IXV Development: An Integrated Approach for Performance Characterization

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Project Objectives

**SYSTEM DEMONSTRATION**
Experience and master the complete design, development, verification loop of an aerodynamically controlled re-entry system

**TECHNOLOGY VALIDATION**
Investigation in the hypersonic regime and verification and improvement of design methodologies and standards

**CRITICAL RE-ENTRY TECHNOLOGY EXP.**
Integration and test in realistic flight conditions
- Aerothermodynamics
- Thermal Protection System
- Guidance Navigation Control
- In Flight Experimentation
  - Conventional
  - Advanced

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The IXV System

SYSTEM AUTHORITY
Margin Policy
Requirements Management
Environments
Verification
Configuration & Layout
MCI ICD

Assembly Integration & Test

Ground Support Equipment

MGSE FES
EGSE ATF
FGSE SVF

Ground Segment

Ground Stations
Mission Control Center
Recovery

Interfaces

Launcher MCC + Stations Facilities Recovery Ship

Operations

Flight Ops Ground Ops Recovery Ops

Disciplines and Subsystems

AED & ATD
In Flight Experimentation
Mission Analysis
Guidance Navigation Control
Thermal Control System
Cold Structure
TPS and HS
Mechanisms
Flap Control System
Reaction Control System
Descent System
Recovery System
Avionics (POW, DHS, RTC)
Harness
Software
System Drop Test

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Mission Profile

Reference Trajectory 3D view

ASCENT

max. altitude 412 km

Separation

ORBITAL ARC

P80 fallout

LIBREVILLE

AVUM fallout

Z23 fallout

MALINDI

Z9A fallout

Re-entry & descent = ~7700 km

Total downrange = ~32800 km

Recovery ship

Downrange

Reference Timeline
1 – Lift off
2 – Separation
3 – Entry gate
4 – Descent gate
5 – Splashdown

120 km entry interface point

25.7 km

[Altitude scale: 10X]
IXV Flight mechanics and aerothermodynamic study loop

MISSION ANALYSIS
- Constraints
- Reentry corridor
- Reference trajectory
- Monte Carlo
- MCI model

GNC
- Constraints
- GNC design
- FES trajectories

ATD
- TPS design
- ATD detailed characterisation
- ATD tool update

OML refinement
Computation of the aero-thermal loads on IXV vehicle, taking into account all the physical phenomena depending on different flight conditions:

- **Flight parameters in trajectory:**
  - Nominal trajectory
  - Hottest trajectory (Maximum Heat Flux)
  - Coldest Trajectory (Minimum Heat Load)
  - Dispersed trajectories

- **Vehicle attitude:**
  - Angle of Attack
  - Angle of Sideslip
  - Elevon Flap deflection
  - Aileron Flap deflection
Usually and in former projects and phases, the methodology adopted to identify the sizing ATD loads is split into different steps:

1. Optimization of a Reference trajectory (Mission Analysis):
   - ATD constraint is represented, usually, by the maximum heat flux/load on the stagnation point

2. Verification of the flight mechanics aspects and GNC performance by means of a Monte Carlo (MC) analysis campaign (GNC)

3. Analysis of MC campaign results aiming to:
   - Estimate GNC performances
   - Identify the sizing trajectories and associated vehicle attitude

4. Computation of the aero-thermal loads for the selected sizing trajectories (ATD):
   - Heat Fluxes
   - Pressure
   - Skin Friction
The mentioned approach entails some drawbacks:

- **Non robust design in some zones of the vehicle:**
  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. The risk is to miss potential flight conditions that could be critical for other zones of the vehicle.

- **Over-Design in other zones (i.e. flap):**
  The worst attitude conditions found analysing all the MC results are used as sizing ones and combined with the worst trajectories:
  - worst AoA, worst AoS, worst flap deflections and worst trajectory

- **Cost and schedule**
  Several iterations between Mission Analysis and ATD teams can be necessary for the trajectory optimization itself
The presented methodology, successfully utilized in the phase C/D of IXV project, is based on a strong coupling between the Aerothermodynamics and Mission Analysis (MA) and GNC disciplines:

- Development of an Aerothermodynamic Database (ATDB) Tool:
  - Able to compute automatically the ATD loads on the whole surface of the vehicle taking into account both the freestream conditions and the vehicle attitude.

- Coupling between the ATDB Tool and the MA & GNC Tools:
  - Significant improvement and reduction of costs and duration of the iteration loops between mission, ATD and system design teams.

- Performing of a Montecarlo GNC campaign, taking into account all the inaccuracies affecting the GNC performances.
  - ‘Light’ ATDB, integrated in FES, allows real-time ATD assessments.

- Post-Processing of the GNC Montecarlo campaign by means of the ATDB Tool:
  - Identification of the sizing trajectories
An ATDB Tool has been developed by Dassault Aviation:

- Free stream condition for any timestep of the analyzed trajectory:
  - \( M_\infty, \rho_\infty, T_\infty, \rho_\infty \)

- Actual vehicle attitude:
  - \( \text{AoA (40÷50)} \) and \( \text{AoS (0÷8)} \)

- Flap deflections:
  - Elevon \( de \) and Aileron \( da \)

- Automatic detection of the transition from laminar to turbulent on both on the flaps and on the body of the vehicle.

- Wall boundary conditions:
  - Radiative equilibrium or fixed temperature
  - Fully or partial catalytic wall

- Both Sizing (including ATD uncertainties) and Nominal Heat fluxes
Skin Tecplot files

Nominal Heat Fluxes
Shallow Trajectory

Q [W/m²]
1.1E+06
1.0E+06
9.5E+05
8.6E+05
7.8E+05
6.8E+05
6.0E+05
5.2E+05
4.3E+05
3.4E+05
2.6E+05
1.7E+05
8.6E+04
2.5E+02

QN
700000
650000
600000
550000
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000

IXV ATDB Tool – Outputs
Time-histories for any geometrical control point on the vehicle
IXV ATD Tool - Development

IXV ATDB Tool is based on the processing of CFD computations by CFSe, R’Tech and University of Rome.

Complementary VKI LongShot WTT:
- Combined effects induced by sideslip, aileron, AoA and transition

ONERA S3ma WTT:
- IXV model featuring some disturbances (4 configurations)
- Address potential LTT on both the body and the flaps and local overheating induced by steps.

VKI Plasmatron Tests:
- Characterization of catalycity and emissivity values of SPS and MTA CMC thermal protection material

S3ma IR measurements

S3ma Model
Conf. #4 w/o flaps
In order to assess the GNC performances a MC analysis campaign has been performed, by means of the Functional Engineering Simulator (FES) Tool, with an embedded ‘light’ release of the ATDB Tool.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Distribution</th>
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<td>Initial Condition</td>
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<td>Velocity</td>
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<td>Attitude rate</td>
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<td>Mass</td>
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<tr>
<td>CoG</td>
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<td>AED Raocified</td>
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<tr>
<td>Atmosphere</td>
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<td>Thruster Orientation</td>
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<td>Flap</td>
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<td>Backlash</td>
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<td>IMU</td>
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<td>Drift of Gyros</td>
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<td>Scale factor of Gyros</td>
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<td>Bias of Accelerometers</td>
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<td>Harmonization error</td>
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GNC MC Post-processing

All the dispersed trajectories, resulting from the GNC MC simulation, are processed by the ATDB Tool. The whole process has been integrated using the commercial software iSight (Simulia)
More than 200 geometrical Control Points have been selected on the vehicle.

Heat flux, $C_p$ and $C_f$ time-histories are extracted for all the trajectories and for more than 200 GCPs on the vehicle.

On CMC assemblies the margin with respect to the Passive to active oxidation transition is computed.
GNC MC Post-processing

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.
GNC MC Post-processing

The geometrical control points are grouped in different assemblies, corresponding to different zones of the vehicle, identifying for each one of them:

- Assembly Steep trajectory: Maximum GCP heat flux on the assembly
- Assembly Shallow trajectory: Maximum GCP heat load on the assembly
- Global Shallow trajectory: Maximum heat load on the whole vehicle
The Assembly Steep and Shallow trajectories are then used as reference ones for the computation of the Sizing ATDB data for all the GCP of the same Assembly.

The Global Shallow trajectory is used as reference one for the computation of the Sizing ATDB data for System level thermal design.

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Assembly Steep Trajectory</th>
<th>Assembly Shallow Trajectory</th>
<th>System Shallow Trajectory</th>
<th>Max Heat Flux [KW/m^2]</th>
<th>Max Heat Load [MJ/m^2]</th>
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<tr>
<td>Nose</td>
<td># 391</td>
<td># 661</td>
<td># 661</td>
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ATDB Computation

Nose

Windward
Conclusion

An advanced ATDB Tool has been developed by DAA for the automatic computation of the main aerothermal data on IXV vehicle for any reference reentry trajectory.

A ‘light’ release of the ATDB Tool has been generated by TAS-I and successfully implemented by DEIMOS Space in the Mission Analysis tools related to trajectory optimisation, simulation and flight mechanics, reducing drastically the iteration loops between Mission, ATD and System design teams.

A dedicated light release on windward ablative panels has been implemented in FEC (GNC simulation) in order to feed input data for the MCI model.

A methodology for the aero-thermal characterization of IXV vehicle, based on a strong coupling between ATD and GNC disciplines and tools (ATDB and FES software), has been successfully developed and implemented by TAS-I, allowing a more robust and less conservative computation of the Sizing heat fluxes.

The light ATDB tool will be used for the pre-flight predictions in phase E, in order to estimate the heat fluxes for the predicted trajectory, and compare with respect to the constraints and sizing trajectories.