A Framework for the Aerodynamic and Thermal Design of Highly Integrated Hypersonic Propulsion Systems

M. Ferlauto, B. Xiong, E. Degregori
Politecnico di Torino, Italy
National Defense University of Technology, China
University of Southampton, United Kingdom

3rd International Symposium on Hypersonic Flight
Air Force Academy (Pozzuoli), Italy, May 30-31, 2019

AAA – Sez. Roma Due "Luigi Broglio"

Outlines

Our vision, work and approaches to the design of High Integrated Propulsion Systems (HIPS) in supersonic/hypersonic aircrafts and spacecrafts

- HIPS characterization and design issues
- MDO design approaches and tools
- Numerical Results
- Conclusions

High Integrated Systems

High Integration means strong Interference between components

- Nonlinear Behavior of the aerodynamic flowfield
- High interference between engine and airframe
- Multidisciplinary coupling between fields
  - Aerodynamic effects
  - Thermal effects
  - Aeroelasticity
- Resonances with the engine control system
- No well-separated time scales

Classical approaches "design by component/by field" become problematic

Need for Automatic Design

- *The design process is nowadays a collaborative work of different teams with different skills, in different field.*
- *The design process is scheduled with severe time constrains.*
- *The deep knowledge of the design space is limited, so that most of the technical choices must be addressed by numerical/experimental investigations rather than designer experience.*
- *Strategies of accounting the interferences between components must be set up in advance, in order to speed up the design process*

Design Tools

The approach we analyze is based on the following techniques

- Multidisciplinary, Multi-objective, Multi-point Optimization (M3DO)

- Inverse Problem Solution

- Coupled Approaches (Inverse method + GAs/ADJ)

- Design Space Exploration (DSE)

M3DO

Because of the nonlinear characterization of the systems under study, two serial loop of optimization are proposed:

- A general purpose Optimizer (e.g. GA, MOGA, SA) based on reduced order models. Search of Global Minima.
- Lower order models based on inviscid flow, compressible Euler Equations, viscous correction etc.

- Advanced Optimization tool based on HPC tools for Shape optimization, Inverse Problem Solution
- Coupled Approaches (Inverse/ADJ)

HIPS Modeling

The key point for the design of HIP systems is to take into account for the interference phenomena even in the preliminary design stage.

- Low-Order Models (LOM) including main interferences with the external flowfield and with the nearest components

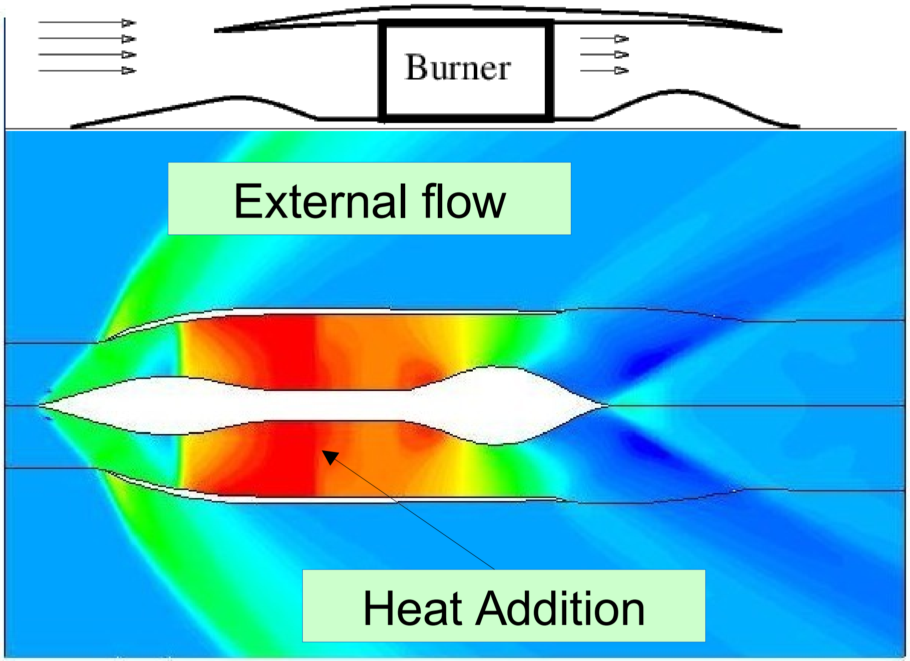
- Models and approaches are selected case by case

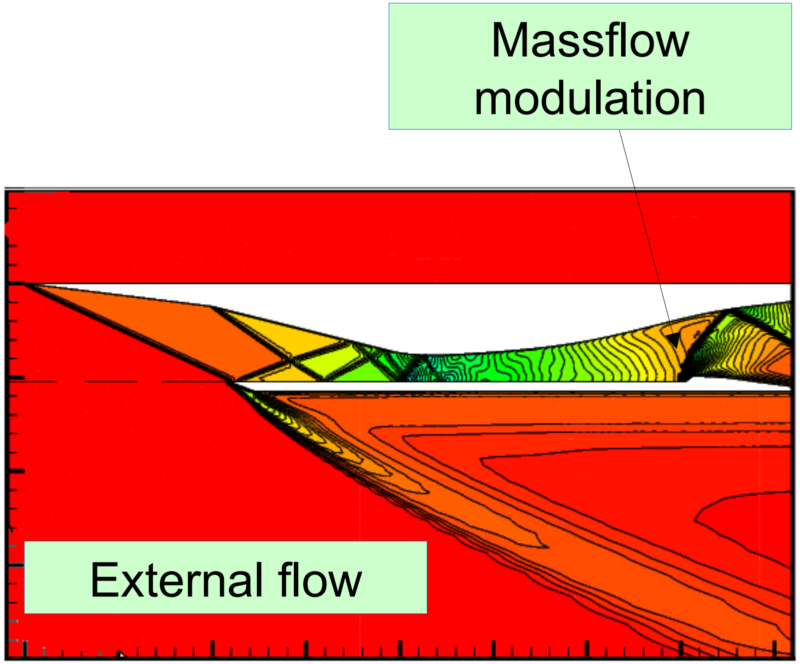
- the LOM must retain most of the nonlinear response of the underlying system

HIPS Modeling

LOM based on the compressible Euler equations.

1) *Representation of the flow inside and around a Ramjet*
2) *Scramjet Intake with mass flow modulation*

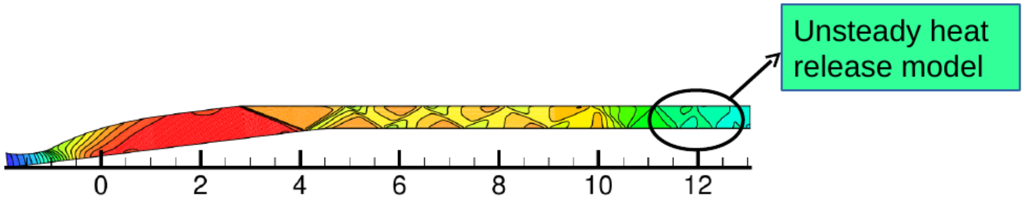




SCRamjet Facility Nozzle Design

Direct-connect Scramjet test-rigs require a Facility Nozzle (FN) that acts also as Inlet Distortion Generator. The nozzle must reproduce at the isolator inlet the same flow occuring at in-fligth conditions.

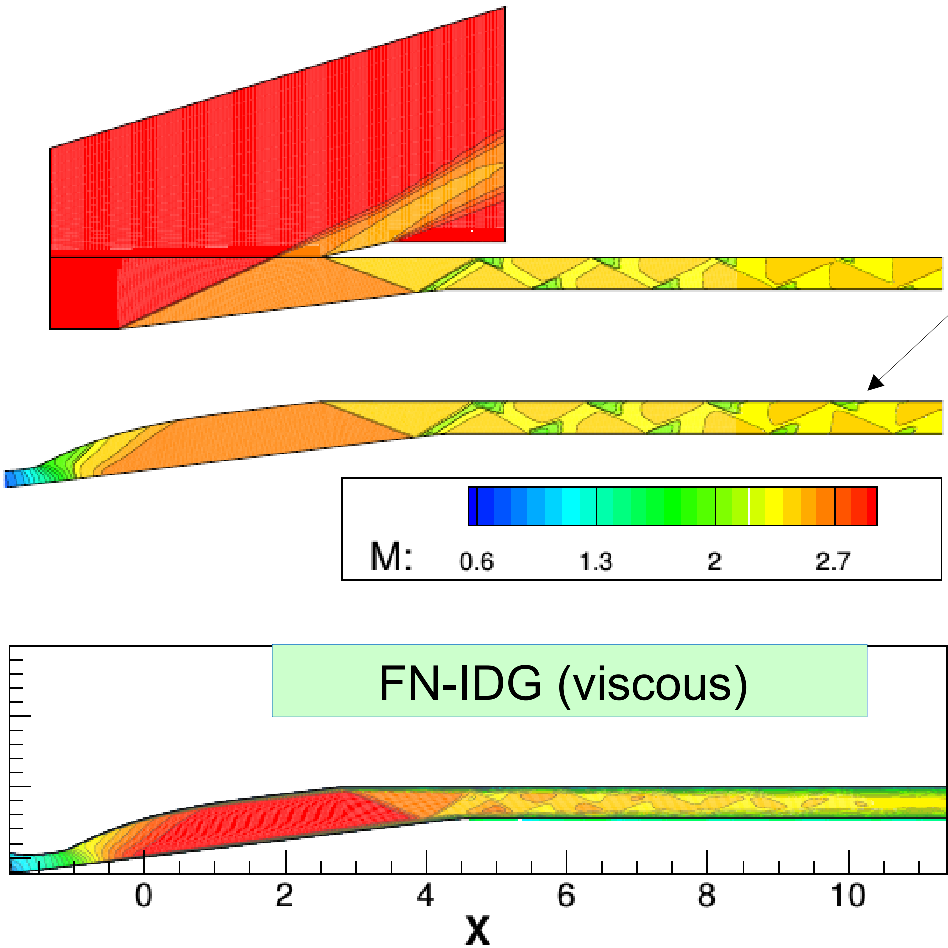
- *The FN-IDG is designed by an inverse method*
- *The inverse solver is driven by GA optimization*
- *The optimal solution is checked and corrected by RANS CFD*
- *The combustion effects are accounted by an heat release model*



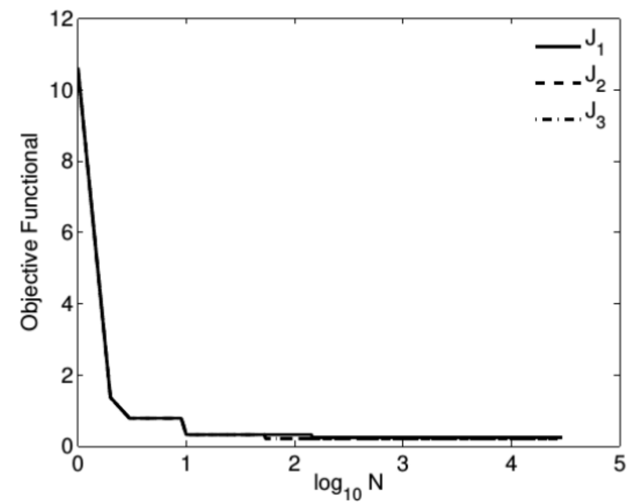
SCRamjet Facility Nozzle Design

In-flight Flowfield (inviscid)

FN-IDG (inviscid)



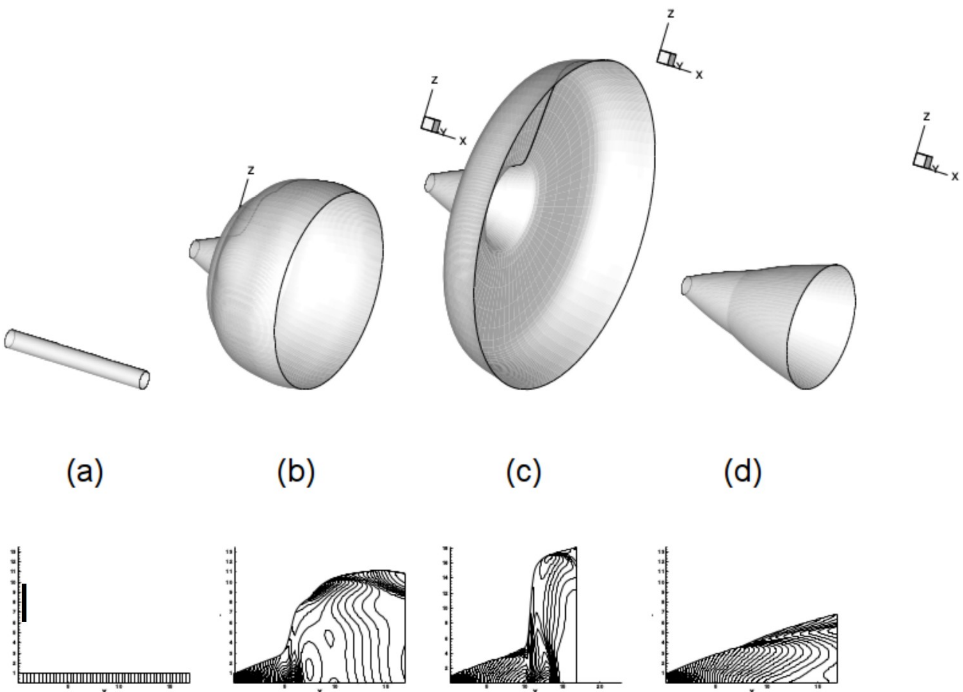
FN-IDG (viscous)



GA Opt Residuals

Inverse Problem Solution

The inverse method of designing is very useful in HIPS.
The method assumes that the walls of the component to be designed can move in order satisfy some flow features at the boundaries. At steady state, the solution fulfill the design targets



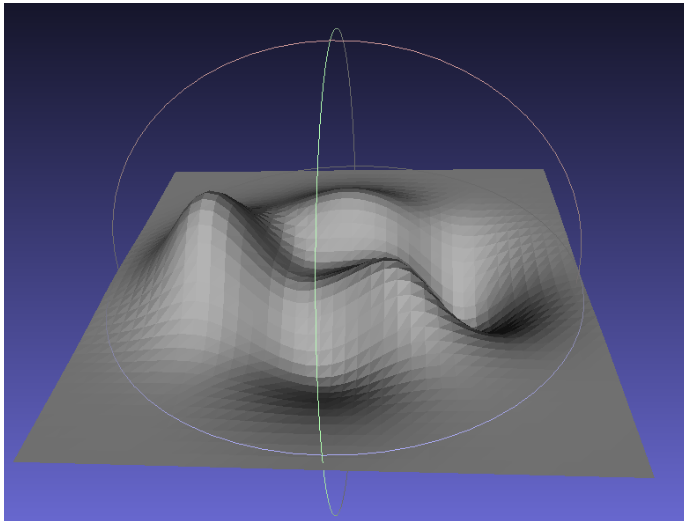
DUAL-BELL NOZZLE DESIGN BY INVERSE METHOD

(a) initial geometry (generic)
(b)-(c) transient solution
(d) final shape and flowfield

Design Space Exploration (DSE)

If the computational cost is affordable, the design space can be "explored" with a parametric analysis.

- DSE gives to the designer a complete scenario of the possible optimal solutions
- No MDO attraction towards local minima
- Faster Redesign Time
- Mapping of optimality zones
- Pareto Front derivation

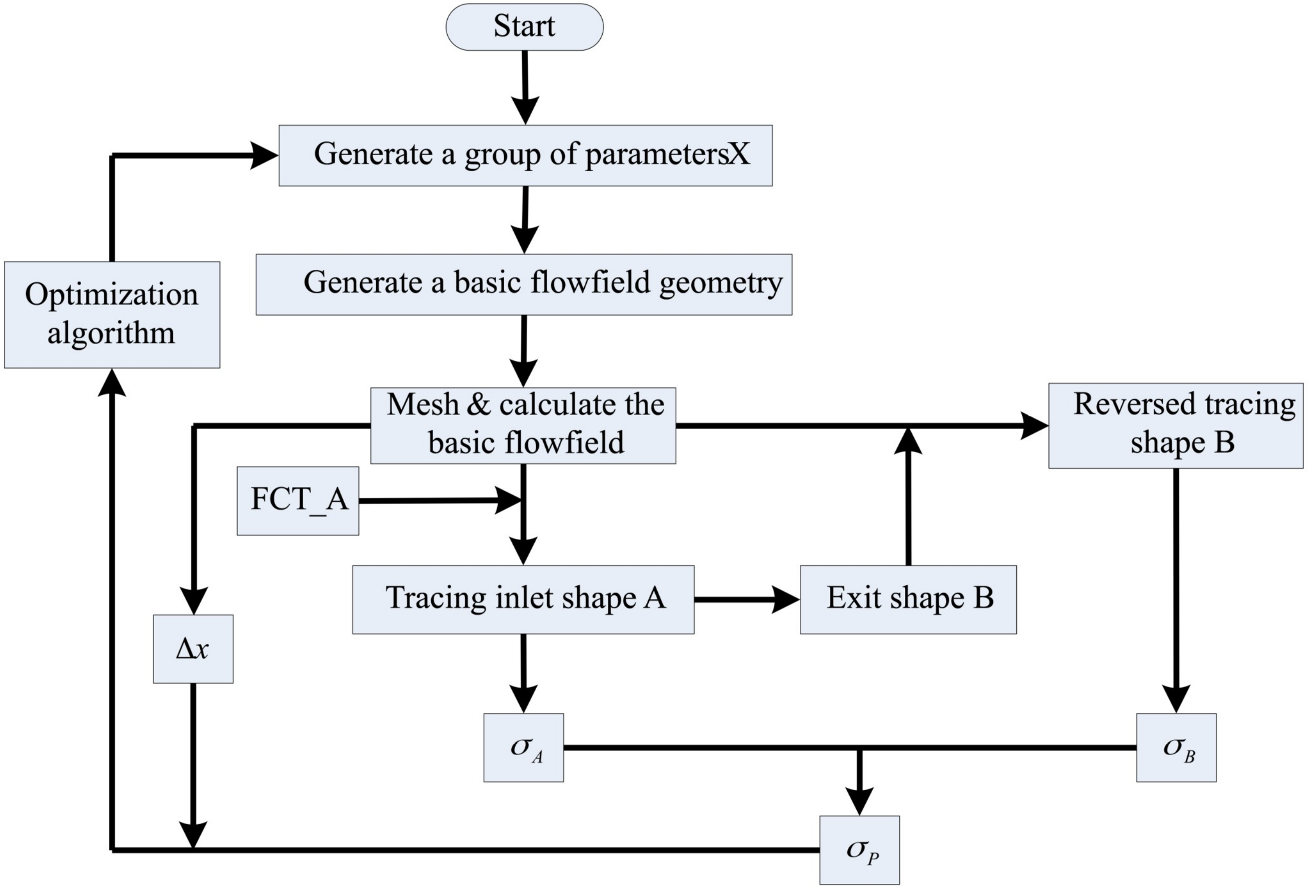


Inward Turning REST Inlet Design

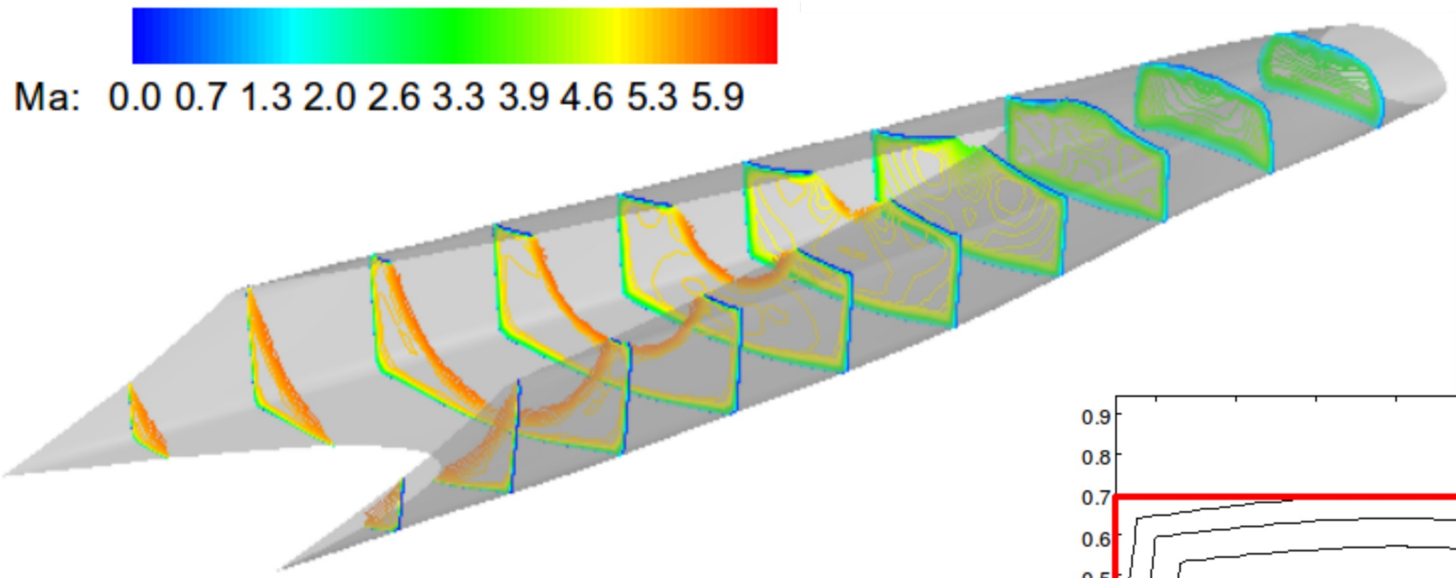
- *The design of an Inward Turning Inlet (ITI) with Rectangular-to-Elliptic Shape Transition (REST) for a hypersonic waverider.*
- *The REST Inlet design procedure is based on the inviscid stream-tracing procedure.*
- *The procedure is driven by a multi-objective optimization solver*
- *The Pareto Front is reconstructed*
- *The LOM-based procedure is tested by RANS CFD analysis.*

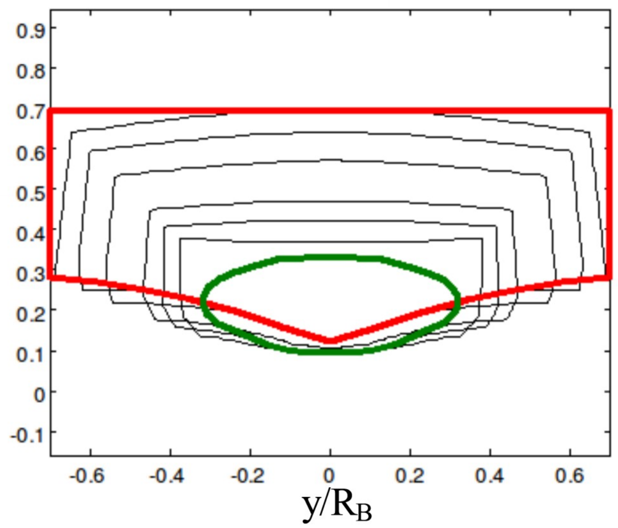
Inward Turning REST Inlet Design

Optimization Loop combined with the Shape Transition process



Inward Turning REST Inlet Design



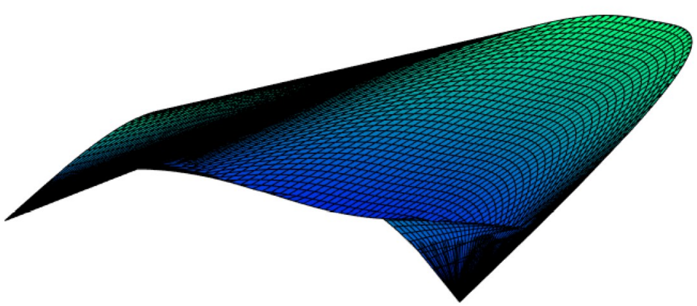


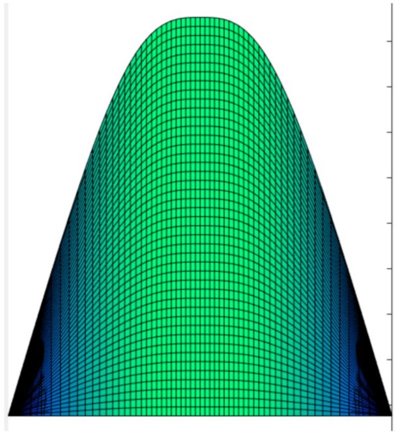
Waverider Integration

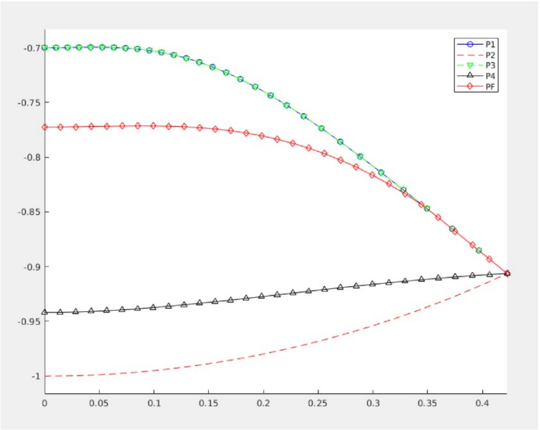
The Inward-Turning REST inlet can be integrated in a waverider configuration, e.g. in the upper surface of the spacecraft.

The design steps follow the guidelines of previous approaches.

Example of stream-traced waverider with parabolic fairing

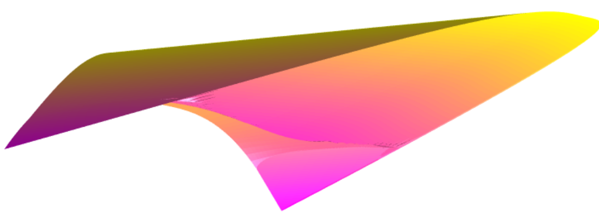






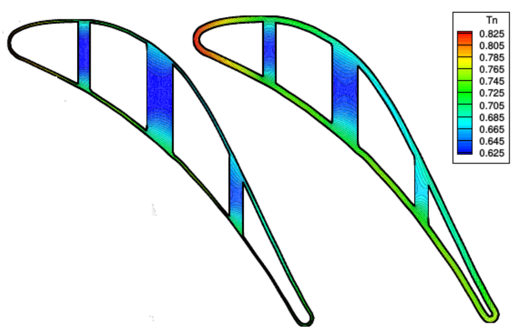
Thermal Design

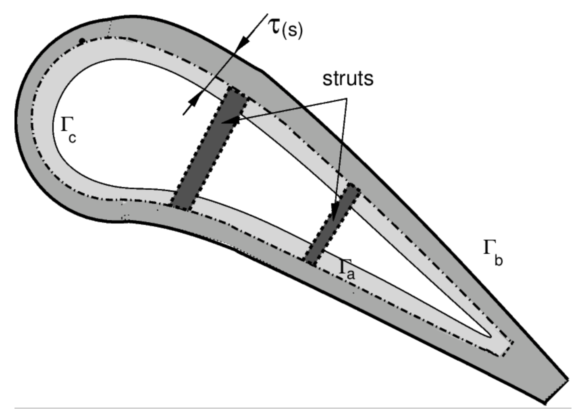
One of the main issues in hypersonic aircraft design is the management of the thermal effects.



In present approach the thermal design is solved as an inverse problem for the lower waverider surface according to a procedure similar to that developed for designing turbine blades with coating (Ferlauto, 2014) .

An external temperature distribution is given as target and the waverider lower surface geometry is computed.





Conclusions

The approaches followed in the automated design of HIPS for hypersonic aircraft have been illustrated

The proposed methods rely on a combination low and high fidelity models of the system and of the external flow.

The main steps can be resumed as

- derivation of a Lower Order Model of the component interacting with the system/external flow
- search of global minima by MDO
- as alternative, Design Space Exploration
- Analysis of the optimal solution by a High Fidelity Model
- Redesign by advanced approaches (RANS Inverse, Adjoint Optimization, etc.)