Methodology for a Preliminary Assessment of Hypersonic Aircraft Powered by Liquid Methane

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This paper aims at improving existing conceptual design methodologies for high-speed vehicle design in order to enable a preliminary assessment of commercial hypersonic aircraft powered by liquid methane. Notably, the paper introduces new formulations and approaches to the characterization of aircraft configuration, mass breakdown and performance analysis, also focusing on comparison with other fuels, such as kerosene and liquid hydrogen, for what concerns overall layout, flight efficiency and environmental sustainability impact. An example of application of the method is presented, with focus on a Mach 6 case study.

I. Introduction

The conceptual design of hypersonic vehicles is radically different from the process adopted for conventional aircraft. Still maintaining the overall objectives, the different steps towards vehicle definition are characterized by substantial differences, for example concerning aerodynamic analysis, propulsive characterization and layout assessment [1]. Several methodologies are available in literature to address this challenge, aiming to provide a solid base to tackle the design problem, especially considering that no statistical basis can be adopted to sketch a first guess dataset for vehicle characteristics, differently from what is usually done for conventional aircraft. The most renowned methods from NASA are defined as in [2] and [3], where a specific approach to mass breakdown definition and an overall conceptual design process are proposed respectively. The first study proposes a wide set of weight estimation relationships in order to evaluate the mass distribution and breakdown of a range of hypersonic aircraft by relating mass with specific design variables, thus providing an explicit method for mass definition. The second study proposes instead a complete and flexible conceptual design approach for the same category of aircraft, with the aim of sketching the configuration of the vehicle in presence of different high-level requirements, fuels and propulsion systems. Both methodologies, however, require a lot of parameters in input, thus they are performing well only if the user already knows many design variables, being aimed essentially at providing an explicit design solution without design space exploration. To bridge this gap, more recently, works such as [4-6] aimed at proposing closed-loop and iterative design methodologies for different kinds of hypersonic aircraft, introducing several strategies to identify proper design solutions, under different perspectives. With the goal of identifying a proper template for representing the design space, these approaches may risk to lose flexibility for what concerns propulsion plant integration and fuel selection. This fact is particularly important when dealing with cryogenic fuels, since the storage requirements has a lot of impact on aircraft configuration, particularly looking at volume relationships and their effect on aerodynamic efficiency and thrust-to-drag ratio.

Among cryogenic fuels, liquid methane may offer a good balance between energy availability and storage requirements, considering its higher energy density with reference to kerosene and its higher volumetric density with reference to liquid hydrogen. In turn, the idea of exploiting liquid methane as fuel to power hypersonic aircraft is not new, being already widely assessed in previous studies, also for subsonic and supersonic aircraft [7-8]. However, the interest in liquid methane for this kind of application has been reduced in the last years, in favor of a progressive shift towards liquid hydrogen, because of the potential introduction of the same fuel also in conventional aviation, as well

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as other transport means, and because of the low environmental impact and carbon dioxide emissions in operations. The situation however may change, considering the expected delays associated to liquid hydrogen supply chain in the next years.

It is thus important to revive the methodologies associated to the conceptual design of hypersonic aircraft powered by liquid methane, by exploiting approaches similar to [4-7], in order to support a proper trade-space exploration for the identification of suitable design points, still maintaining the parametric approach suggested in the early stages of research in the field [1-2].

Particularly, this paper aims at proposing a conceptual design methodology to support the initial sizing and assessment of hypersonic aircraft powered by liquid methane, with the goal of improving the rationale and the formulations suggested in [2]. Updates to the performance requirements definition, the configuration analysis, as well as the mass breakdown formulations are provided in this study, targeting the introduction of a proper design space characterization in the method. The approach is specifically designed also to be flexible, in order to ensure the possibility of comparing the results with other case studies and potential competitor, featuring different kinds of fuels, such as kerosene and hydrogen, also looking at competitiveness (e.g. costs) and green-house gas emissions.

After this short introduction, the paper focuses on the description of the methodology adopted for the conceptual design process, with the definition of the different formulations in Section II. Moreover, Section III provides the main results of the analysis associated with the case study selected for the verification process. Ultimately, Section IV draws major conclusions and paves the way for future works.

II. Methodology

The conceptual design methodology proposed in this work is based on the main steps described in [2]. The related study, known as HASA, i.e. "Hypersonic Aerospace Sizing Analysis for the Preliminary Design of Aerospace Vehicles", and developed by NASA in 1988, had the limitations of being oriented to a "rapid-prototyping" of the concept under development, lacking a proper solutions space exploration and considerably relying on the experience of the user for what concerns initial input. Crucial design variables, such as the wing loading, were necessary in order to start the sizing process, since different semi-empirical formulations required an extensive set of input in order to complete the mathematical model. Still, the approach had the flexibility of supporting different kinds of fuels and propulsion plants, offering the perfect basis for the update of the mathematical formulations.

Notably, this work proposes the introduction of a new performance estimation routines, introducing requirements on the wing loading and thrust-to-weight ratios, in order to be able to compute these crucial variables iteratively, rather than providing them as initial input, as well as an updated mass breakdown evaluation, especially introducing a proper mission parametrization and associated fuel consumption estimation routines for propellant mass estimation, originally missing in the method.

The workflow of the methodology can be summarized as reported in Fig. 1. Notably, starting from the definition of high-level mission requirements and potential reference concepts, an initial calibration phase, inspired by the one present in [2] is included. Then the identification of vehicle layout characteristics is performed, followed by the aerodynamic analysis. The two steps are preparatory to the mass and volume breakdowns computation, where fuel type (e.g. cryogenic) and consumption trends are crucial to understand the impact on the configuration. A convergence check both on mass and volume is then performed before moving to the representation of the design space, where a performance map, known as Matching Chart [9, 10], is shown in order to identify a suitable design space and reference sizing point, as function of thrust-to-weight ration and wing loading. Ultimately, a reference sketch of the vehicle is provided, taking into account the overall type of configuration (tube and wing, blended, waverider, etc…), as well as propulsion plant integration needs (intake/nozzle, type of propulsion plant, etc…).

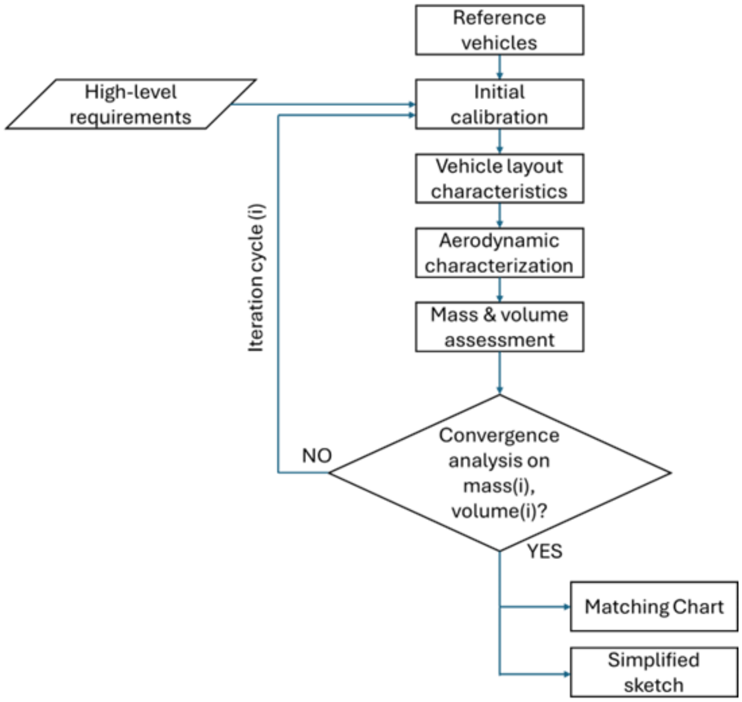

Fig. 1. Proposed conceptual design methodology

The complete conceptual design process and supporting methodology will be included and described in detail in the full paper.

III. Case study and Results

The reference case study, adopted as verification case for the proposed methodology, is a Mach 6 aircraft conceived to carry 200 passengers over a design range of 10,000 km, enabling connections between North America and Asia-Pacific regions (Fig. 2). Exploiting a tube and wing configuration, the aircraft uses liquid methane as fuel and it is supposed to be powered by a Turbine-Based Combined Cycle (TBCC) powerplant, coupling turbojet and ramjet technologies in "over-under" configuration, with a common variable-geometry intake.

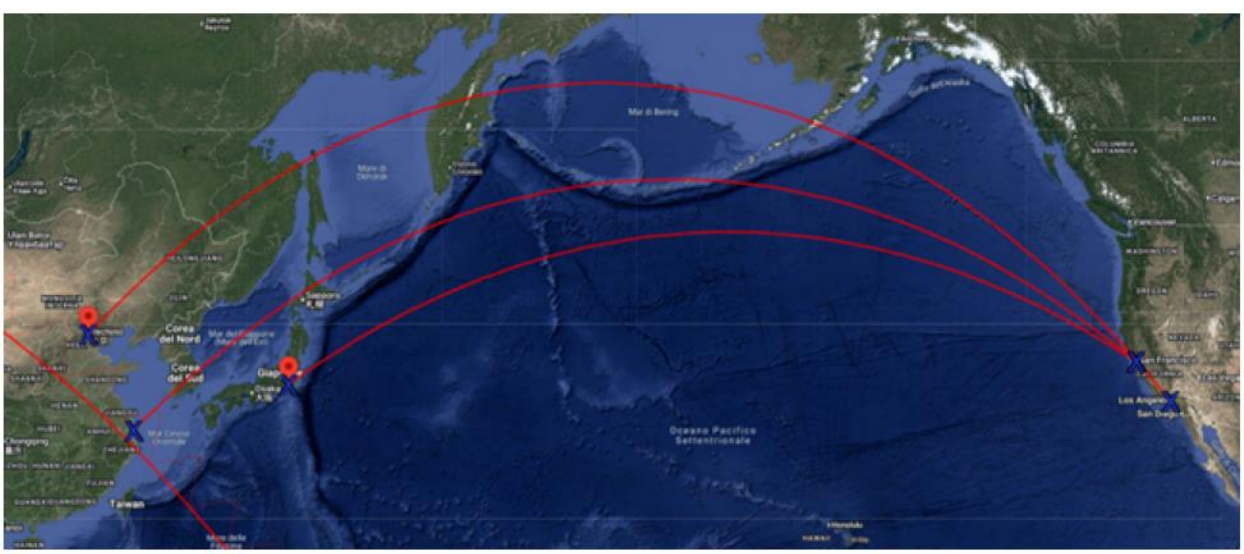

Fig. 2. Potential missions and city-pairs connections available for reference case study

Results of the analysis applied to this case study will be available in the full paper. Verification of the results will be performed with reference to similar concepts included in [2], and comparisons with different kinds of fuels will be run exploiting the newly developed conceptual design routine as validation process. A discussion on the competitiveness of liquid methane with reference to kerosene and hydrogen will also be included, focusing on environmental aspects and operating costs.

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