Earth Reentry Tool for Preliminary Mission Analysis

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Abstract: *The preparation of atmospheric Earth reentry vehicles requires the estimation of heat and mechanical loads along the trajectory, as well as the impact point. A dedicated tool for axial symmetric capsules is prepared for trajectory propagation, providing relevant data for the thermal protection system sizing, such as the heat flux in the stagnation point calculated with five different models. Translational dynamics only are considered for the moment. The aerodynamic drag is computed using the minimal input as Mach dependant curves. The Reynolds number influence is also included, since the flow regimes to compute the drag coefficient are derived from a preliminary reference trajectory. Automatic generation of quality plot files is included, as well as 3D plot objects for Matlab, for later usage.*

Key Words: *planetary reentry dynamics, Fay-Riddell, reentry black box.*

1. INTRODUCTION

The large amount of space debris accumulated in the last decades requires both passive and active methods for both the limitation and elimination of the debris. As a first step, a better knowledge of debris fragmentation and reentry process is needed.

Thus, small reentry capsules with the role of black boxes have recently been tested [1] and more are to be developed in US and Europe.

They are to be installed on both upper stages of the launchers, and on the spacecraft, as in the future the process may become part of the standards regulating space activities.

More ideas are related to how these capsules will fly with respect to the cloud of fragments: inside or in the forefront. This has a significant impact in the ballistic coefficient of the capsule.

Since the mass budget allocated for this purpose is typically small especially on small launchers, a careful design is needed, so that all the components should be optimized for the given mission.

A trajectory propagation tool is developed to solve the reentry problem in three degrees of freedom, also accounting for the heat transfer in the stagnation point.

2. DYNAMICS MODEL

A simply translational model is implemented, in a cartesian inertial reference frame. The spherical coordinate system has been ruled out in order to eliminate the singularity in the case of the vertical trajectories.

$$\ddot{\bar{r}} = -\frac{\bar{r}}{\|\bar{r}\|} g - \frac{\dot{\bar{r}} - \bar{\omega}\times\bar{r}}{\|\dot{\bar{r}} - \bar{\omega}\times\bar{r}\|}\frac{D}{m} = -\frac{\bar{r}}{\|\bar{r}\|} g - \frac{\dot{\bar{r}} - \bar{\omega}\times\bar{r}}{\|\dot{\bar{r}} - \bar{\omega}\times\bar{r}\|}\frac{0.5\rho\|\dot{\bar{r}} - \bar{\omega}\times\bar{r}\|^2}{BC} \tag{1}$$

$$g = g_{WGS84}\frac{\bar{r}_s^{\,T}}{\|\bar{r}_s\|}\frac{\bar{n}_s}{\|\bar{n}_s\|} \tag{2}$$

$$\bar{r}_s = \begin{bmatrix} \sqrt{r_1^2 + r_2^2} \\ r_3 \end{bmatrix} \tag{3}$$

$$\bar{n}_s = \begin{bmatrix} rpol \cdot \cos(lat) \\ req \cdot \sin(lat) \end{bmatrix} \tag{4}$$

$$\bar{\omega}^T = \left(0\ \ 0\ \ 7.292115e-5\right)^T \text{ [rad/s]} \tag{5}$$

Where g is the gravitational acceleration, $\bar{r}_s$ is the position vector in the symmetry plane, $\bar{n}_s$ is the surface normal in the symmetry plane and $\bar{\omega}$ is the rotational speed vector.

The wind velocity is considered as $\bar{\omega}\times\bar{r}$, which states that the atmosphere rotates perfectly attached to the surface as in [2] page 88, equation 4.13 and [3] page 658, equation 12.8 and 12.9.

The dynamics model is integrated with the 6th order Runge-Kutta method [4]. Time step adaptation is performed a posteriori with respect to a weighted combination of three criteria: heat flux, axial loading coefficient and dynamic pressure.

The atmosphere model is US 76 [5], which covers up to 1000 Km in altitude. A Matlab implementation has been adopted, from [6]. The code is too slow to be used in the computations.

Instead of using it, a dense table has been generated, with a step of 50m, which is linearly interpolated and the subinterval index is directly found, avoiding a computationally expensive table search.

The World Geodetic System 1984 (WGS 84) has been used, since it is already implemented in Matlab.

3. HEAT FLUX MODELS

Five heat flux methods are implemented in order to provide lower and upper bounds. Fay-Riddell is implemented in two versions: hot wall and cold wall.

Fay-Riddell hot wall equation, as in [7], while some clarifications have been found initially in [8].

$$h_q = 0.76 \Pr^{-0.6} (\rho_2 \mu_2)^{0.4} \sqrt{\left.\frac{du}{dx}\right|_{x=0}} \left(\frac{p_2}{RT_w} \mu(T_w) \right)^{0.1} \frac{\gamma R}{\gamma - 1} \quad (6)$$

The wall temperature T_w is obtained by solving (Newton method) the equation:

$$h_q (T_0 - T_w) = \sigma \varepsilon T_w^{\ 4} \quad (7)$$

$$\left.\frac{du}{dx}\right|_{x=0} = \frac{1}{RN} \sqrt{\frac{2(p_2 - p)}{\rho_2}} \quad (8)$$

Where T_0 is the stagnation temperature, $\Pr$ is the Prandtl number, set to 0.7 as for laminar flow, RN is the nose radius and $\varepsilon = 0.9$ is the radiation emissivity of the ablative material.

Index 2 for pressure, density and viscosity refers to the stagnation condition, considered as post shock parameters in supersonic and just stagnation parameters in subsonic.

The other models are: Detra & Hidalgo, Sutton-Graves, Tauber and Van Driest from reference [9].

4. AERODYNAMICS

The current work considers only axial symmetric capsules in the hypothesis that they are aligned with the relative flow direction, where all that is needed is the drag coefficient. This is implemented as a function of the Mach number, which is typically a result of a numerical flow analysis. A set of Reynolds and Mach numbers is chosen after a preliminary trajectory computation as and applied for running the CFD code. Then, the Mach number dependency of the drag is considered in the reentry dynamics.

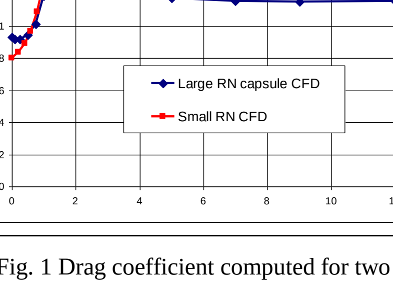

Fig. 1 Drag coefficient computed for two capsules, with different nose radii

Case 10						
Large nose radius						
		Mass [Kg]				
Parameter		10	8.33	8	6.66	6
Reentry time [s]		777.7	804.4	810.69	841.08	859.79
Heat Flux max. [W/m2]	Fay Riddel Hot Wall	2.04E+06	1.88E+06	1.84E+06	1.70E+06	1.62E+06
	Fay Riddel Cold Wall	2.56E+06	2.34E+06	2.30E+06	2.11E+06	2.01E+06
	Tauber	2.46E+06	2.26E+06	2.22E+06	2.03E+06	1.94E+06
	Dedra-Hidalgo	2.60E+06	2.38E+06	2.34E+06	2.15E+06	2.04E+06
	Van Driest (Anderson)	2.05E+06	1.88E+06	1.85E+06	1.70E+06	1.61E+06
Acc/g [-]		10.2	10.1	10.129	10.079	10.123
V_{crash} [m/s]		50.1	45.7	44.735	40.78	38.686
q_{max} [Pa]		12241.0	10078.0	9668.1	8004.2	7234.5
Potential emitting time [s], M < 5		304.8	334.5	341.5	375.21	395.67
Downrange [Km]		3357.8	3334.8	3329.7	3306.5	3293.3

Small nose radius				
		Mass [Kg]		
Parameter		10	8	6
Reentry time [s]		771.5	802.7	848.9
Heat Flux max. [W/m2]	Fay Riddel Hot Wall	2.48E+06	2.24E+06	1.97E+06
	Fay Riddel Cold Wall	3.13E+06	2.82E+06	2.46E+06
	Tauber	3.02E+06	2.72E+06	2.37E+06
	Dedra-Hidalgo	3.19E+06	2.87E+06	2.50E+06
	Van Driest (Anderson)	2.52E+06	2.27E+06	1.98E+06
Acc/g [-]		10.1	10.1	10.2
V_{crash} [m/s]		52.7	47.2	40.9
q_{max} [Pa]		10079.0	8009.9	6087.7
Potential emitting time [s], M < 5		302.1	336.7	388.1
Downrange [Km]		3335.4	3307.2	3270.7

Fig. 2 Flight segments statistics (automatic data gathering)

5. TOOL FEATURES

The tool has been written in order to solve a set of trajectories in the same run. Comma separated values files are saved for each of the trajectories in their distinct folders, providing the whole dataset, flight segments statistics and global values, as they are intended to be used. The dataset contains 30 parameters, related to dynamics, aerodynamics and heat transfer.

A significant number of plots are automatically generated for each trajectory. The 3D trajectories are saved in fig format, being useful for a later interactive inspection. For formatted data centralization in Excel, macros have been written to collect the data from each folder.

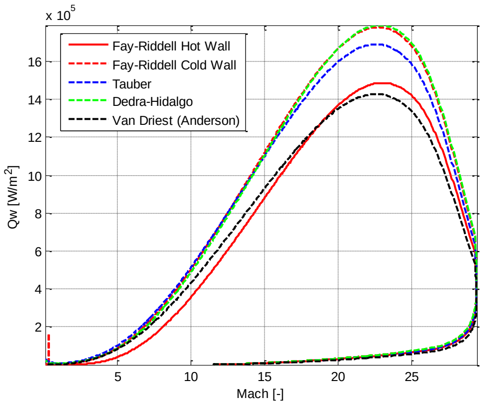

Fig. 3 Mach/Heat flux correlation

Column No.	Parameter
1	Time[s]
2	X[m]
3	Y[m]
4	Z[m]
5	Vxi[m/s]
6	Vyi[m/s]
7	Vzi[m/s]
8	Altitude[m]
9	P [Pa] freestream
10	Rho [Kg/m^3] freestream
11	T [K] freestream
12	gamma – post shock adiabatic expansion ratio
13	P2 [Pa] post shock
14	Rho2 [Kg/m^3] post shock
15	T2 [K] post shock
16	Velocity[m/s]
17	Reynolds [-]
18	Mach [-]
19	Knudsen [-]
20	Dynamic pressure [Pa]
21	Axial loading [m/s^2]
22	Ballistic coefficient [Kg/m^2]
23	Heat flux Fay-Riddell **Hot Wall** [W/m^2] - equation
24	Heat flux Fay-Riddell **Cold Wall** [W/m^2] - Tw=300K
25	Heat flux Tauber [W/m^2]
26	Heat flux Dedra-Hidalgo [W/m^2]
27	Heat flux Van Driest [W/m^2]
28	Wall temperature [K]
29	Flight path angle [deg]
30	Downrange [Km]

Fig. 4 The dataset

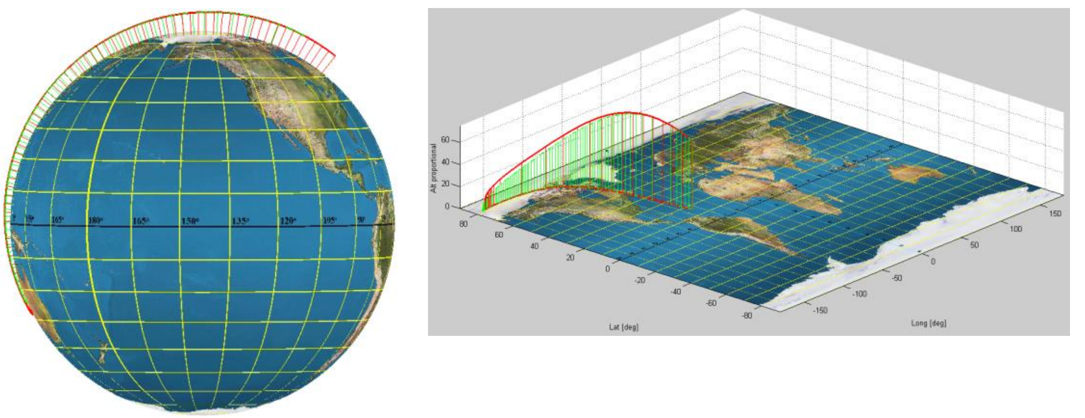

Fig. 5 Flight segments statistics (automatic data gathering)

6. CONCLUSIONS AND FUTURE WORK

The code has been validated against reference numerical results obtained with a commercial code used by ESA. Two reference trajectories have been available: short and long. Since the reference results are based on unknown inputs as aerodynamics and atmosphere model, the comparison is relatively limited. The ballistic coefficient has the most significant effect in the results and there is no simple way to have a good guess of the values (function) used in the reference trajectories. However, the basic elements of the trajectories are in line with the reference ones. As it would be expected, the divergence between reference and computed trajectories is growing as the capsule descends into the atmosphere. The long trajectory case is the most relevant as error accumulation.

For the first 1500 seconds there is a very good correlation as altitude and velocity, since the altitude is greater than 400 Km. The dynamic pressure peak is then quite separated in time at tens of seconds and creates an even larger divergence.

The tool has been intensively used in a space project and was subject of a number of modifications and corrections.

A translation of the code in FORTRAN is planned in order to decrease the run time for the Monte-Carlo approach, where the number of runs could be on the order of 100000 and for long term trajectory propagation (200 years).

Libraries for gravity field, standard atmosphere (NRLMSISE-00) and wind models are freely available and will be linked to the code. Another add-on would be the rotational dynamics.

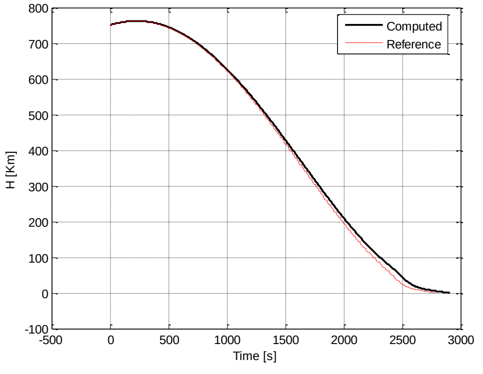

Fig. 6 Reentry altitude comparison

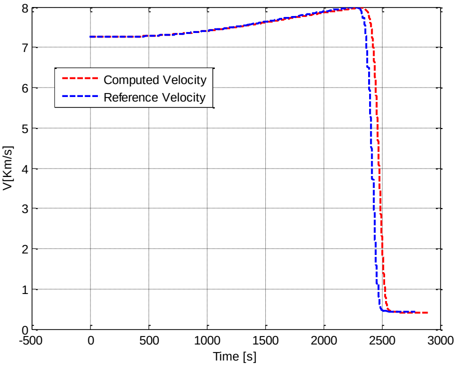

Fig. 7 Reentry velocity comparison

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