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Optimization of Fuel Depletion Sequence for Trim Drag Minimization of a Commercial Hypersonic Aircraft Powered by Liquid Hydrogen

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Trim drag is a well-known problem for high-speed aircraft since it has a considerable impact on aerodynamic efficiency during different phases of flight, depending on vehicle attitude. The source of drag is usually related to control surfaces deflections, which, in turn, are required to trim the aircraft in different conditions because of the evolution of its mass distribution during the mission. The influence on flight performance may be so critical that neglecting trim drag contribution, i.e. considering aircraft clean configuration, may lead to overestimation of range, especially when trim drag is high during cruise phase, potentially jeopardizing the initial guess about feasible routes. This paper proposes a methodology for the optimization of fuel depletion sequence for a hypersonic aircraft powered by liquid hydrogen, in order to minimize trim drag. The work exploits a flexible multi-disciplinary approach, analysing both fuel storage as well as distribution strategies on-board and assessing stability and trim conditions for different positions of the centre of gravity of the aircraft. Secondary functionalities associated to fuel system such as thermal management and on-board power generation needs are also considered. The method is applied to a Mach 8 waverider aircraft concept.

I. Introduction

The intrinsic complexity of the configurations which typically characterize hypersonic aircraft makes very difficult to approach the on-board systems design problem with traditional sizing processes. In fact, if for conventional aircraft it is often possible to simplify the preliminary analysis at systems-level by facing their design in an independent way, it is definitely not possible to decouple the studies in case of hypersonic, and, in general, high-speed aircraft. The main reason is the increased level of interfaces and dependencies among the different elements of the aircraft, as well as the relationships with the external environment.

One of the typical mistakes in the initial design phases of a commercial hypersonic aircraft is associated to the underestimation of trim drag resulting from the deflection of control surfaces and related impact on vehicle attitude necessary to maintain equilibrium in different flight conditions, especially when dealing with rapid mass distribution changes and shift between flight regimes. The impact of control surfaces deflection on aerodynamic performance of the aircraft are so important that the initial assessments made on the so-called "clean" configuration may be characterized by substantial overestimation of available range, potentially jeopardizing the aircraft concept and related competitiveness in operation [1]. As the name suggests, trimming the vehicle while extensively using control surfaces may increase drag, reduce lift and impact negatively on fuel consumption, especially if this conditions are encountered in phases characterized by long duration, such as hypersonic cruise. Minimization of trim drag is thus a primary objective of the designer in order to reach the optimum aero-propulsive balance in operation. In order to do so, a

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careful analysis of center of gravity shift during flight is needed to reduce maneuvers and guarantee a smooth transition between different attitude conditions. This can be done by closely looking at propellant system design, in order to ensure that the distribution strategy and depletion sequence on board are in line with this objective. However, for hypersonic aircraft conceived for point-to-point transportation, known as Cruise and Acceleration Vehicles (CAV) according to [2], thermal management is also quite important because of the need of maintaining airframe parts within operational limit for a long period of time. Fuel tanks location as well as distribution line routing are thus conceived also to work in synergy with the on-board thermal management system, especially in case of exploitation of cryogenic fluids. Moreover, the adoption of high-speed propulsion plant, required to fly in the hypersonic regime, such as ramjets and scramjets, may introduce additional problems related to the secondary power generation (e.g. electrical power) to be used on board for different utilities, because of the absence of moving parts which can feed generators. Complex multi-functional systems have been developed in order to unlock combined energy management systems for hypersonic vehicles [3-7], increasing even more the order of the problem.

Minimizing the trim drag by optimizing the fuel depletion sequence on board is thus not only a matter of coupling engine fuel flow needs with flight control system operation, but it shall also take into account the management of the fluid in order to meet at the same time the thermal and power generation requirements, potentially extending the problem to additional systems. This paper thus describes a methodology associated to the optimization process of the fuel depletion sequence for a hypersonic aircraft powered by liquid hydrogen in order to minimize trim drag, defining a multi-disciplinary on-board systems design and optimization approach. The work is based on the preliminary results described in [8] where the non-optimized conditions are presented.

After this short introduction, Section II introduces the case study used as reference aircraft configuration for the implementation of the method. Section III then presents the multi-disciplinary analysis and optimization strategy, with focus on the interaction between the different on-board systems, as well as the main results of the study. Ultimately, Section IV draws major conclusions and highlights potential future works for the improvement of the method itself.

II. Case Study

The reference case study adopted to develop the proposed methodology, is a Mach 8 waverider aircraft conceived to carry 300 passengers over a design range of 18,000 km, which has been developed within the framework of STRATOFLY project [9] and known as the "MR3" (Fig. 1 left). Exploiting hydrogen as fuel, it is powered by a dual propulsion plant consisting in six Air Turbo Rockets (ATR) and one Dual-Mode Ramjet (DMR) [10]. The aircraft is supposed to be equipped with four groups of control surfaces, including canards, elevons, rudders and body flaps in the upper part of the fuselage trailing edges (Fig. 1 right). The main data of the vehicle are collected in Table 1.

Fig. 1. The STRATOFLY MR3 aircraft concept rendering (left) [8] with details on control surfaces (right)

Table 1. Main characteristics of STRATOFLY MR3

Parameter	Value	Unit of Measurement
Length	94.7	*m*
Wingspan	41.1	*m*
Wing surface	1365	*m*
Aspect ratio	~1	-
Internal volume	~10,000	m^3

MTOW	400,000	*kg*
Propellant mass	190,525	*kg*

The geometric characteristics of control surfaces are listed in Table 2.

Table 2. Control surfaces data for STRATOFLY MR3

Surface	**Root Chord** $[m]$	**Tip Chord** $[m]$	**Span** $[m]$	**Surface** $[m^2]$	**Sweep Angle [deg]**	**Inclination [deg]**	**Maximum Deflection [deg]**
External elevon	3	3	5	15	N/A	N/A	+/-25
Internal Elevon	3	3	5	15	N/A	N/A	+/-25
Canard	8.7	2.8	8.7	50	49	N/A	+/-20
Rudder	3.6	2.5	6.5	19.8	54	33	+/-20
Body flap	7.14	7.14	3.3	23.7	N/A	N/A	+30

The reference mission of the aircraft, in its clean configuration, is reported in Fig. 2.

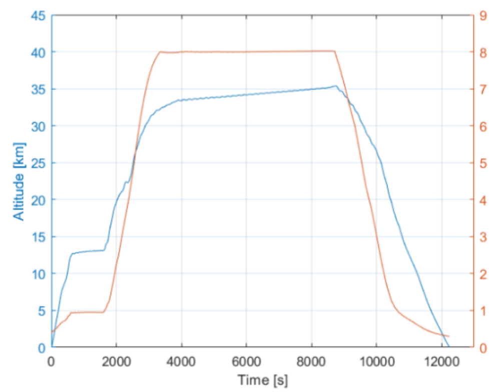

Fig. 2. Reference mission for STRATOFLY MR3 [8]

The hydrogen storage subsystem is organized as described in Fig. 3. The aircraft features a multi-bubble tanks structure, with three main tank assemblies (FAT-MFP, FAT-MP and FAT-MRP) and several auxiliary tanks for trim and heat management purposes.

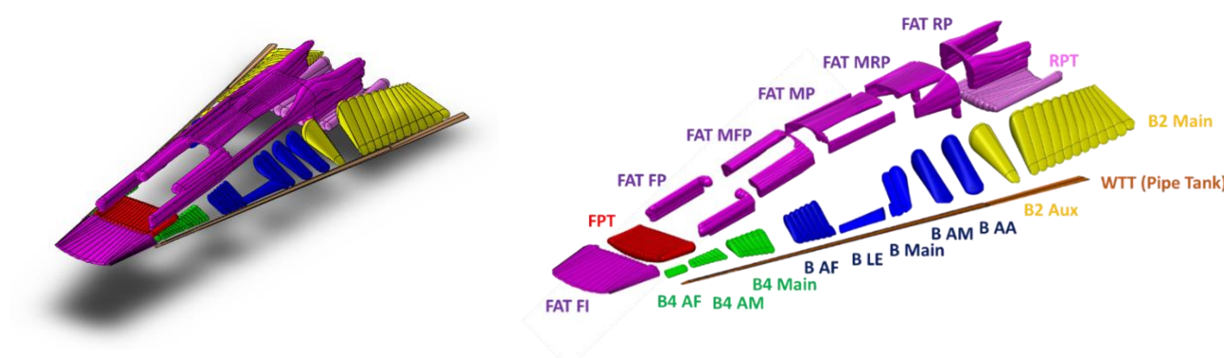

Fig. 3. Tanks layout of the STRATOFLY MR 3 vehicle (left – overall shape, right – tanks ID) [8]

The overall tanks configuration makes benefit of most of the residual free volume available on board, not occupied by airframe structure, propulsive flow-path cabin and other systems. The details about fuel quantity in the different tanks is reported in Table 3.

Table 3. Fuel quantity breakdown in the different tanks of the vehicle (global assemblies)

Tank assembly	Fluid volume [m3]	Fluid mass [kg] @13K
FAT (overall)	836	75,241
FPT	125	11,291
FWT (B4)	30	2735
CWT (B)	198	17,806
RWT (B2)	616	55,374
RPT	294	26,454
WTT	18	1624
Total	2117	190,525

III. Methodology and Results

The methodology is based, first, on an iterative multi-disciplinary analysis of different aircraft systems working cycles in order to compute the required thrust T and resulting fuel mass flows $\dot{m}_i$ for the mission under initial trim conditions for the aircraft X_0 and assumptions Y_N. The actual mass flow required to feed the engines, in fact, influences the position of the center of gravity CoG and, as consequence, the deflection angles of control surfaces δ_i and the attitude of the aircraft α itself. This produces a variation of aerodynamic coefficients C_L, C_D, C_M and, especially, drag, which shall be re-evaluated up to convergence. Moreover, the actual mass flow rates among the different aircraft compartments influence also thermal management functionalities, having an impact on the actual temperature T_i and cooling capabilities in the different compartments, as well as on potential power generation means P, in case an energy management architecture similar to [7] is expected.

Once the convergence is reached, it is possible to start the optimization process by acting on the timing t_i and the sequences ϕ_i of fuel tanks depletion in order to minimize trim drag.

The implementation of the methodology is shown in Fig. 4 exploiting an eXtended Design Structure Matrix (XDSM).

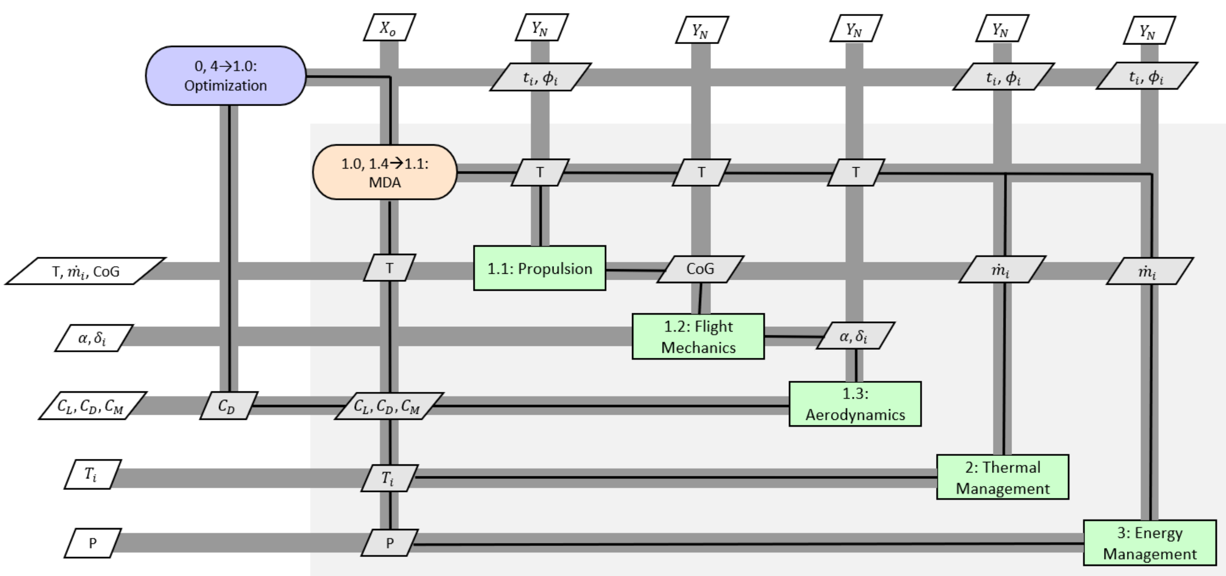

Fig. 4. Implementation strategy for the trim drag optimization methodology

The complete methodology will be included and described in detail in the full paper, together with all the main steps and the results of the analysis.

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