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Improved Method for Estimation of Spacecraft Free-Molecular Aerodynamic Properties

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A numerical procedure for calculating free-molecular aerodynamic properties of spacecraft is revisited and redeveloped using improved discretization and shading techniques. New complex geometric shapes are included, allowing the user to model a high-fidelity spacecraft model divisible into elemental panels of approximately equal area to conserve resolution. The forces on exposed elements are summed across the entire geometry. New analytic methods for determining exposed panels have been developed. Combined with the use of array algebra, the improvements considerably enhance processing speeds. The fidelity of the data is tested by application to the geometry of the Mars Reconnaissance Orbiter. The resulting data are compared with direct simulation Monte Carlo predictions. Additional case studies serve to inspect implications of geometry design versus output accuracy and processing speed.

Nomenclature

A_e = elemental area
C_{Fx} = force coefficient in the x direction
C_{Fy} = force coefficient in the y direction
C_{Fz} = force coefficient in the z direction
C_{Mx} = moment coefficient about the x axis
C_{My} = moment coefficient about the y axis
C_{Mz} = moment coefficient about the z axis
$F_{n,e}$ = normal elemental force
$F_{t,e}$ = tangential elemental force
k = Boltzmann constant
m = atmospheric mean molecular mass
S = molecular speed ratio
T = freestream temperature
T_w = average spacecraft surface temperature
U = flow velocity
α = aerodynamic pitch angle
β = aerodynamic yaw angle
ε_n, ε_t = normal and tangential components of unit flow vector to element
θ = flow incidence angle
ρ = atmospheric density
σ_n, σ_t = normal and tangential momentum accommodation coefficients

Introduction

THE aerodynamic properties of spacecraft operating in hyperthermal, free-molecular flow have long been estimated by the calculation of momentum transfer based on gas-surface interaction theory [1–3]. This method has been found accurate when dealing with spacecraft operating at altitudes at which the mean free path between molecular collisions is larger than the spacecraft reference length. Dividing a spacecraft geometry using a discrete element panel method is the most convenient way to apply these calculations, because force contributions are functions of flow characteristics, incidence angle, and exposure. Evaluating exposure of the geometry to the flow suggests the use of the panel method as well. The procedure presented here is a new application of this theory with improved shading and discretization that also takes advantage of modern computer programming language in MATLAB®. This procedure shares the force calculation theory of previous methods, adds additional components, provides a complete redevelopment of all components, and includes new element generation and shading processes. Spacecraft designs may be input in the form of geometric shapes such as plates, prisms, cylinders, cones, frustums, and spherical dishes. These geometric shapes are referred to as components. Each component is discretized into several panels, called elements, of the user-defined resolution. This newly developed discretization process maintains a relatively constant elemental area across the geometry as opposed to routines that can result in elements differing significantly from the user-defined resolution. Smaller elements can lead to increased processing requirements with no added fidelity.

A common problem with estimating aerodynamic forces by means of discrete elements is determining elemental flow exposure, more commonly called shading. Shading analysis requires the most processing time of the method and is important when dealing with complex spacecraft geometries in which components are shielded by instruments, solar panels, and dish antennas. In this approach, elements that are shielded from the flow do not contribute aerodynamic forces. The ability to ascertain which elements are not exposed to the hyperthermal flow is essential to this analysis and can hamper processing speed if not handled appropriately. Analytic shading processes are developed using array manipulation, in which several elements can be analyzed with respect to a single shading component at a time. These analytic processes constitute a new design of the original procedure.

The implementation of this procedure into a MATLAB program, entitled FreeMat, sought to allow users to easily create a spacecraft geometry to complex specifications while maintaining minimal processing time for varying orientations. Using the array manipulation capabilities of MATLAB in combination with the new shading processes enabled a significant reduction in processing speeds. Specific components of satellites may be easily defined with the included component types. The program generates a set of aerodynamic coefficients given a range of yaw and pitch angles. This set of data may then be interpolated for trajectory calculations. For satellites that tumble or present a large variety of orientations to the flow, an alternate approach would be to calculate the aerocoefficients during the trajectory analysis. The program is applied to the Mars

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