment about the center of gravity, N $\cdot$ m
M = Mach number
M_x, M_y, M_z = components of aerodynamic moment in aeroshell reference axes system, N $\cdot$ m
m = entry system mass, kg
N = normal force, N
$\mathbf{n}$ = surface outward normal unit vector
p = static pressure, Pa
q = dynamic pressure, Pa
S = surface area, m^2
V = volume, m^3
$\mathbf{V}$ = velocity vector, m/s
x, y, z = Cartesian coordinates in aeroshell reference axes system, m
Y = side force, N
α = angle of attack, deg
β = ballistic coefficient, kg/m^2
β = sideslip angle, deg
$\Delta x_{\text{c.g.}}$ = axial offset in center of gravity, m
$\Delta z_{\text{c.g.}}$ = vertical offset in center of gravity, m
γ = ratio of specific heats
η_V = volumetric efficiency

Subscripts

max = maximum value
trim = trimmed value
α = derivative with respect to angle of attack, rad^{-1}
0 = initial value
∞ = freestream value

I. Introduction

AEROSHELLS are designed to deliver payloads safely through a planetary atmosphere, protecting these payloads from the high aerodynamic heating and loads encountered during hypersonic entry, descent, and landing (EDL). The aeroshell also provides the aerodynamic drag force necessary for deceleration, dissipating approximately 90% of the EDL system's kinetic energy from the point of atmospheric interface. The aeroshell is designed to perform these functions with minimal mass so that useful landed mass is maximized.

An aeroshell generally consists of a forebody (or heat shield), which faces the flow, and a backshell, which completes the encapsulation of the payload. The specific shape of a particular aeroshell is driven by EDL performance requirements and thermal/structural limitations. Four different aeroshell shapes are shown in Fig. 1: the Viking-era 70 deg sphere cone, the Mars Microprobe, the Aeroassist Flight Experiment, and a swept biconic design. Primary drivers of these specific aeroshell designs include drag, stability, nonequilibrium aerothermodynamics, and radiative heating, respectively [1–4]. This diversity in configurations is a direct result of differing mission and flight system requirements: that is, form has followed function in every case.

One fundamental characteristic of an aeroshell is its drag area $C_D A$. Essentially, $C_D A$ represents the amount of drag force that an aeroshell can generate at a given freestream condition (i.e., D/q_∞). During the hypersonic EDL phase, this drag force provides the means of deceleration, suggesting that $C_D A$ should be maximized for a given entry system mass m. The ballistic coefficient is an aeroshell performance parameter that embodies this principle, relating inertial and drag forces, as shown in Eq. (1):

$$\beta = \frac{m}{C_D A} \tag{1}$$

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[*] Graduate Research Assistant, Daniel Guggenheim School of Aerospace Engineering. Student Member AIAA.

[†] David and Andrew Lewis Associate Professor of Space Technology, Daniel Guggenheim School of Aerospace Engineering. Fellow AIAA.