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Multi-disciplinary Design and Optimisation of a Minimum Scale Hypersonic Flight Demonstrator

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This work is part of a joint effort between the French Aerospace Lab (ONERA) and the Japan Aerospace Exploration Agency (JAXA) to demonstrate a number of key enabling technologies for future reusable space transportation systems. A pre-cooled turbojet engine is currently being investigated at the JAXA as a key technology that could enable the design of a sub-orbital space plane - i.e. the first stage of a two-stage-to-orbit space plane - and, potentially, that of a future hypersonic airliner. More particularly, the present study focuses on the planning and technical feasibility of a scaled-down, low-cost, and reusable hypersonic flight demonstrator, based on the pre-cooled turbojet concept explored by the JAXA, using a Multi-disciplinary Design and Optimisation (MDO) environment. This paper thus describes the inception of a framework for the sizing of a potential flight testbed under a number of mission, operational and budget specifications that are representative of the full-scale vehicle. The sizing of the experiment is thus undertaken using a series of reduced-order models for the evaluation of the performance of a round mission from a given take-off point. The mission of the experimental flight vehicle will indeed be to accelerate from a standstill up to a target Mach number before initiating a deceleration phase in order to return to its take-off point.

Keywords: *Multi-disciplinary Design, Optimisation, Hypersonic, Demonstrator*

Nomenclature

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1. Introduction

The Holy Grail in aeronautics remains the insertion, within the global air-traffic management, of regular intercontinental hypersonic flights. Future hypersonic airliners would fly from a conventional airport to an antipodal point on the planet in less than a couple of hours - i.e. a Paris-Tokyo trip in about 3 hours.

More than a decade ago, as part of their long-term vision, the Japan Aerospace Exploration Agency (JAXA) has initiated an in-depth work on the idea of using a pre-cooled turbojet (PCTJ) as a means to propel a high-speed transportation system up to Mach 5 [1]. The main idea behind the JAXA's air-breathing engine consists in using a pre-cooling heat-exchanger in front of a conventional turbojet in order to increase the density of the air - thereby, increasing the amount of thrust it can generate - while reducing the temperature of the ingested air. The temperature at the inlet of the turbojet would thus be reduced by the recirculation of a cryogenic propellant inside a counter-flow heat-exchanger. This cooling effect should permit the use of a turbojet up to Mach 5.

After a series of ground-test at the JAXA's facilities [2, 3, 4], the French aerospace lab (ONERA) and the JAXA have defined a common framework in order to study the feasibility of a hypersonic flight testbed whose purpose would be to examine the performance of a PCTJ air-breathing engine in real hypersonic flight conditions.

The design of the flight experiment will necessitate the use of a number of optimisation techniques in order to trade-off all objectives of the mission - i.e. an acceleration phase followed by a return phase - while fulfilling a series of mission constraints (e.g. cost, reusability, etc.). The scale of the experimental testbed shall be sufficient in order to prove the technical feasibility of a PCTJ. The JAXA and the University of Tokyo has already led a number of technical studies on the multi-disciplinary design of an experimental vehicle [5]. Similarly, preliminary studies derived from the concept of the PREPHA vehicle were undertaken by ONERA [6].

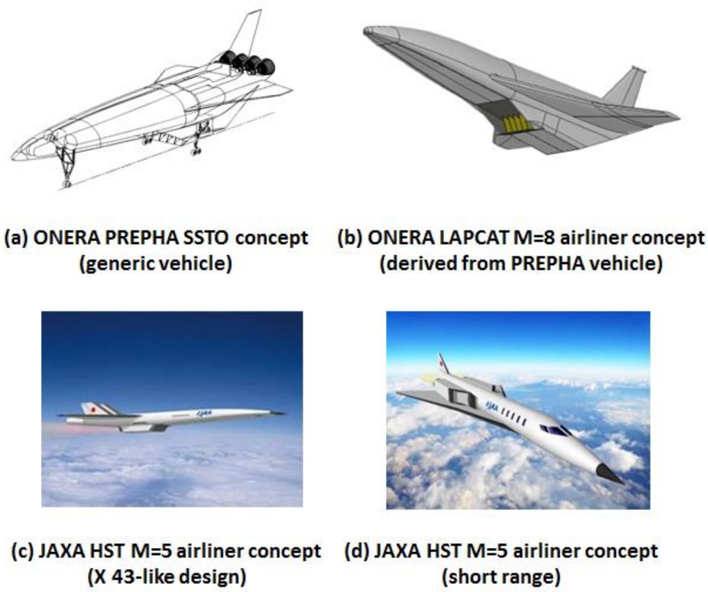

Fig 1. A series of concepts from ONERA (top – a and b) and JAXA (bottom – c and d)

In this work, a demonstrator will be designed around a downscaled version of a PCTJ engine and will be as close as possible to the planform of a potential full-scale vehicle – see Fig. 1. The air-breathing engine will either be a PCTJ alone, or a combined-cycle engine. In the latter case, the switching between the PCTJ and the ramjet mode will also be an integral part of the current design problem.

2. Definition of a minimum scale hypersonic experiment as an MDO problem

The design of any hypersonic system is characterised by a very large number of technical challenges, across a wide variety of engineering disciplines, which will require a strong coupling between many technical disciplines, namely aero-thermodynamics, structures (weights), propulsion systems, flight mechanics, controls, economics and operations.

Therefore, it is paramount that a cross-disciplinary methodology be used in order to design and optimise a reusable hypersonic flight demonstrator. To be efficient when used for concept exploration, an MDO framework shall be modular, efficient and provide accurate predictions [7, 8].

In the present work, an open-source MDO framework, dubbed OpenMDAO and whose development is led by the NASA [9], is used in order to connect all reduced-order models together. Indeed, this MDO framework has been chosen in order to handle the flow of information between all disciplinary components.

An essential part of aerodynamic analysis is a precise geometry definition. In-house Python scripts built on top of various open-source solid modellers such as OpenSCAD and OpenVSP [10] are used in order to accurately represent a variety of configuration shapes. This minimum set of geometric parameters – carefully chosen as a means of reducing the overall design space - is then converted into a surface mesh on which aerodynamic loads can then be computed. The geometric parameters are thereafter fed into the optimiser as design variables.

An in-house code, called Shaman and developed in the vein of the CBAERO code [11] and the HyFlow code [12], is used in order to evaluate the aerodynamic performance of each candidate solution for our flight demonstrator configuration. Shaman takes a partitioned triangular mesh (such as a .tri or .stl file) in order to assess the distribution of loads on each part of the vehicle. Local Surface Inclination (LSI) methods such as Tangent-Wedge, Tangent-Cone, modified Newtonian, Shock Expansion and Prandtl-Meyer can be applied on compressive and expanding surfaces to estimate surface pressure on the entire configuration.

In this work, the vehicle is modelled dynamically as a point with variable mass flying around a spherical, rotating Earth. The translational motion of the vehicle is thus studied using a 3DOF trajectory analysis model. Control surfaces such as the elevons will be sized in order to trim the vehicle over its flight trajectory. For instance, when planning the path of the vehicle, the controls will have to steer the different mission phases along a corridor that is heavily constrained by considerations of both structural loading and aerodynamic heating.

The ability of the demonstrator to withstand the thermal loads will equally be a source of particular concern when establishing the technical and operational viability of our reusable demonstrator. A thermal model, based on a nodal method, will thus be used in order to assess the thermal survivability of the demonstrator throughout its mission lifetime.

Indeed, despite the extreme flight conditions to which the hypersonic demonstrator will be confronted, there will be strict emphasis on the full reusability of the flight experiment in order to ameliorate its acquisition cost over a predicted lifetime of more than 50 flights per prototype.

Finally, as a means to demonstrate the economic viability of a potential full-scale system, our hypersonic experimental platform shall aim towards a turnaround time of about a day. The cost of acquisition will indeed be significantly lowered by the number of flights the demonstrator can sustain without significant refurbishments.

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