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Aerodynamic Characteristics of the Magellan Spacecraft in the Venus Upper Atmosphere

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The aerodynamic flight characteristics of the Magellan spacecraft in the Venus atmosphere are computed at a nominal altitude of 140 km over a wide range of incidence angles and roll angles. Computational methods are described that can be used to simulate flowfields in the transition and free-molecule domains over vehicles of arbitrarily complex geometry. Values of the drag, lift, and transverse forces and of the pitch, yaw, and roll moments are given for incidence angles of -60 to 60 deg and roll angles of 0 to 360 deg. Transitional-flow effects are quantified and shown to be small, but not negligible and should be accounted for if high accuracy is required.

Nomenclature

A, B, C	= viscosity coefficients
C_D	= drag coefficient
$C_{F_x}, C_{F_y}, C_{F_z}$	= force coefficients, force/0.5ρ V^2
C_p	= pressure coefficient, pressure/0.5ρ V^2
C_s	= shear coefficient, shear/0.5ρ V^2
D	= high-gain antenna diameter, 3.66 m
M_X, M_Y, M_Z	= aerodynamic moments, N · m
S	= reference surface area, 23 m^2
T	= temperature, K
T_{ref}	= VHS reference temperature, K
$\mathbf{V} = (V_x, V_y, V_z)$	= spacecraft velocity, m/s
α	= incidence angle
θ	= temperature ratio, T/T_{ref}
ρ	= gas density, kg/m^3
ρ_∞	= freestream gas density, kg/m^3
μ	= gas viscosity, kg/m · s
ϕ	= roll angle
ω	= viscosity temperature coefficient

Introduction

MAGELLAN has been orbiting Venus since August 1990 to map its surface using radar imaging, and to measure its gravity field. The spacecraft orbit is highly elliptical, with a periapsis of 300 km and an apoapsis of 8500 km. As the planned data collection mission is coming to an end, the scientific community is expressing interest in extending its life to attempt measurements at higher spatial resolution. Higher resolution requires lowering and circularizing the spacecraft orbit to an altitude of 150–250 km. The fuel reserves on board Magellan are not sufficient to perform such a maneuver, and it has been proposed to aerobrake the spacecraft in the planet's upper atmosphere.[1] Magellan, however, was not designed for such a mission, and there is a need to assess the magnitude of the aerodynamic forces and moments on the vehicle to ensure controllability and survivability during the aeropasses. The aerobraking mission itself could yield valuable information on both the Venus atmospheric structure and the aerobraking physics in the predominantly carbon dioxide atmosphere.[2] The purpose of the present article is twofold: 1) to assess the aerodynamic characteristics of the Magellan spacecraft for typical re-entry conditions and provide the mission designers with the basic data required to plan the aerobraking mission, and 2) to document and discuss the methods that were developed and used in the study. The article is not intended to ascertain the feasibility of aerobraking Magellan, but rather to provide the means to study the maneuver.

In this article, the aerodynamic forces and moments on Magellan are evaluated at a nominal altitude of 140 km for a range of incidence angles and roll angles. The study was conducted using both a particle code (Direct Simulation Monte Carlo [DSMC]) and a free-molecule code to assess transitional-flow effects. The flow simulation was performed in three dimensions and at high spatial resolution (2 cm). Previous studies of Magellan aerodynamics had been conducted either in the free-molecular-flow regime only or at zero incidence and coarse resolution.[3]

The next two sections describe the numerical codes and methods that were developed and used. The three-dimensional DSMC code is based on Bird's F3 algorithm.[4] The free-molecule code relies on a line-of-sight algorithm and takes into account mutual shading by individual components of the spacecraft. The fourth section describes the interactive graphical preprocessor that was developed to define and input the spacecraft's complex geometry. In the fifth section, the properties of Venus's atmosphere at the simulation altitude are presented and the gas model used in the DSMC simulation is explained. The characteristics of the flowfield around Magellan are described in the last section. Magellan aerodynamic forces and moments are presented for incidence angles from −60 to +60 deg and roll angles from 0 to 360 deg. Comparisons are made with results of previous studies.

Three-Dimensional DSMC Code

The DSMC code used for the present study was devised by Bird[4] and further developed and described by Rault.[5–7] High efficiency is achieved through the use of a Cartesian/unstructured computational grid, as illustrated in Fig. 1, which shows the actual grid used in the present computation. The body geometry is defined and entered in the code as an ensemble of small cubic elements (pixels), each one being characterized by a wetted surface area and a normal direction cosine. To simulate the Magellan geometry, 200,000 pixels were used (each pixel with a side of 2 cm), and the computational grid was composed of about 7500 cells. For the present simulation, the code was run in a full three-dimensional mode, i.e., no symmetry was assumed for either the body or the flowfield. Details on the code setup and performance are summarized in Appendix A. Diffuse reflection with full thermal and momentum accommodations was assumed in modeling molecule-surface interaction. The reflection characteristics of Venus atmosphere molecules on Magellan structural material and scientific equipment are not known, but accommodation coefficients on typical engineering surfaces are usually close to unity. Our code has been used in the past to simulate the flowfield around slender hypersonic vehicles (delta wings,[5] waverider[6]) and around

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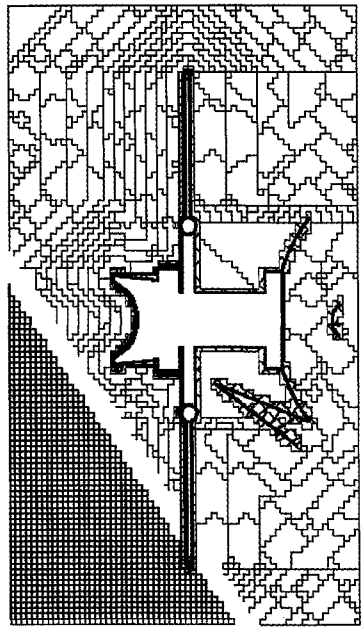

Fig. 1 Computational grid for DSMC simulation.

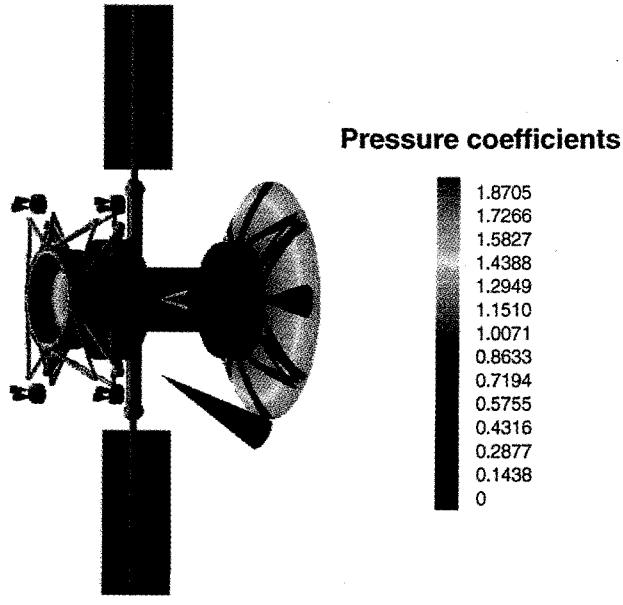

Fig. 2 Pressure coefficients on Magellan surface at 0-deg incidence, 0-deg roll (free-molecule simulation).

blunt re-entry bodies (AFE and Viking[7] and the Space Shuttle[5]), as well as in various other studies (such as shock interaction in a compression corner).[7,8] Comparison with experimental measurements, when available, has yielded excellent agreement. The code has recently been optimized for vector architecture and has been complemented with a set of utilities for diagnosis, preprocessing, postprocessing, grid adaptation, and Knudsen-layer definition.

Three-Dimensional Free Molecule Code

The free-molecule (FM) code uses the same preprocessor as the DSMC code, i.e., it uses the same definition of the vehicle body as an ensemble of cubic pixels and associated surface areas. The three-dimensional free-molecule simulation is performed in two steps. In the first step, the body surface pixels that are shaded from the freestream by other components of the spacecraft are identified and tagged. Ray tracing originating at each of the surface pixels is used. In the second step, the forces and moments acting on each surface pixel are computed for each species, assuming diffuse reflection on the vehicle surface.[9] The total forces and moments on the vehicle

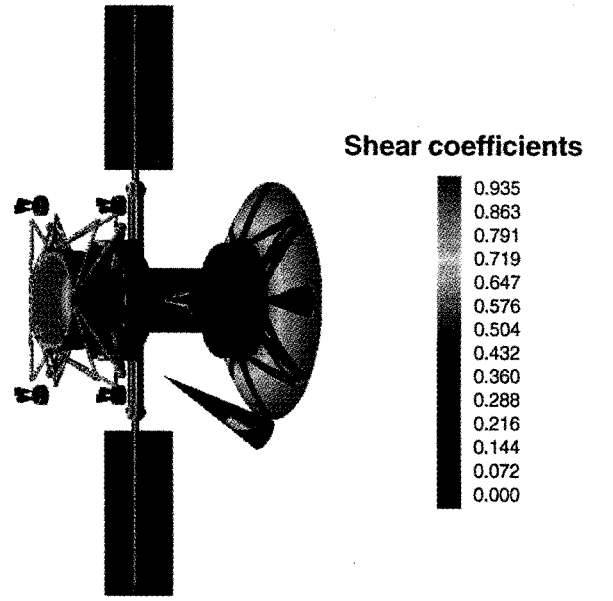

Fig. 3 Shear coefficients on Magellan surface at 0-deg incidence, 0-deg roll (free-molecule simulation).

are evaluated by summing the individual contributions from each surface pixel and each species. Extensive graphical diagnosis has been developed to visualize and verify the code results, as illustrated in Figs. 2 and 3. These figures show the surface pressure and shear coefficients on Magellan for incidence and roll angles of 0. The FM code is mostly analytical and is therefore considerably faster than the DSMC code, as shown in Appendix A.

Graphical Interactive Preprocessor

To define and input the complex geometry of the Magellan spacecraft, it was necessary to develop an interactive three-dimensional preprocessor with a graphical interface. The preprocessor relies on the fact that even a very complex three-dimensional body geometry can be decomposed into a series of simple primitives such as spheres, cones, cylinders, planes, ellipsoids, or parts thereof. The geometric properties of each primitive subelement constituting the spacecraft body are entered into the preprocessor through an editable spreadsheet. The format of the spreadsheet is described in detail in Ref. 10. The spreadsheet is divided into records, each one corresponding to a primitive subelement. Each record is made up of a series of fields, each one describing the nature of the subelement and its dimensions and coordinates. The Magellan geometry was defined using 85 subelements selected from a library of 16 basic primitives.[10] The preprocessor reads the spreadsheet data file and creates a binary graphical file in a TecPlot format. (TecPlot is a commercial two-dimensional and three-dimensional graphical program developed by AMTEC.) The body geometry thus generated can therefore be readily visualized in three dimensions and analyzed using the several TecPlot utilities (Rotation, Zoom, Shading, etc.). By interactively editing the spreadsheet data file and graphically examining the generated geometry, it is possible to construct and reproduce the geometry of very complex objects. Upon completion, the preprocessor generates a geometry file in the format required by both the DSMC and FM codes.

Freestream and Atmospheric Conditions: Gas Model

The simulation described in the paper was performed at a specific altitude, namely 140 km, at which Venus's nominal atmospheric characteristics are as follows[1]:

Density: 9.5×10^{16} molecules/m^3
Temperature: 225 K
Molar composition: 75.7% CO_2, 9.6% CO, 8.9% Ar, 5.8% N_2

The spacecraft velocity is 8600 m/s, and its surface temperature is assumed to be 300 K.

Bird's VHS model was used to simulate the collision characteristics of the gas mixture. The VHS parameters were evaluated using Yos's numerical viscosity data as described in Appendix B. The mean viscosity temperature coefficient is 0.80 with a reference temperature of 3000 K. The molecular diameters at the reference temperature are 3.77 Å for CO_2, 3.34 Å for N_2, 2.98 Å for Ar, and 3.26 Å for CO. Internal energy exchange among the molecular species was simulated with the Larsen-Borgnakke phenomenological model.[11] Chemical reactions were not considered, due to the low collisionality in the flowfield.

Flowfield Structure; Transitional-Flow Effects

Figures 4 and 5 show the gas density around Magellan as computed with the DSMC code for incidence angles of 0 and 30 deg and roll angles of 0 and 50 deg, respectively. The incidence and roll angles are defined so that the freestream velocity vector relative to the spacecraft is (see Fig. 6 for reference frame)

$$V_x = -V \sin\alpha \sin\phi$$
$$V_y = -V \sin\alpha \cos\phi$$
$$V_z = V \cos\alpha$$

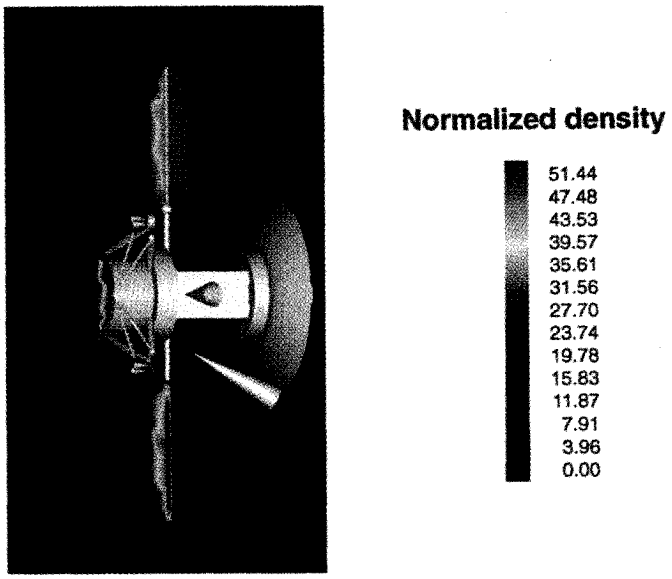

Fig. 4 Gas density around Magellan at 0-deg incidence, 0-deg roll (DSMC simulation).

These figures correspond to the plane perpendicular to the solar panels (plane XZ in Fig. 6). The largest density increases ($\rho/\rho_\infty = 70$) occur in front of the solar panels and the truss support of the main engine. (The engine itself was jettisoned upon arrival in Venus orbit.) Substantial density increases are observed on the lee side of the solar panels due to reflection of molecules from the high-gain antenna (HGA) and the payload bay surfaces.

Tables 1, 2, and 3 show the value of the aerodynamic force and moment coefficients (about the spacecraft reference center of gravity) computed with the DSMC and FM codes for several incidence and roll angles. The reference area is the frontal surface area of the high-gain antenna and solar panels, and the reference length is the diameter of the high-gain antenna. The values of the aerodynamic coefficients are sometimes very small, and values less than 10^{-2} are probably beyond the accuracy of the methods. The first two columns

Table 1 Aerodynamic force and moment coefficients on Magellan at 0-deg incidence, 0-deg roll

	DSMC with collisions	DSMC without collisions	FM
	Force		
Drag	2.00	2.13	2.06
Lift	2.0E−3	9.1E−4	7.6E−4
Transverse	4.2E−4	2.7E−5	2.9E−4
	Moment		
M_X (yaw)	5.0E−2	5.4E−3	2.2E−4
M_Y (pitch)	4.3E−3	4.9E−3	1.0E−3
M_Z (roll)	3.3E−5	1.1E−4	4.0E−6

Table 2 Aerodynamic force and moment coefficients on Magellan at 30-deg incidence, 50-deg roll

	DSMC with collisions	DSMC without collisions	FM
	Force		
Drag	1.90	2.00	1.90
Lift	4.2E−2	1.0E−2	1.3E−2
Transverse	5.0E−2	1.6E−2	1.6E−2
	Moment		
M_X (yaw)	9.6E−2	1.0E−1	9.4E−2
M_Y (pitch)	6.1E−2	6.9E−2	7.1E−2
M_Z (roll)	1.3E−2	1.7E−2	1.4E−2

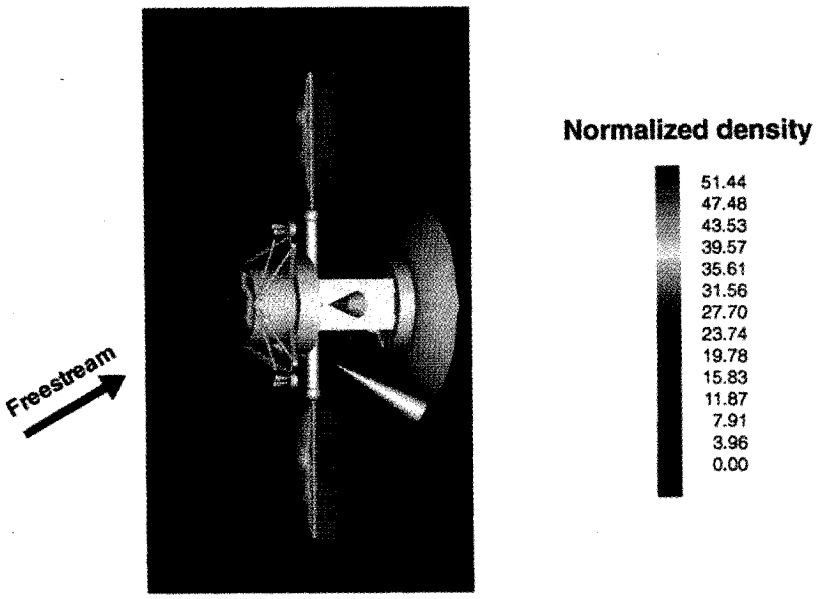

Fig. 5 Gas density around Magellan at 30-deg incidence, 50-deg roll (DSMC simulation).

Table 3 Aerodynamic force and moment coefficients on Magellan at 15-deg incidence, 75-deg roll

	DSMC with collisions	DSMC without collisions	FM
	Force		
Drag	1.91	2.03	1.95
Lift	9.6E−3	1.3E−3	2.0E−3
Transverse	3.8E−2	1.1E−2	1.2E−2
	Moment		
M_X (yaw)	1.7E−2	2.1E−2	2.7E−2
M_Y (pitch)	3.7E−2	5.4E−2	6.3E−2
M_Z (roll)	7.1E−4	1.1E−3	2.3E−3

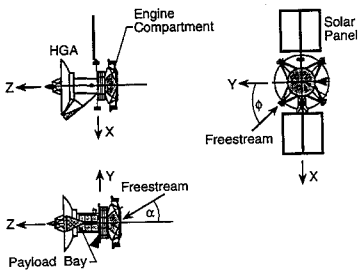

Fig. 6 Magellan reference frame.

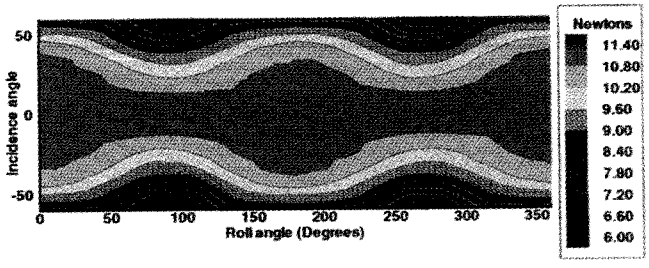

Fig. 7 Drag force (free-molecule simulation).

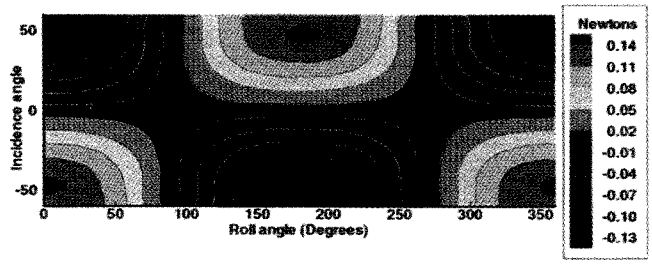

Fig. 8 Lift force (free-molecule simulation).

were obtained with the DSMC code run in collisional and collisionless modes, respectively. The difference between these two results is a measure of the transitional-flow effects, i.e., the effects due to intermolecular collisions. It can be observed that these effects are small, but not negligible, especially at nonzero incidence. The third column in Tables 1–3 shows the results obtained with the FM code. Differences between the aerodynamic coefficients computed with the FM code and the collisionless DSMC code are due to 1) the possibility of multiple wall collisions, which are naturally accounted for in DSMC but not in FM, and 2) the representation of the spacecraft surface as a series of cubic pixels in the DSMC code (with an effective wetted surface area larger than the actual one, as shown in Ref. 6) as opposed to a series of planes with a set surface area and direction cosine in the FM code implementation. These differences are minimal, and therefore, fairly good agreement exists between the FM code and the collisionless DSMC code.

Figures 7–12 show maps of the free molecular forces (drag, lift, transverse) and moments [M_X (yaw), M_Y (pitch), and M_Z (roll)] as

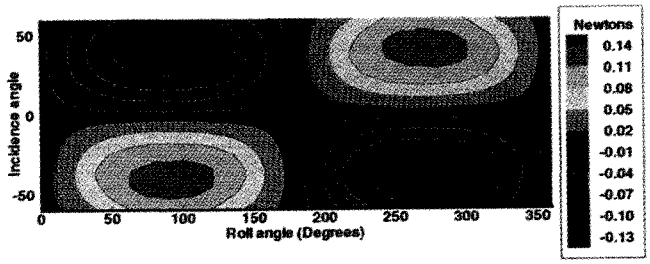

Fig. 9 Transverse force (free-molecule simulation).

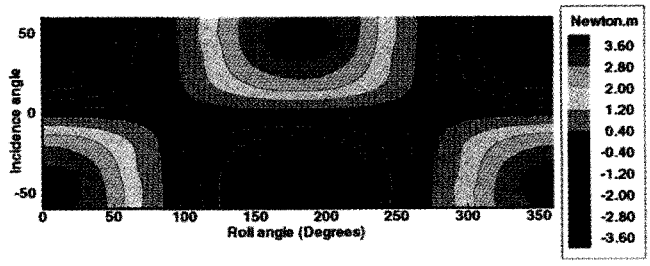

Fig. 10 Moment M_X (free-molecule simulation).

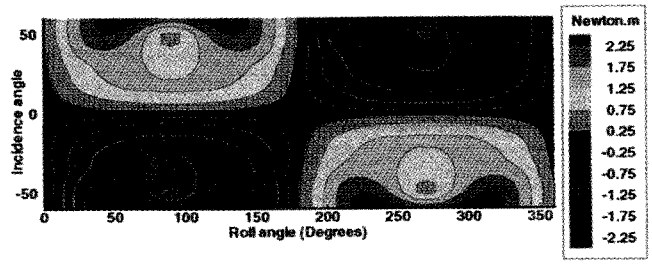

Fig. 11 Moment M_Y (free-molecule simulation).

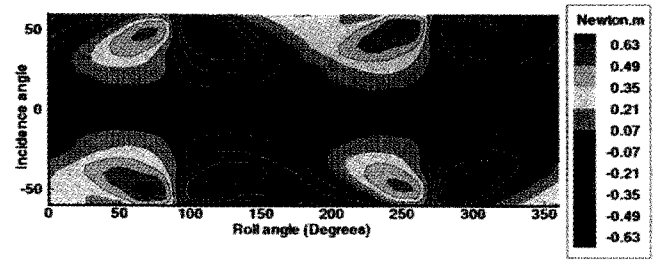

Fig. 12 Moment M_Z (free-molecule simulation).

the incidence and roll angles are varied, respectively, from −60 to +60 deg and 0 to 360 deg, at a 5-deg increment. Figures 13–16 show the free molecular moments in the X and Y directions as a function of incidence and roll angles. These figures and corresponding tables should provide the mission designers the information necessary to assess the stability of Magellan at most attitudes of interest.

The present DSMC results have been compared with Haas and Feiereisen's[3] particle simulation. The drag coefficient computed by Haas ($C_D = 2.03$) at 0-deg incidence, 0-deg roll, and 140-km altitude is in good agreement with our present value of $C_D = 2.00$.

Conclusion

The work presented herein has shown that it is now possible to simulate the flowfield around a complex geometry spacecraft and evaluate its aerodynamic characteristics in the transition and free-molecule flow regimes. The graphical preprocessor described above, together with the three-dimensional general-application direct-simulation Monte Carlo and free-molecule codes that we have been developing and using, form a unique combination which can be used to solve very difficult problems. The simulation of Magellan aerodynamics at the high spatial resolution described

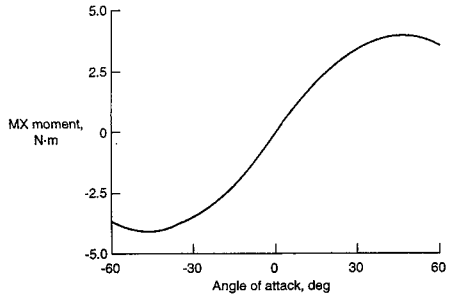

Fig. 13 Variation of moment M_X with incidence angle (roll = 0 deg).

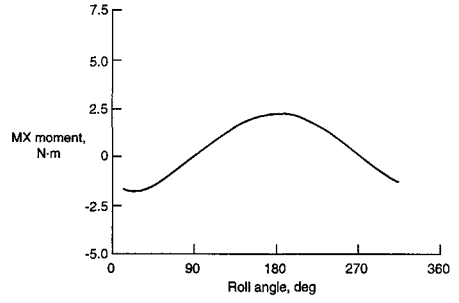

Fig. 14 Variation of moment M_X with roll angle (incidence = 15 deg).

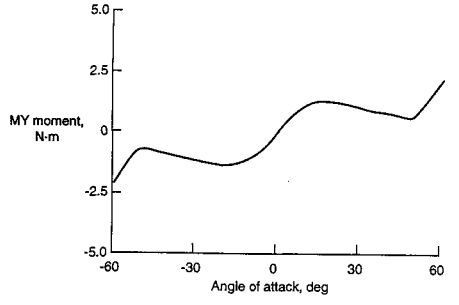

Fig. 15 Variation of moment M_Y with incidence angle (roll = 90 deg).

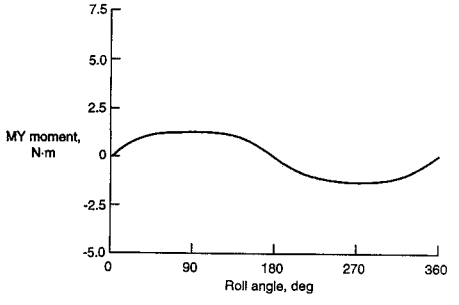

Fig. 16 Variation of moment M_Y with roll angle (incidence = 15 deg).

above is one of the most complex three-dimensional problems ever attempted with a particle code.

The forces and moments on Magellan have been computed for a nominal re-entry altitude, namely 140 km, and for a wide range of incidence angles and roll angles. At the conditions considered, the transitional-flow effects are relatively small but should not be neglected in the final analysis.

Appendix A: Code Setup and Performance

The DSMC and FM codes were run on a Sun Sparc 2 workstation with 64 meg RAM. The DSMC code was run for six different cases, as shown in Table A1, and required about 45 Mbyte of core memory [23 Mbyte for geometry definition and 22 Mbyte for molecule data (position, velocity, internal energy, species)]. The number of simulated molecules in each case was about 250,000, corresponding to a weight factor FNUM = 6.2E14. The time step was 2.35E−6 s. The

Table A1 DSMC simulation performance

Case	Incidence angle, deg	Roll angle, deg	Molecular collisions	Number of time steps		Total CPU time, h
				Transient	Steady state	
1	0.0	0.0	Yes	6000	21,000	108
2	30.0	50.0	Yes	3000	10,000	44
3	15.0	75.0	Yes	10,000	4000	54
4	0.0	0.0	Yes	34,000	7000	160
5	30.0	50.0	No	9000	10,000	75
6	15.0	75.0	No	32,000	9000	130

computational volume was 11.24 m × 4.66 m × 6.68 m, respectively, in the X, Y, Z directions (see Fig. 6). The coarse Cartesian grid (CCG) was defined by 111 × 46 × 66 equal subdivisions in the X, Y, Z directions. The fine Cartesian grid (FCG) was composed of 5 × 5 × 5 pixels. (See Ref. 7 for the definition of the CCG and FCG grids.) The numbers of time steps used in the transient and steady phases of the simulation are shown in Table A1, together with the CPU times. These values were not optimized. In each case, the simulation had converged in a fraction of these times, but the code was run for extended periods of time to increase sample sizes and improve the quality of the postprocessed density maps.

By contrast, the FM code is semianalytical, and therefore much faster. The FM code takes about 90 s for each incidence–roll-angle configuration. The maps shown in Figs. 7–12 were generated by running the FM code in nested loops over incidence and roll angles with increments of 5 deg. These maps and corresponding aerodynamic tables were constructed in 40 h of total CPU time.

Appendix B: Gas Model

Bird's variable-hard-sphere (VHS) model was used to simulate intermolecular collisions. The pertinent parameters of the model (effective viscosity temperature coefficient and molecular diameters) were computed using the viscosity data tabulated by Gupta et al.[12,13] In these references, the dependence of viscosity on temperature is expressed as

$$\mu = e^{C} T^{A \ln T + B} \tag{B1}$$

where A, B, and C are characteristic constants for a given gas. The approximation of this equation with a power law

$$\mu = \alpha T^{\omega} \tag{B2}$$

was performed using a least-squares method, from which the mean value of the coefficient ω can be expressed as

$$\omega = A \frac{[\theta(\ln\theta)^3]_{\theta_1}^{\theta_2}}{[\theta(\ln\theta)^2 - 2\theta\ln\theta + 2\theta]_{\theta_1}^{\theta_2}} - 3A + 2A\ln T_{\text{ref}} + B \tag{B3}$$

where $\theta = T/T_{\text{ref}}$ and T_{ref} is the reference temperature. θ_1, θ_2 correspond to the upper and lower temperature limits.

The mean value of ω for the Venus atmosphere at 140 km was computed based on the viscosity of the predominant gas, namely, carbon dioxide. At the reference temperature $T_{\text{ref}} = 3000$ K, the value of ω is 0.80. The VHS molecular diameters of each of the constituents at the reference temperature were computed with this value of ω using the equation derived by Bird.[14] The results are as follows:

Carbon dioxide: 3.77 Å
Diatomic nitrogen: 3.34 Å
Argon: 2.98 Å
Carbon monoxide: 3.26 Å

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