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Multidisciplinar Optimization in Conceptual Design of Hypersonic Vehicles

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Abstract

The design of hypersonic vehicles and their propulsion systems is complex, which requires knowledge of several engineering disciplines to guide the decisions of their designers. This work presents a multidisciplinary optimization involving aerodynamic efficiency (lift/drag ratio or L/D), longitudinal stability (static margin) and volume in the conceptual design of a hypersonic vehicle of the WAVERIDER class with different horizontal and vertical stabilizers (tail empennage) and fin shapes (clipped-delta and swept ones). Preliminary optimized solutions show that WAVERIDER vehicles with conventional tail empennage featuring three swept fins are preferable in terms of aerodynamic performance and flight control feasibility under volume restrictions.

Keywords: *Waverider, Aft tail, Fin planforms, Multidisciplinary Optimization.*

1. Introduction

1.1. Multidisciplinary Optimization Design (MOD) of Aerospace Systems

The design of aerospace systems is very complex, which requires knowledge of several engineering disciplines to guide the decisions of its designers. During the life cycle of an aerospace system, the conceptual phase (PHASE 0) is the one in which designers must collect as much information as possible about the aerospace system so that their decisions and choices are the most assertive and correct in a manner that does not impact the later phases with engineering design change requests. To this end, synergy between the various disciplines, including aeronautics, astronautics, stability, flight dynamics, structures, materials, propulsion, among others, is mandatory.

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In this context, the use of multidisciplinary optimization (MDO) in conceptual design has become usual in the recent years in a manner that aerospace designers can act in advance on physical quantities that are generally not closely related to each other at the beginning of life cycle project.

1.2. MOD in Hypersonics

The design of hypersonic systems is challenging as they are at the frontier of Aeronautical Engineering (see Fig. 1). The MDO philosophy has already been used and, often, early in the conceptual phase of the hypersonic systems [1-5]. The use of multidisciplinary optimization in hypersonics is increasing, where the vast majority of published works focus mainly on the multidisciplinary optimization of civil hypersonic projects (for passenger and cargo transportation). There is also a preference for multidisciplinary optimization of the WAVERIDER class of high-lift hypersonic vehicles, but their optimized integration with hypersonic airbreathing engines of the SCRAMJET type should also be considered soon. This is because multidisciplinary optimization is very promising when it involves new concepts and systems, for which there is not yet a broad database available as a starting point for designers.

In this context, this work proposes the multidisciplinary optimization of both cruise aerodynamic efficiency(lift/drag ratio or L/D) and fuselage volume in the conceptual design of a WAVERIDER class hypersonic vehicle for flight demonstration. The best trade-off solutions should size vehicles with adequate volume for payload accommodation with enough aerodynamic efficiency for cruise at Mach number 10 into the stratosphere. The selected vehicles encompass fuselage with horizontal and vertical stabilizers without scramjet-airframe integration (glider).

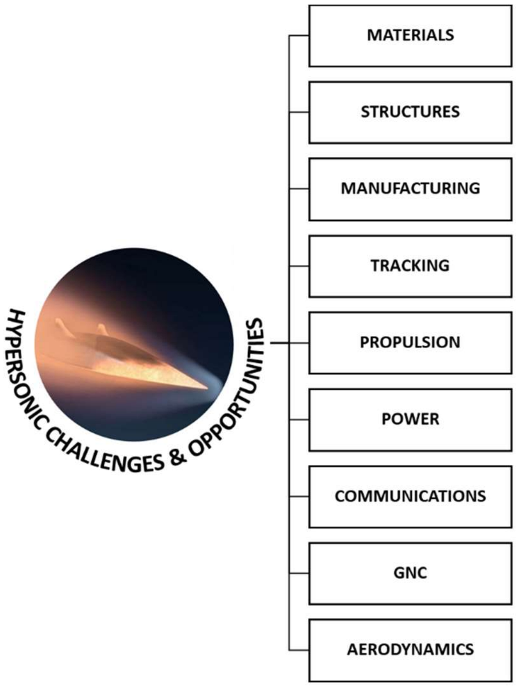

Fig 1. Current challenges and opportunities in hypersonics. Adapted from [6].

2. Methodology

2.1. Mission Profile Definition

The WAVERIDER vehicle was sized to provide enough cruise range gliding at Mach 10 into the sensitive atmosphere. Assuming that the WAVERIDER vehicle is a glider demonstrator, its mission profile requirements like takeoff distance, maneuverability, and climb rates were ignored for simplification of the multidisciplinary sizing optimization of this paper. Thus, the cruise range requirement guided the optimal configurations of the WAVERIDER vehicle, that is, its fuselage and empennage dimensions and geometries. Also, for hypersonic flight testing purposes, rockets have been often utilized as accelerators in a manner that the WAVERIDER vehicle should be able to be accommodated within the payload dynamic envelope of the rocket fairing during ascent, which represented a hard constraint. Such a size constraint had to be satisfied herein.

2.2. System Requirements Definition

Top-Level system requirements of the WAVERIDER vehicle are summarized as follows: a) Its compression surface should be derived from wedge flow; b) Its freestream surface should be based on the Haack Series or Von Karman nose; and c) Its empennage should be selected from conventional, "V" or thruster tail layouts with trapezoidal or swept stabilizers shapes. These aerodynamic and flight control requirements guided the sizing optimization of the WAVERIDER vehicle. Likewise, the impact of them on the cruise performance of the WAVERIDER vehicle at hypervelocities was analyzed.

2.3 Multidisciplinary Optimization Solutions

Figure 2 shows the block diagram of the multidisciplinary optimization software of the WAVERIDER fuselage utilized herein. Basically, it is an extension of the algorithm presented in [7] to form a package that involves spreadsheets, MATLAB and Python scripts, and CAD tools whose final purpose is to provide the best trade-off solutions for the WAVERIDER fuselage size and geometry. As mentioned before, the aerodynamic ratio at cruise flight in the sensitive atmosphere and size of the WAVERIDER fuselage were the quantities maximized (objective functions) under the restriction of payload fitting inside the rocket fairing during ascent (constraint function). At the moment of writing this paper, the software package has been rewritten in C++ language for allowing users to access and use it more easily and efficiently.

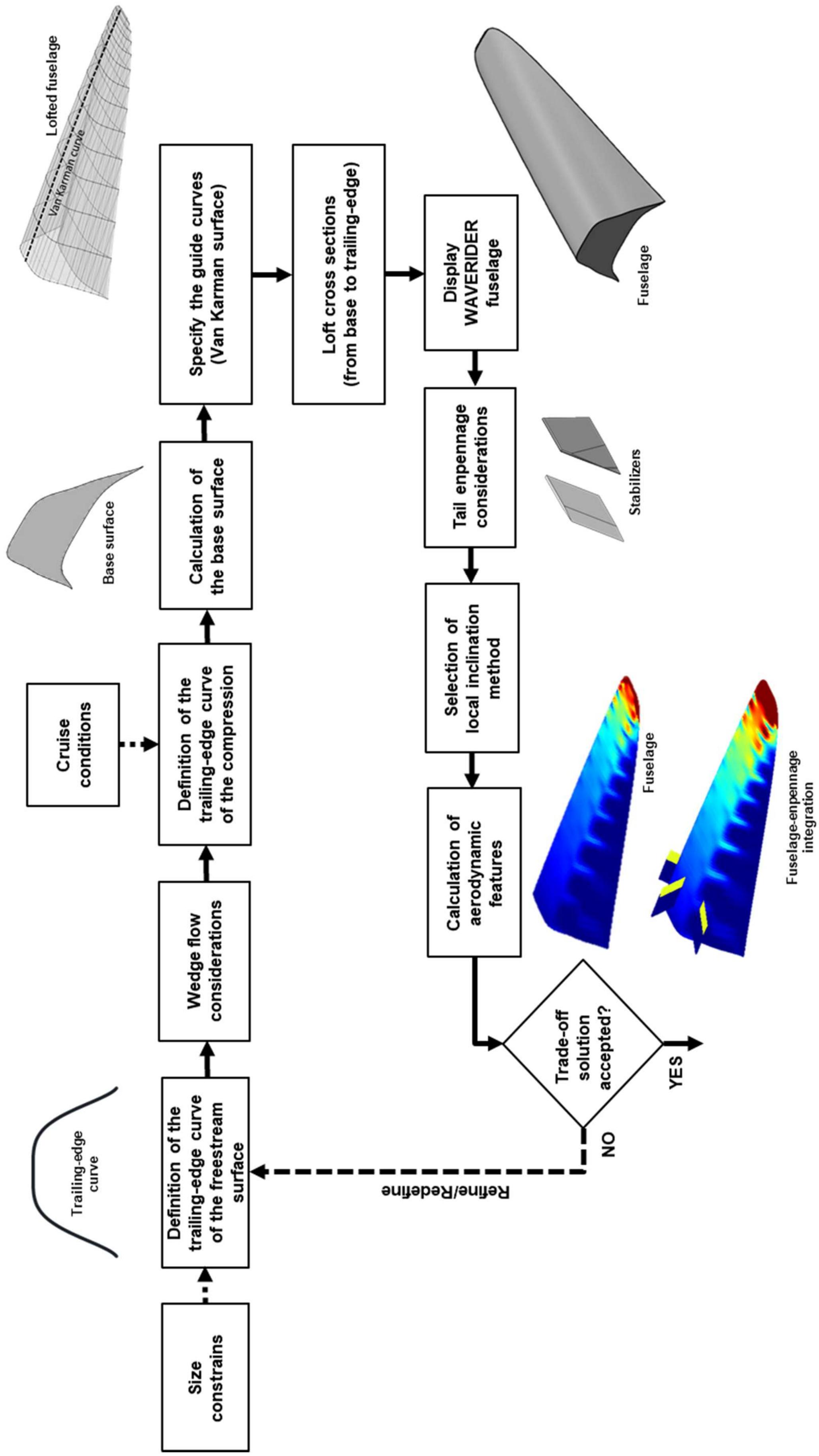

Fig. 2. Software package for optimization of the WAVERIDER vehicle size and geometry [8].

3. Results

3.1 Aerodynamic Features

Figure 3 presents the surface pressure coefficient distribution on the WAVERIDER fuselage with and without tail empennages for a cruising flight at Mach number 10 with angle of attack (AoA) null into the sensitive atmosphere (stratosphere). As expected, the wall pressure is higher around the leading-edge of the fuselage under the cruise conditions. Also, note that the wall pressure on the compression surface of the fuselage is higher relative to the freestream surface, a necessary condition for the WAVERIDER to produce lift. Now, regarding the fuselage with tail empennage, Fig. 4 shows the surface wall pressure distribution on them in comparison with the isolated fuselage (reference) for the same cruise conditions. Note that the influence of the tail empennage on the surface wall pressure distribution on the isolated fuselage can be neglected (no flow disturbance) but, for all geometry and tail empennage layouts pressure drag is always added as expected.

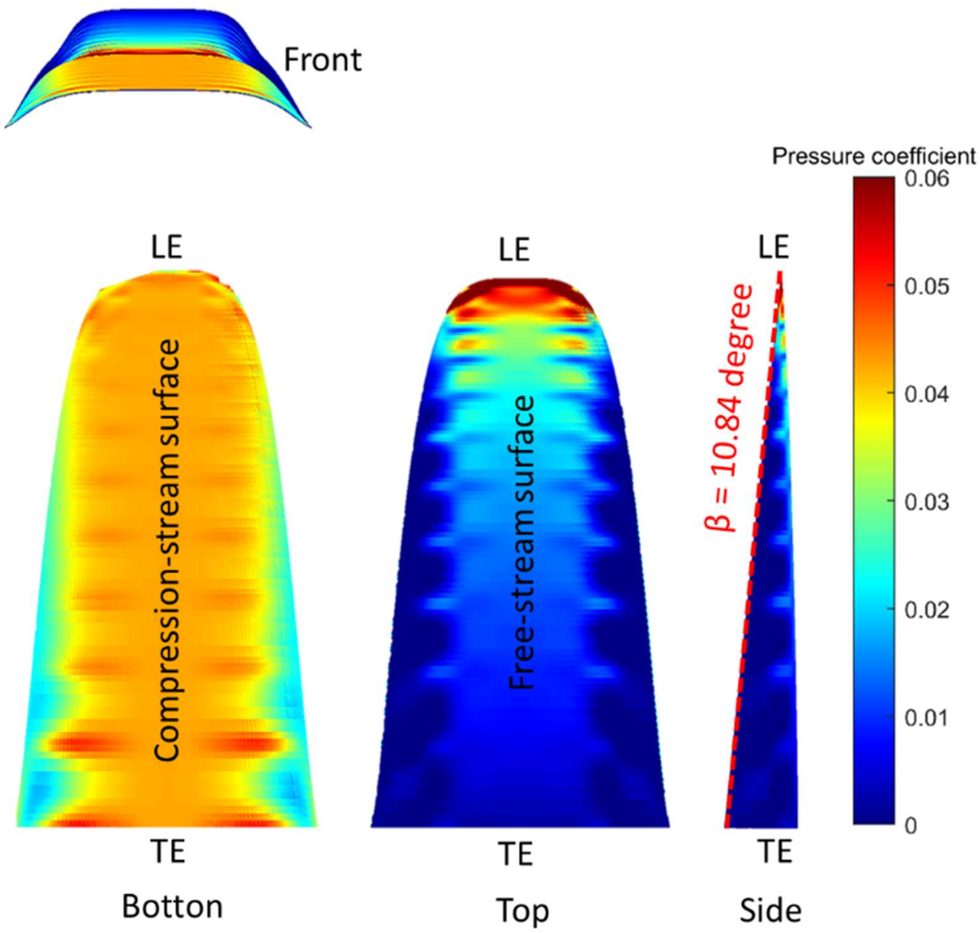

Fig. 3. Surface pressure coefficient distribution (based on the tangent-wedge method) over the WAVERIDER fuselage (top, down, side and front views) for level cruising at Mach 10 into the stratosphere.

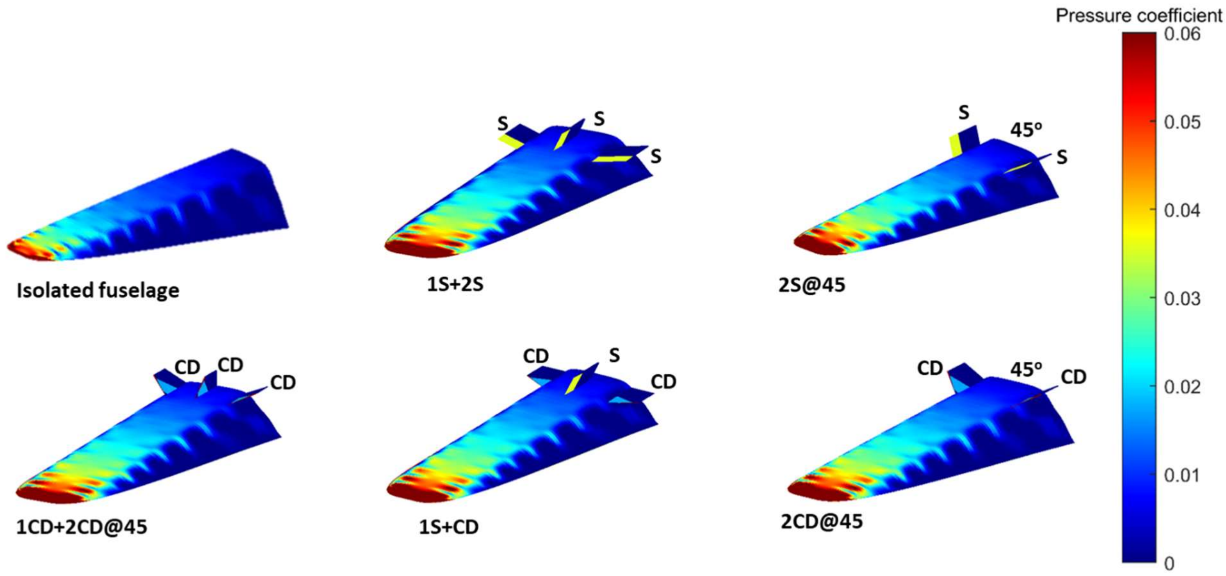

Fig. 4. Surface pressure coefficient distribution (based on the tangent-wedge method) over the WAVERIDER fuselage (reference) with and without tail empennage at level cruising at Mach 10 into the stratosphere. S refers to swept fin while CD to clipped delta one.

Modulated wall pressure on compression and freestream surfaces of the WAVERDIER looks unreal and maybe related to fails during the surface meshing of the 3D CAD fuselage model. Nevertheless, these aerodynamic features were calculated based on Newton flow theory for hypersonic flows which is a simple and inexpensive method for rapid and preliminary prediction of the aerodynamic properties of bodies at hypervelocities. Thus, future CFD verifications of aerodynamic features of the selected configurations must be done in a manner to include viscous effects, flow separation, thin shock layers and real gas phenomena in hypersonics.

3.2 Preliminary Trade-off Solutions

Table 1 summarizes the trade-off solutions in terms of volume and aerodynamic efficiency of the WAVERIDER vehicles selected for the level cruise flight at Mach 10 into the stratosphere zone. As observed, the 2S@45 layout (fuselage with "V" tail empennage and two swept fins with 45º tilt angle) presents the highest L/D value under volume constraint. However, it may impose further design difficulties regarding the flight control due to its "V" tail empennage. Because of this complexity, the 1S+2S layout (fuselage with conventional tail empennage and three swept fins) is preferable in terms of flight control, while presenting an adequate L/D and with enough volume for subsystem accommodation (e.g., flight control, engine and fuel control, power supply, avionics, electrical, hydraulic and pneumatic subsystems) into the hollow shell of the fuselage. Tail empennage with three clipped-delta fins (1CD+2CD@45 layout) resulted in more pressure drag in comparison with other tail empennage layouts as inferred from the L/D degradation (around 52 % less than that of the isolated fuselage).

Table 1. Preliminary trade-off solutions for the WAVERIDER vehicle

Case	Fuselage	Aft tail	L/D	Volume [m^3]
No tail	WAVERIDER	-	5.03	610
2S@45	WAVERIDER	V	4.92	610
1S+2S	WAVERIDER	Conventional	4.87	610
1S+2CD	WAVERIDER	Conventional	3.28	610
2CD@45	WAVERIDER	V	3.17	610
1CD+2CD@45	WAVERIDER	Conventional	2.62	610

4. Final Remarks

This work discussed a multidisciplinary optimization in the conceptual design of a hypersonic vehicle (glider) of the WAVERIDER class with fuselage integrated with different tail empennage layouts and fin shapes. Preliminary trade-off solutions (aerodynamic efficiency versus volume under size constraints) have revealed that fuselage with conventional tail empennage and three swept fins is preferable and a promising candidate for the level cruise flight at Mach 10 into the stratosphere zone in terms of aerodynamic efficiency for cruise range, fuselage volume for subsystems accommodation, and tail empennage configuration for simplification of flight control. The selected configurations shall be further studied using higher-order computational approaches, CFD tools and experimental methods for more detailed assessment.

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