GNC (Guidance Navigation & Control) and Aerothermal Characterization of a Re-entry Vehicle

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Abstract: The computation of the aero-thermal loads on a re-entry vehicle, taking into account all the physical phenomena depending on different flight conditions, is one of the key tasks in the design of such type of vehicles, mainly for those activities dealing with the Thermal Protection and Control System design. The paper presents a methodology implemented in TAS-I that, starting from any reference trajectory, is able to compute the aerothermal loads on the whole surface of a reentry vehicle and for any time step of the trajectory, taking into account all the inaccuracies affecting the trajectory itself (i.e. entry conditions, atmosphere model, Aerodynamic Database, etc.). The whole process used to elaborate those data, coupling GNC and Aerothermodynamics analyses, has been implemented in Isight environment.

Keywords: Guidance, Navigation, Control, GNC, Aerothermodynamic, Re-entry

NOMENCLATURE

AoA	Angle of Attack
AoS	Angle of Sideslip
ATD	Aerothermodynamics
ATDB	Aerothermodynamic Database
Cp	Pressure Coefficient
Cf	Skin Friction Coefficient
DOF	Degrees of Freedom
EIP	Entry Interface Point
GNC	Guidance Navigation and Control
GCP	Geometrical Control Point
IMU	Inertial Measurement Unit
MC	Monte Carlo (simulation campaign)
MCI	Mass, Centering and Inertia
p	Pressure
Q	Heat Flux
T	Temperature

TPS	Thermal Protection System
TCS	Thermal Control System
TAS-I	Thales Alenia Space Italia

1. Introduction

Before going into more depth in the contents of the presented paper, some general definitions are provided in the following paragraphs:

Sizing Aerothermal Loads: the heat loads used to size the system (or functional part of it) so that the survival of the vehicle is ensured during the re-entry phase down to the recovery. Those loads, represented mainly by the distribution on the vehicle of the aerothermal heat flux (*Q*), pressure (*p*) and Skin friction coefficients (*Cf*) vs. time, are strongly dependent on the re-entry trajectory of the vehicle and on its attitude during such re-entry.

Reference Re-entry trajectory: trajectory that the vehicle has to follow (target) during the re-entry phase. The GNC has to command the actuators so that the vehicle would follow such reference trajectory, taking into account all uncertainties (e.g. aerodynamics, atmosphere, initial condition, etc) and complying all design constraints (e.g. maximum heat flux, heat load, dynamic pressure, etc.). Of course, considering all the uncertainties affecting the design parameters the actual trajectory can deviate from the reference one.

Hottest re-entry trajectory: trajectory dispersed around the reference one, providing the maximum heat flux on the vehicle (for ballistic vehicles corresponds to the steepest entry angle).

Coldest re-entry trajectory: trajectory dispersed around the reference one, providing the maximum heat load on the vehicle (for ballistic vehicles corresponds to the shallowest entry angle).

This paper deals mainly with the aerothermal characterization of re-entry vehicle, proposing a new methodology based on a strong coupling between ATD and GNC disciplines.

Usually and in former projects and phases of the development, once a reference re-entry trajectory is defined, the methodology adopted to identify the sizing ATD loads is split into different steps:

1. Verification of the flight mechanics aspects and GNC performance by means of a Monte Carlo (MC) analysis campaign. All design parameters affected by uncertainty are identified and a probability distribution function is associated to them. Utilizing a flight mechanics simulation tool (in-house developed Matlab/Simulink-based model) which includes also GNC algorithms), able to simulate the flight behavior of the vehicle along a trajectory taking into account the GNC algorithms and performances, a MC campaign is performed varying randomly the design parameters (a minimum of 1000 of trajectory simulations is performed for sake of good statistical confidence).
2. The results of the MC campaign are analyzed statistically aiming on one hand to estimate the GNC performances and the compliance with all requirements, on the other hand to identify the sizing trajectories (hottest and coldest ones) and the associated sizing attitude conditions of the vehicle (i.e. *AoA*, *AoS*, flap deflection if any). Usually this trajectory identification is performed focusing just on a limited zone of the vehicle (stagnation point, leading edges, flaps) and then it is used for all the other zones of the vehicle too.

3. Computations of the aerothermal loads associated with the two the sizing trajectories. This task requires the availability of a specific tool (ATDB), able to generate the aerothermal data (*Q*, *p* and *Cf*) on the vehicle as function of time.

This approach entails some drawbacks especially for what concerns the identification of the sizing trajectories:

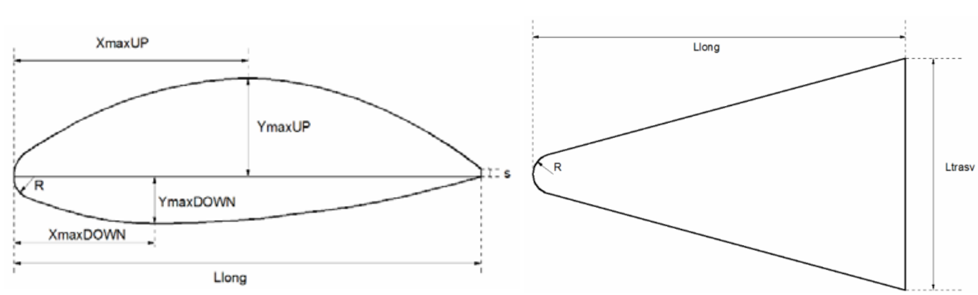
- A trajectory, which is sizing (e.g. generating the maximum heat flux) on a specific point of the vehicle, is not necessarily sizing for other zones of the vehicle. That could be not conservative form some zones of the vehicle. Hence there may be a need to identify sizing trajectories for all critical points on vehicle's surface, however this increases the trajectory and TPS design efforts.
- On the other hand, the worst attitude conditions found analyzing all the MC results are used as sizing ones. That implies a quite conservative approach, since we are combining all the worst conditions: worst AoA, worst AoS, worst flap deflections (if any) and worst trajectory. In the real flight the vehicle tends to perform oscillations around desired trim angle producing heat flux peaks only for fraction of time, while average value remains lower.

The risk is on one hand to be extremely conservative with a subsequent possible over-design effect, on the other hand to miss potential flight conditions that could be critical for other zones of the vehicle.

The mentioned approach however is good for the initial development phases when high degree of uncertainty exist.

2. Proposed methodology

In order to solve the above mentioned issue, TAS-I has investigated and implemented a new methodology based on a strong coupling between GNC and ATD simulations. As reference vehicle, the lifting body shown in the following Figure 1 has been utilized.



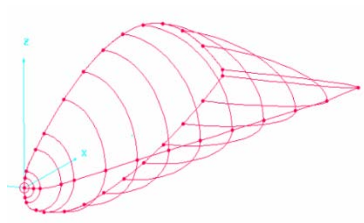


Figure 1: Lifting Body geometry

As first step an ATDB tool has been built; this tool allows to compute the aerothermal data for any point of the analyzed vehicle and for any reference trajectory. An example of the output is report is shown in Figure 2 (Cp distribution on the whole vehicle) and Figure 3 (Heat flux vs. time on 4 locations on the nose for a specific reference trajectory). The development (in Fortran) of the Tool, including its validation and debugging, has requested about 12 man-months, due to the high complexity of the code and possibly correlating data with experimental results.

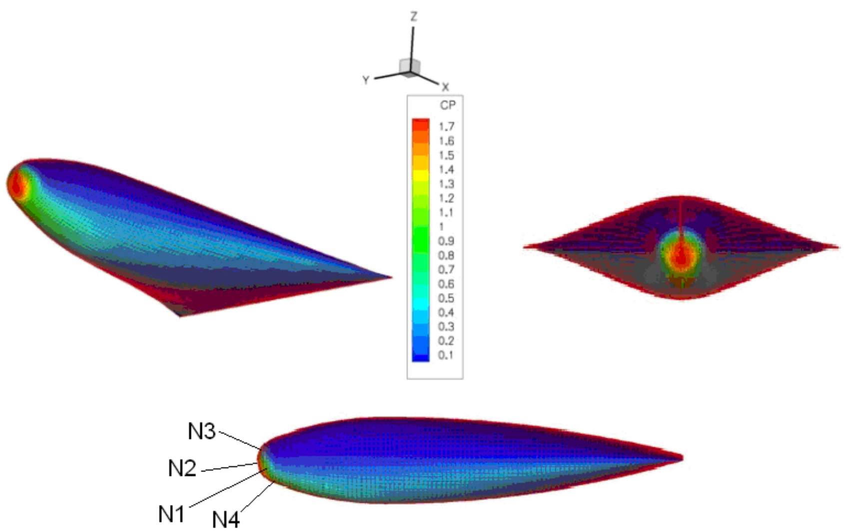


Figure 2: Cp distribution on the vehicle

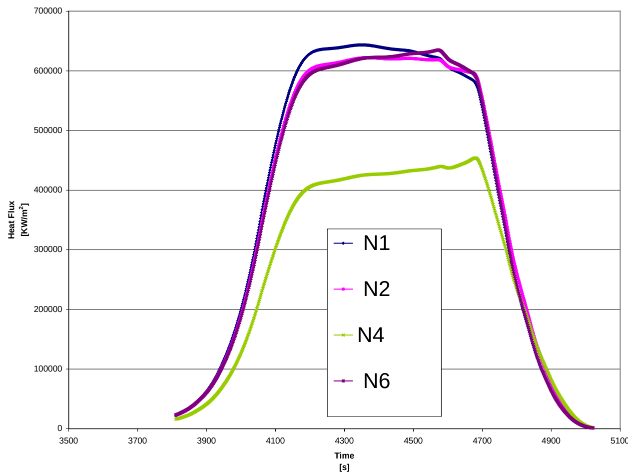


Figure 3: Q vs time in the Nose region

The main idea is to process a complete set of MC GNC results using that ATDB Tool: all the dispersed trajectories, resulting from a MC GNC simulation, are processed by the ATDB Tool, considering for each time step of each trajectory the actual attitude vehicle. Such approach allows, on one hand to consider less conservative but more realistic flight conditions, on the other hand to find for any zone on the vehicle the actual sizing flight conditions.

The whole process has been integrated using Isight tool, as shown in the following Figure 4.

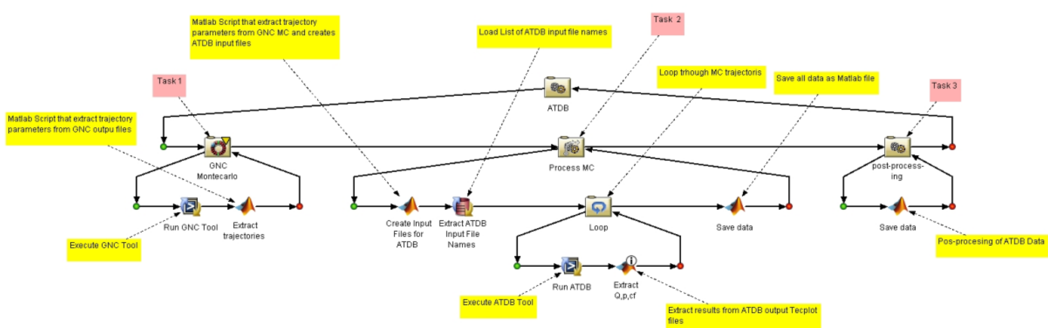


Figure 4: Isight Workflow of the process

The first task is dedicated to perform a MC campaign utilizing a flight mechanics simulation tool with GNC model in loop, able to simulate the flight behavior of the vehicle along a trajectory taking into account the GNC algorithms and performances. The following parameters have been considered for the statistical GNC performances evaluation:

Parameter	Distribution		Parameter	Distribution
Initial Condition			**RCS**	
Position	Gaussian		Thruster Location	Gaussian
Velocity	Gaussian		Thruster Orientation	Gaussian
Attitude	Gaussian		Torque (Flow interaction)	Uniform
Attitude Rate	Gaussian		**Flap**	
MCI			Static offset	Uniform
Mass	Uniform		Backlash	Uniform
Inertia	Uniform		**IMU**	
CoG	Uniform		Drift of gyros	Gaussian
Aerodynamics			Scale factor of gyros	Gaussian
Aerodynamics Continuum	Gaussian		Misalign of gyros	Gaussian
Aerodynamics FMF	Gaussian		Bias of accelerometers	Gaussian
Atmosphere			Scale factor of accelerometer	Gaussian
Density	Gaussian		Misalign of accelerometers	Gaussian
Temperature	Gaussian		Error in alignment	Gaussian
Wind	Gaussian		Harmonization Error	Gaussian

Table 1: Design parameters and associated uncertainties

The output of this task is constituted by 1000 dispersed trajectories, stored as time-histories of flight conditions (freestream Mach, pressure and temperature) and of vehicle attitude (*AoS* and *AoA*).

In the second task, the GNC MC results (all the dispersed trajectories) are post-processed by the ATDB tool, as described above. In particular the heat flux, *Cp* and *Cf* time-histories are extracted for all the trajectories and for 100 of control points on the vehicle. The output is constituted by 100 time-histories of *Q*, *Cp* and *Cf* for each dispersed trajectory. Therefore a total of 300,000 time-histories has to be stored.

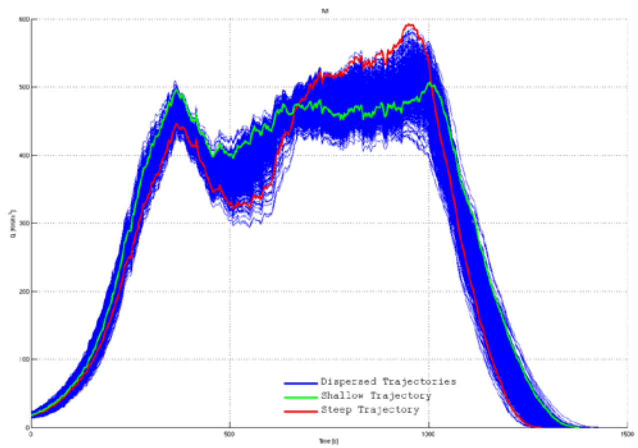


Figure 5: Generic output from post-processing – Heat Flux vs. time

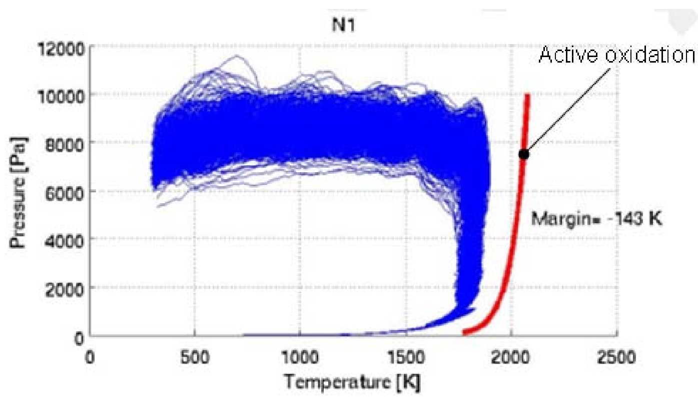


Figure 6: Generic output from post-processing – *p* vs *T* and comparison with passive to active oxidation transition

Finally, in the third step, all the time-histories generated in the second task are post-processed by means of a Matlab script:

- For each GCP all the available time-histories are analyzed in order to identify:
    - Local Steep Trajectory, generating the local maximum heat flux
    - Local Shallow Trajectory, generating the local maximum heat load (integral of Q along the complete trajectory)
    - Trajectories generating the combination of local Temperature and Pressure that can induce Passive to Active transition (it depend on the TPS material properties).

- The geometrical control points are grouped in different assemblies, corresponding to different zones of the vehicle (Nose, Windward and Leeward), identifying for each one of them:
    - Assembly Hottest trajectory, generating the maximum GCP heat flux on the analyzed assembly
    - Assembly Coldest trajectory, generating the maximum GCP heat load on the analyzed assembly
    - Global Hottest trajectory, generating the maximum heat load on the whole vehicle (Sum of all GCP Heat Load)
- The Assembly Hottest and Coldest trajectories are used as reference ones for the computation of the Sizing ATDB data for all the GCP of the same Assembly, while the Global Coldest trajectory is used as reference one for the computation of the Sizing ATDB data for System level TCS design

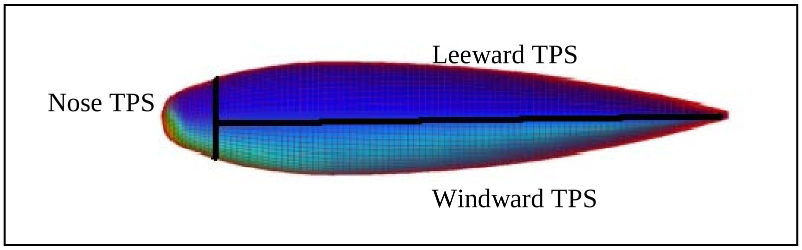


Figure 7: TPS assemblies

Just for example in Figure 8 the sizing ATDB data (Q, p and Cf) are shown for the Nose assembly.

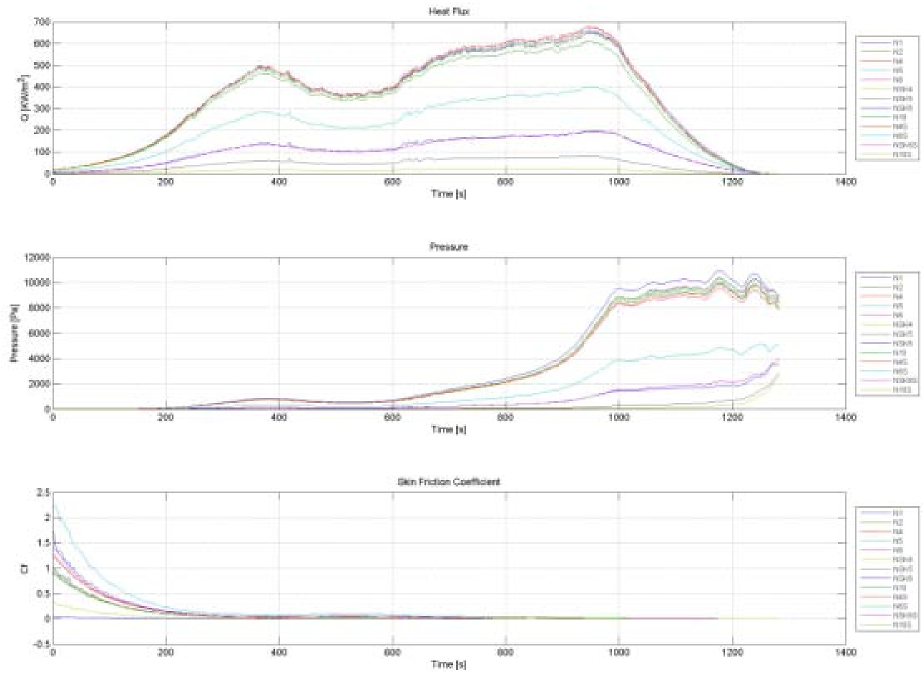


Figure 8: Nose Sizing ATDB Data (Maximum heat Flux)

3. Steps ahead

The introduced methodology is a base for planned future refinements and enhancements of functionality, particularly the robust optimization with the main objective of improving the shape for better heat flux distribution over the surface and maintaining the GNC performance. This process

Regarding the application on the ballistic entry vehicles (particularly sample return capsules of interplanetary probes), no GNC is usually in control of the trajectory however a similar methodology to the one described in this paper would allow optimizing the TPS thickness on the windward surface together with an optimization of shape and taking into account also the uncertainties of aerodynamics, atmosphere and the entry interface point. A similar ARD tool would be developed to obtain heat fluxes on different surface points, including the leeward side. For each iteration of shape and TPS configuration, a set of MC would be performed in order to perform the robust optimization.

4. Conclusions

A new methodology for a complete aerothermal characterization has been implemented in TAS-I and tested on a reference re-entry vehicle. Starting from any reference re-entry trajectory, the approach, based on a strong coupling with GNC analyses, is able to compute the aerothermal loads on the whole surface of a reentry vehicle, taking into account all the inaccuracies affecting the trajectory itself (i.e. entry conditions, atmosphere model, aerodynamic database, etc.). The whole process used to elaborate those data, coupling GNC and Aerothermodynamics analyses, has been implemented successfully in Isight environment.

Specific Matlab scripts have been developed in order to couple the different analysis tools (GNC Flight mechanical tool and ATDB) and to pre and post process the huge amount of input and output data.

On one hand the methodology allows to obtain less conservative but more realistic sizing aerothermal data; on the other hand it is more robust allowing the exploitation of a huge amount of data on the whole vehicle surface.

It has to be remarked that, thanks to Isight functionalities, the integration of the whole process has requested about 2 weeks. A complete loop of analysis, constituted by 1000 GNC simulations, 1000 ATDB simulations and subsequent post-processing of the data with automatic generations of tables and plots (of the order of some hundreds) lasts about 48 hours. The whole process has been validated and consolidated and it’s going to be used in TAS-I re-entry projects.

The Isight may also be used to tune the GNC guidance and control gains together with the optimization of the shape. As this process would require a lot more simulations, certain efforts will be dedicated to improve simulation velocity and parallelize the process.