AN INITIAL DESIGN METHODOLOGY FOR OPERATIONAL HYPERSONIC MILITARY AIRCRAFT

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Abstract

HICAD (Hypersonic Interactive Combat Aircraft Design) is a GUI-based design tool being developed to facilitate the design of hypersonic cruise vehicle configurations. Analytical techniques and simple mathematical models are used in conjunction with multi-variable optimization to rapidly analyze vehicle concepts and their propulsion system. In this context, a waverider forms the baseline cruise vehicle with a Scramjet and TurboRamjets integrated onto the lower part of the airframe. The TurboRamjet and Scramjet are designed using one-dimensional idealized analysis while the waverider and its wing curve shape is designed using a conical flowfield solution. It is shown that the entire undersurface forms the propulsion system with the forebody behaving as the precompression surface and the afterbody functioning as a nozzle extension. The proper integration of the propulsion systems with the airframe, therefore, is crucial to the success of a hypersonic vehicle. Results are presented for the aerodynamic performance including the design of a two-dimensional nozzle, along with the optimization methodology used to generate lift-to-drag maximized vehicle configurations.

1 Overview and Introduction

The speed and range offered by hypersonic cruise vehicles are two fundamental advantages for both military and civilian operations. Potential applications using hypersonic technology, include horizontal takeoff and landing reusable launch vehicles (RLV) for flexible and affordable access-to-space, space tourism as well as military global reach and rapid response vehicles. The focus for the present study is on endoatmospheric long-range cruise vehicles for military payload delivery. These vehicles will use airbreathing engines to maximize propulsive efficiency and be capable of horizontal takeoff and landing from conventional runways.

The lack of baseline vehicles such as flying prototypes or any relevant practical design experience have challenged the development of such aircraft, together with uncertainties associated with hypersonic aerothermodynamics, innovative propulsion systems, optimized airframe / engine integration, high development costs, etc. The key enabling technology is widely considered to be advanced airbreathing propulsion systems that offer high efficiencies and easy integration with a suitable airframe. This requires a precise configuration definition. A recent successful application was demonstrated by NASA's Scramjet-integrated X-43A research vehicle that achieved sustained hypersonic cruise using hydrogen fuel [1].

A rich parameter set and design options for hypersonic cruise vehicles range from high specific impulse propulsion selection (airbreathing or rocket engine), reusability, takeoff /landing options, high temperature materials and fuel selection, safety and control technology. It is the task of the designer to find the optimum combination of these variables eventually leading to affordable and flexible design solutions for a given set of requirements [2].

In order to be able to study and analyze a wide range of hypersonic vehicle concepts, various preliminary design tools and mathematical models have been developed and combined with existing selected processes to form a unified automated design methodology . This reduces the initial design cycle time compared to detailed component CFD analysis, which is too slow and expensive at the preliminary design level.

The aim of this initial design methodology is to provide an aid for the expedited development and analysis of hydrogen-fueled hypersonic cruise airbreathing vehicles, having global reach and horizontal takeoff and landing capabilities. This is achieved through consolidation of many existing relevant research results into a single design synthesis that integrates new advances in high-speed propulsion, materials, structures, high temperature effects etc. This paper outlines the various elements of the new initial design methodology. This aims to maximize the product of the Lift-to-Drag ratio (L/D) and specific impulse (I_{sp}. The full methodology has not yet been completed. The on-design case is fully documented here while the off-design issues are still undergoing development.

A number of vehicle concepts are available to the designer. A possible candidate to address this challenge is a hypersonic waverider first proposed by Nonweiler [3]. A waverider generates a bow shock wave that is attached all along its leading edge thereby containing a high pressure region on its lower surface and the vehicle rides its own shock wave, hence the deserved title. The attached shock wave permits the independent design of the lower and upper surfaces and maximizes the (L/D) by preventing high-pressure flow spillage to the top surface. Waveriders can be generated either by a pure conical flowfield [4] or using the osculating cones technique [5]. Both have demonstrated their suitability for Scramjet (SJ) integration producing good values for L/D. The former method was selected for this study due to its computational simplicity and low processing power needed for optimization.

In this study, airbreathing engines were selected over rocket engines based on performance benefits offered during endoatmospheric cruise missions. In particular, the takeoff weight and hence speed are reduced as storage of an onboard oxidizer is not required. Instead, airbreathers will use atmospheric oxygen along the vehicle's mission trajectory and that will extend the operational envelope. The mission of a hypersonic vehicle can be divided into the *low-speed* part, which includes subsonic and hypersonic flight and the *high-speed* part that encompasses the hypersonic cruise operation.

For the low-speed part of the mission, TurboRamjet's (TRJ) were selected due to weight saving and performance benefits over separate turbojet and ramjet (RJ) units [6]. TRJ is an example of an advanced Turbine-Based-Combined-Cycle (TBCC) engine and other possible engines include the RBCC engine [7]. A dual-mode RJ / SJ combination was selected as the high-speed engine due to its integration conformity with a waverider and near-term development potential [8]. The hypersonic airbreathing propulsion system extends over the entire undersurface of the hypersonic vehicle with the forebody acting as the precompression surface and the afterbody acting as the nozzle; shown by the X-43A [1]. The SJ and TRJ units are integrated in an over / under configuration, which will be described later.

2 Design Methodology

A target design study was carried out based on the mission profile shown in Fig. 1. A description of the various segments is given in Table 1. The vehicle will takeoff horizontally followed by an accelerated climb through supersonic flight using an array of TRJ's until the desired cruise altitude specified by the user is achieved at Mach 5. Prior to this point, the SJ will start and continue to operate in parallel with the TRJ's until the thrust between the two types of engines units is matched. At this point, the airflow to the TRJ will be shut off. The SJ will then throttle-up and the aircraft will begin a constant-altitude acceleration to a sustained hypersonic cruise at a specified Mach number (9/10 in this study). At the end of the cruise segment, the vehicle will decelerate to supersonic speeds and gradually revert to TRJ propulsion, descend to a specified loiter altitude and release the payload. The vehicle will return from the target area by accelerating, gaining sufficient momentum to initiate an accelerated climb to cruise altitude, where propulsion unit transition takes place, followed by further acceleration, hypersonic cruise and deceleration in a fashion similar to the that in the outbound leg. Then it will descend, loiter for a short period and land.

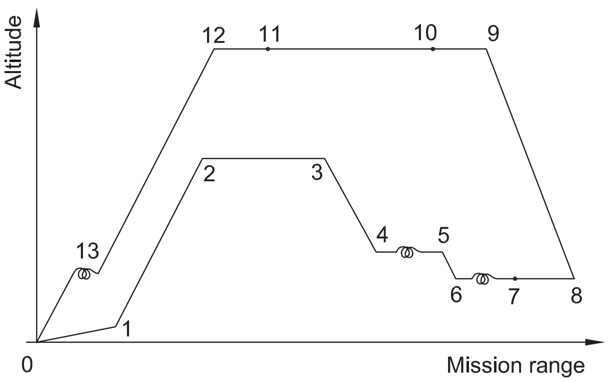

Fig. 1 Design mission profile for cruise-type vehicles

Segment	Description
0 – 1	Takeoff
1 – 2	Climb & Acc.
2 – 3	Acc., hypersonic cruise (const. Alt.), Dec.
3 – 4 – 5	Descent & loiter
5 – 6 – 7	Descent & payload release
7 – 8 – 9	Acc. & climb
9 – 10 – 11	Acc. & hypersonic cruise
11 – 12	Dec.
12 – 13 – 0	Descent, loiter & landing

Table 1 Definition of mission profile segments in Fig. 1. (Acc. = acceleration, Dec. = deceleration)

To capture the synergy between the several aircraft components discussed above, a method needs to be in place to concurrently analyze multiple variables to determine the most optimum combination from a given set of user requirements and constraints. To do this at a CFD level would be too expensive and time consuming and the tradeoff between accuracy and rapid results is the purpose of a preliminary design methodology. HICAD or Hypersonic Interactive Combat Aircraft Design, is an interactive computer software with the aim to rapidly generate hypersonic configurations from a small set of initial parameters. This has been developed as part of this research programme and is structured using an object oriented programming approach written in Visual C++ / MFC. This is an efficient way of developing algorithms and subroutines, combining the flexibility of a graphical user interface (GUI) and the power of a numerical language. The methodology also consolidates various preliminary design tools, mathematical models and analytical techniques to define the design space and to facilitate the rapid generation of practical operational aircraft. Results indicate that the design cycle is reduced significantly.

An example HICAD page is illustrated in Fig. 2, which shows the user's flexibility in adjusting variables with the potential to output data in a graphical format in real time. Data can also be written to files to output in different plotting programs. Currently plotting is enabled using a simple graphics class available in the public domain, which was appropriately modified for this study.

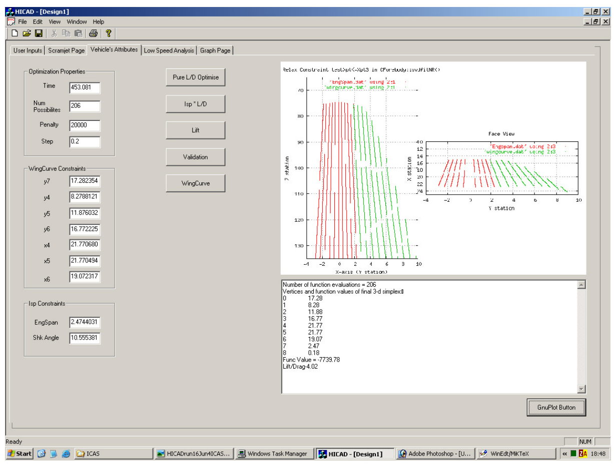

Fig. 2 Example page from HICAD

The key steps in the HICAD's methodology are illustrated in Fig. 3 by means of a flowchart, which shows the highly integrated nature of the design process and provides further information of the computational steps required for a complete design.

Key elements of the methodology are: a) input of basic user requirements such as cruise Mach number and altitude. The mission profile defines the aircraft constraints and determines the fuel required for the specified range. b) Design of a baseline waverider vehicle and iterating until the desired length is achieved using specified constraints, c) analysis and integration of the SJ and TRJ inlets and flowpath using one-dimensional idealized cycle analysis, d) nozzle design and analysis to determine thrust produced by the SJ e) uninstalled thrust-matching of low and high-speed engines for smooth transition and airframe / propulsion integration to satisfy performance requirements f) The final waverider shape is determined by optimizing the wing-curve until L/D reaches a maximum value g) the weight, balance and stability is iterated and when the desired stability levels are achieved, the aircraft flight performance is estimated and the initial design is completed. This also determines takeoff and landing requirements. These processes are discussed in further detail in the following section.

This study focuses on an uninhabited vehicle, which is a likely development strategy considering the inherent complexities associated with accommodating a human pilot, on board. Although future versions of HICAD will be capable of dealing with manned missions. The airframe / propulsion integration was discussed in Ref. [9] to highlight the potential applicability of such a methodology. Correct modeling of this closely linked interaction will define the success of a proposed concept and are developed from experimental data and fundamental principles.

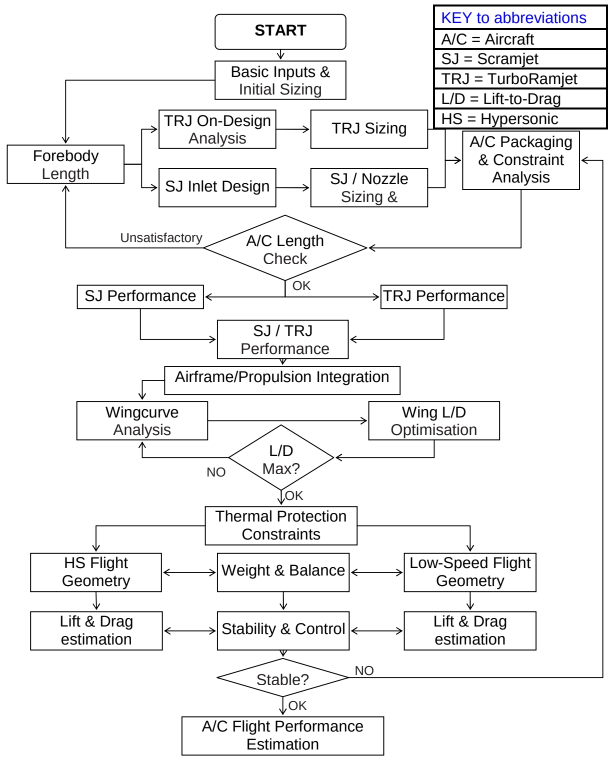

Fig. 3 Flowchart schematic illustrating the structure of the methodology.

3 Component development

Brief descriptions of the methods used for the design of the waverider forebody, the analysis of the inlets and cycle analysis for the SJ and TRJ as well as for the design of the nozzle afterbody will now be presented. The models are suitable for the conceptual level of design ensuring fast computational time for practical optimization results.

3.1 Waverider

By specifying a conical shock angle, the right-circular cone angle that generates this shock can be calculated by solving the Taylor-Maccoll equation [10]. This conical flowfield is used to rapidly generate a waverider shape using an inverse design approach by specifying an elliptical curve in the inlet spanning the width of the SJ. Streamfunction values determined at each point along this curve determine the spatial position of the upstream streamline. This streamline tracing continues until the conical shock is intersected and repeated spanwise for the engine span. This results in the definition of the lower surface with a bow shock attached to its leading edge. Fig. 4

shows a schematic of the shape within a conical shock. The top surface is simply the leading edge streamlines traced back towards the inlet plane parallel to the freestream flow.

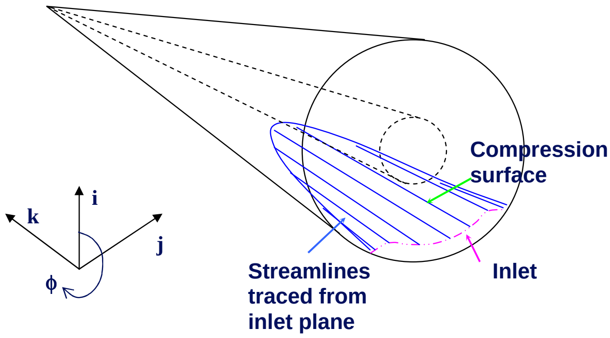

Fig. 4 Inverse design of the waverider forebody adapted from Ref. [4]

This shape is computationally inexpensive to generate and is dependent on mission requirements, engine capture area and minimized drag. Inlet ramp angles are computed based on combustor inlet conditions specified at the start of the program. The forebody alone cannot provide the desired compression, which necessitates an additional ramp. A single 2D planar ramp is used with the same width as the engine, which transforms the 3D conical flow into 2D thereby providing greater flow uniformity in the combustor. The forebody thus behaves as an extension to the precompression surface.

A typical length for a waverider is 60m and the length of the resulting forebody is acceptable if the combustor and nozzle length can be accommodated. The inlet ramp angle and dimensions are calculated according to specified combustor entrance conditions. With an upper limit imposed at 2000K and 1 atm, the ramp angle is varied iteratively until the desired conditions and freestream capture area are met. The latter is also a function of the user-selected cruise altitude. This analysis is made for the on-design case where a shock-on-lip condition is imposed. The reflected shock off the cowl cancels on the upper shoulder of the combustor. The geometric parameters of the vehicle are illustrated in Fig. 5.

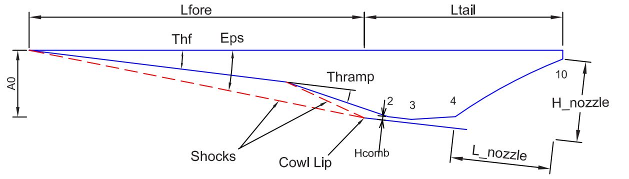

Fig. 5 Key geometric parameters in Waverider design

The wing cross-section of the waverider is defined by a third order polynomial fit through a set of geometric points in the inlet plane, which establishes a wing-curve [11]. The wing-curve extends from the engine span to the shock radius as the upper limit. The choice of these points is the subject of optimization for maximum L/D. A limitation of the conical waverider is that the usable volume is less than it could be produced by the osculating cones concept, although similar L/D values may be achievable.

3.2 Propulsion System

For hypersonic vehicles, there is a need to develop high-performance propulsion systems to satisfy the required weight and sizing constraint, operating efficiently across the speed regime from takeoff to hypersonic cruise. Propulsion is a key enabling technology in defining such vehicles. Since a SJ operates only when a supersonic stream flows through it's combustor, a TBCC-type powerplant was selected to provide thrust between brakes release and Mach 5, where smooth transition to a SJ occurs followed by an acceleration to the desired cruise Mach number. The lower aft fuselage was modified to accommodate four TRJ engine modules and the engine nozzle with flow diverters in place to shut down the air flow to the TRJ's during high-speed cruise above Mach 5.

3.2.1 Scramjet

A dual-mode SJ is designed using quasi-1D idealized cycle analysis using Shapiro's influence coefficients [12]. This determines the axial

Mach number variation assuming constant pressure combustion and an expansion ratio of 2:1 relative to the inlet height. Other assumptions include equilibrium combustion, frictionless and mass-averaged intake, frozen nozzle flow and reaction kinetics and prescribed specific heat ratios without mass addition. The SJ is a rectangular modular engine highly integrated with the lower surface and the heat release schedule is based on complete combustion.

The SJ operates during a supersonic stream and during subsonic combustor flow, a constant area section known as an isolator [13], contains the precombustion shock structure to prevent undesirable inlet interactions such as inlet unstart. Station 2 in Fig. 5 shows the inlet / combustor junction, 2-3 represents the isolator and station 4 is the combustor exit / nozzle entrance.

Both the I_{sp} and thrust (F) are calculated using stream thrust analysis with knowledge of the mass flow rate and capture area, $\dot{m}_0$, A_0 respectively and an assumption for the fuel/air ratio, f. $Isp = F/m_0/[f * g]$, where F/m_0 is the specific thrust and $g = 9.81$; the gravitational acceleration. F/m_0 is dependant on the Mach number and pressure at the nozzle exit, or station 10. These properties are obtained from the 2D nozzle analysis discussed below.

I_{sp} is the amount of thrust you get for the weight of fuel you burn, and has been introduced to describe propulsive efficiency of engine units, which generate thrust by expelling mass. It is an order of magnitude greater for airbreathers than rocket engines. Hydrogen is the preferred fuel at hypersonic Mach numbers due to its high performance yield, low molecular weight, producing high I_{sp} due to the higher heating value compared to hydrocarbon fuels and rapid ignition, reaction and combustion. HICAD could potentially incorporate different fuels by allowing the user to change the heating value. Hydrogen will, however, require a larger volume for storage due to it lower density. Combustor length is estimated using an analytical expression for the reaction time [14] (reduced compared to subsonic flow) and complete mixing must occur within this length.

3.2.2 TurboRamjet

The TRJ performance was calculated using 1D idealized cycle analysis based on the formulation by Heiser [13] that assumes no friction or heat transfer to the walls and the flow is treated as steady and compressible. The TRJ generates static thrust at takeoff and subsonic speeds by mechanically compressing the air for stable combustion of fuel. The prominent components making up an axisymmetric TRJ are illustrated in the schematic of Fig. 6.

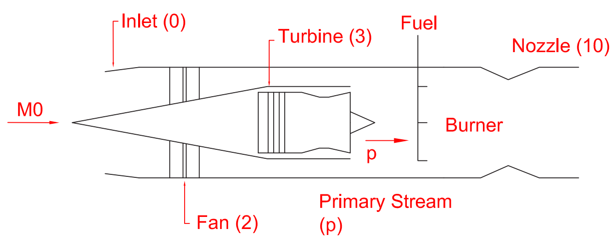

Fig. 6 Schematic of a TRJ propulsion System

A turbojet exists in the core of the TRJ producing high temperature and pressure gases and the flow is referred to as the primary stream, p; its operation being independent from the altitude. The turbines provide the power to the fan inlet, which compresses the air and the flow is treated as isentropic without losses. Complete mixing of the outer airflow and primary stream occurs at the turbine exit when additional unreacted fuel is injected as shown, before it reaches the burner and flameholders. The injection of fuel can be considered analogous to afterburning in Turbojets. The total temperature of the flow increases and expands isentropically to the freestream static pressure.

User inputs are required for the influence of the fan on the airflow, defined by the total pressure ratio, $\pi_F = p_{t3}/p_{t2}$ and the total pressure and temperature of the primary stream p_{tp}/p_0 and T_{tp}/T_0 respectively, where 0 represents freestream flow. The upper TRJ operating limit occurs when the bypass ratio (fan versus primary flow) diminishes to zero, which occurs when the product $\pi_F(p_{t0}/p_0)$ is equal to p_{tp}/p_0. At this point, the flow is entirely due to the primary flow and the device is considered to behave like a rocket. Hence, airbreathing performance measures such as F/m_0 no longer have a physical meaning. To delay the bypass ratio reaching zero, the military specification (MIL-E-5008B) for total pressure recovery is applied for supersonic Mach numbers. In addition, the diminishing pressure that accompanies flying at increasing altitudes, increases the value of p_{tp}/p_0 and T_{tp}/T_0, which has a favorable effect in achieving higher Mach numbers under TRJ power. Throughout HICAD, the 1976 Standard Atmosphere model is used and can be called at any point that takes altitude as an input and outputs static flow properties.

For a given thrust generated by the SJ, an equivalent thrust must be produced by the TRJ to ensure a continuous transition when sizing the TRJ. HICAD calculates F/m_0 between $0 \leq Mach \leq 5$ at the hypersonic cruise altitude, which determines a value for the $\dot{m}_0$ required for smooth transition at Mach 5. An inlet must be designed that incorporates variable geometry producing good total pressure recovery according to MIL-E-5008B over the Mach range from brakes release to Mach 5 transition point. The inlet should a) provide the necessary airflow for the TRJ from low subsonic to high supersonic flight conditions at all altitudes considered, (b) deliver high total pressure ratio, (c) ensure off-design conditions are fully met i.e shock-on-lip and (d) minimize losses. A four-ramp inlet system based on constant pressure jumps, the first of which is the waverider forebody, has been used and their angles can be determined using $\dot{m}_0$ data from Mattingly's off-design cycle analysis code [15]. OFFX requires a user-selected on-design Mach number, altitude, $\dot{m}_0$ and F/m_0 for the TRJ, which determines the reference area, A_{0ref} and the $\dot{m}_0$ known above is sought through iteration. OFFX can be operated from within HICAD's GUI rapidly generating thrust plots at various altitudes.

Several parameters can be adjusted within HICAD to achieve the desired result which demonstrates its flexibility. These include, number of TRJ engines, compressor pressure ratio, inlet total temperature, specific heat ratios at various engine stages and various component efficiencies. Any changes to these parameters significantly influences the performance. The reference area is constrained to not exceed the waverider forebody limits. Further details on the inlet design, air flow requirement and thrust-matching can be found in Ref. [9].

3.3 Nozzle

The nozzle flowfield is determined using the 2D method of characteristics [10] for supersonic irrotational flow assuming frozen chemistry. This method calculates a flowfield defined by a mesh composed of a characteristic line along which flow properties are continuous and the derivatives are indeterminate. An implementation of IMOC - Interactive Method of Characteristics, developed by Jacobs [16] has been integrated within HICAD to provide similar functionality from the program files. A thrust surface and lower surface geometry is specified with inflow conditions and the code calculates properties at various nodes and connects them using C-plus and C-minus characteristic lines downstream until the trailing edge is reached. The mesh is created by a series of unit processes and an example 2D mesh for a Mach 9 waverider using an implementation of IMOC is illustrated in Fig. 7. The nozzle has an entry Mach number of 2.77 and specific heat value of 1.24. The nozzle length was 19.2m for a 64m waverider and upper wall expansion angle was 19°.

The upper surface has constant total pressure flow, which enables the static pressure to be calculated.

The length and height of the nozzle, as shown on Fig. 5, are determined from the remaining length after the forebody and combustor lengths have been accounted for. The nozzle upper surface is defined by a third order polynomial and an initial and exit angle define the overall shape.

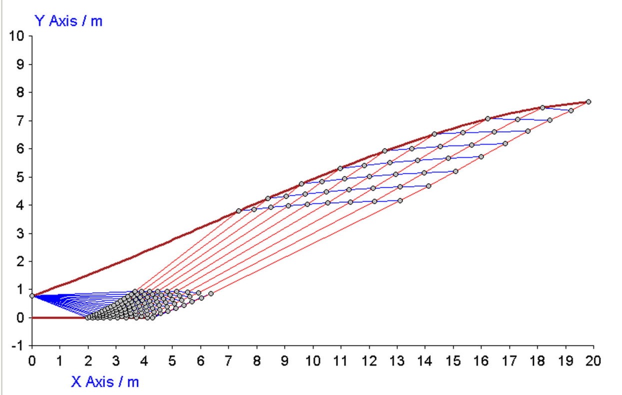

Fig. 7 Expansion net comprising nodes and characteristic lines

The combustor exit flow is treated as steady and irrotational and considered to be uniform across the span of the engine; maintained by holding a constant spanwise upper wall angle.

The initial upper wall angle is iterated until expansion occurs such that the final characteristic emanating from the lower cowl impinges on the extreme point of the upper thrust surface. This condition fixes the extension of the cowl, which is aligned parallel to the combustor exit flow, into the nozzle flowfield. Although the cowl extension could be increased producing greater thrust but also increased drag, that has not been considered in this study. This is illustrated in Fig. 7. By maximizing the expansion length and height, the greatest thrust for that geometry is produced. In addition, the angle at the exit of the nozzle can be changed to vary the trailing edge parameters. The performance of the propulsion system can be determined in terms of thrust and I_{sp}.

A second expansion fan can be produced if the cowl is canted to the local flow direction. This can increase the Mach number and pressure on the upper wall. A typical cowl chamfer angle is 6 degrees although this has not yet been considered.

4 Lift and Drag

Lower surface lift and drag are calculated using the conical flowfield solution computed earlier. The flowfield on the top surface can be taken directly from the freestream static flow quantities. Within the propulsion flowpath, flow ratios are used to compute the static pressures as for example at the combustor exit / nozzle entry boundary, which have different specific heat values. Using a control volume force accounting procedure, the thrust, drag and lift can be calculated at the nozzle exit.

The lift produced by the forebody and ramp are estimated to be equal to the negative lift produced by the cowl for the span of the SJ such that they equate to zero [4]. Therefore, the lift generating surfaces include forebody outside of the engine span, lower wing-curve surface from nose to tail, nozzle and cowl exit. The latter of which produces negative lift due to characteristics at station 4.

All viscous drag forces are included in the analysis apart from the base drag, which is ignored with the condition that the base is at freestream pressure. Assuming that the flow over the waverider is turbulent, the viscous contribution to the force is determined by Eckerts Reference temperature method [17]. The forces on each element on the surface of the vehicle are numerically integrated by using average values for the pressure and shear stress acting on the vertices of that element. A vector product determines the area and orientation of each element. The top surface merely produces skin friction drag.

The nozzle expansion surface contributes to thrust, lift and pitching moment of the vehicle.

5 Optimization

One of the most important aspects of a vehicle design of this nature is to incorporate optimization into the analysis. This can account for the non-linear interaction between aircraft components. Multidisciplinary optimization (MDO) has been shown [2] to produce significant performance benefits over non optimum concepts.

To find the optimum combination on N parameters, an objective function is required that reflects the effects of variation of each parameter. A good figure of merit for cruise-type applications is to maximize the product of I_{sp} and L/D. A range of numerical optimization methods are available but a robust and widely accepted method for severely constrained waverider optimization is the non-linear downhill simplex method by Nelder and Mead [18]. This method does not require calculation of gradients although restarting the process using converged values is recommended to ensure the solution is not contained within a local minimum.

Currently, nine parameters are used in optimization. These include the generating conical shock angle, the seven geometric wing-curve variables and the SJ and intake size in the inlet plane. Optimization for this work follows a three-step procedure 1) determination of I_{sp}, 2) wing-curve selection and 3) L/D estimation.

In addition, the streamlines produced by each point on this curve should not exceed the length of the central streamline for the span of the engine. Upper and lower limits on the selection of 7 wing-curve variables include the shock angle and corresponding cone surface respectively. The engine must be non-zero and less than the width of the waverider in the inlet plane. The conical shock was constrained between a minimum and maximum of 10° and 14° respectively. It was noted that a change in the ellipticity of the inlet curve produced a more pointed nose as the Mach number increased for L/D maximized waveriders. A large penalty value is assigned to the objective function if any of the constraints are violated.

Several variables remained fixed during optimization. The total vehicle length was kept at 60m, the cowl was parallel to the streamlines crossing the conical shock to reduce drag, a zero cowl chamfer was assumed that could potentially increase thrust. No upper surface expansion is required as the top surface is designed parallel to the freestream. The A Mach transition point was fixed at Mach 5.

For a Mach 9 baseline waverider cruising at 30km, optimization produced a maximum $L/D = 4.0$. The conical shock converged to 10.6° and the SJ resulted in a span of 5.0m. The total flow turning for the TRJ was constrained to a

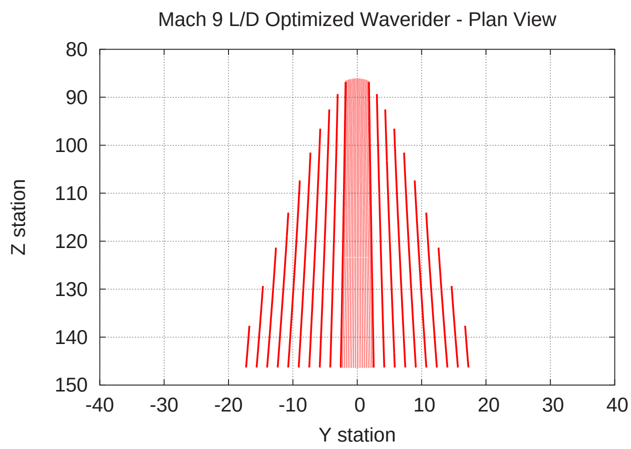

Fig. 8 Plan view of L/D maximized Mach 9 waverider

maximum of 40°. The SJ produced a thrust of $9.2 \times 10^5 N$, which was matched by the TRJ's at transition altitude and $I_{sp} = 1919s$.

6 Concluding Remarks

Part of a design methodology for the conceptual and preliminary level of hypersonic vehicle design has been outlined. A conically-derived waverider was chosen over the osculating cones concept primarily for the reduced computational resource required. Two types of engines have been addressed; a SJ for the high-speed, (hypersonic cruise segment of the mission) and TRJ's for the low-speed, (brakes release to SJ transition at Mach 5). The flowpaths of these engines can be effectively integrated onto the waverider airframe and smooth thrust transition can be achieved for safe vehicle operation. A large part of this study is concerned with multi-variable optimization used to capture the important synergy between the various components of the vehicle. The non-linear simplex method was used. This type of design is highly coupled and requires efficient airframe-powerplant integration. The emphasis for this work has been on the rapid generation of hypersonic vehicle concepts using widely accepted models and computational techniques. A vehicle with maximum $L/D = 4.0$,

$I_{sp} = 1919s$ and an engine span of 5.0m has been demonstrated as an example of the potential of HICAD. The run time was approximately 10 minutes on a 1.5 GHz processor. Optimization was shown to produce aerodynamically superior results by maximizing an objective function subject to severe tight constraints.

7 Further Work

HICAD will ultimately be extended to analyze the full synergy between aerodynamics, weights, propulsion, stability, control and packaging. A weights sizing routine that is based on empirical correlations will be integrated with HICAD. The effect of deflecting the cowl at the combustor exit will be investigated using IMOC for maximizing thrust. As always, off-design analysis is important to establish confidence in a design and this will be an area of future investigation. The osculating cones technique will be further investigated as an alternative option for possible integration with HICAD and its run time requirements and volumetric efficiency will be assessed in comparison to the current method.

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