HYPersonic AIRCRAFT CONCEPTUAL DESIGN METHODOLOGY*

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Abstract

In the development of an aircraft great importance resides in the early phase of its design (conceptual design). In this phase computer programs are commonly used in order to synthesize the most important design requirements in a preliminary configuration. These programs generally contain performances relationships, weight estimation relationships and mathematical models for aerodynamics and propulsion: all these connections are managed by means of parametrical analysis and/or optimization algorithms in order to reach a level of design useful to point out difference among configurations.

Compared with the conventional aircraft field, a conceptual design computer program for the hypersonic planes presents some peculiarities: it has to take into account several kind of performances, different weight estimation relationships, a greater complexity in modelling the aerodynamic phenomena and the propulsion, etc....

Such a computer program has been developed at our Department: it is intended in performing preliminary studies of feasibility, evaluation of technical hypotheses, comparison of alternative configurations.

The characteristics of this methodology and some different applications will be outlined in the following paper.

Introduction

In the aeronautical field the computerized methodologies for the conceptual design have great importance; in fact it is well known that the choices made in the preliminary phases of the design heavily affect the success of the future aircraft. Furthermore a simple and versatile calculation program for the aircraft conceptual design easily allows to do evaluations of capability and analysis of feasibility, whoever conceived the various hypotheses of the system.

From this point of view, we think that the University could also have the interest in developing this kind of software.

At Turin Polytechnic, under the guide of Prof. G. Gabrielli\(^1\)\(^2\), an activity was planned in order to work out some researches inherent to the conceptual design of an aircraft; this activity also continued during the years\(^3\)\(^4\)\(^5\), and now, we are trying to extend the methodology from the field of conventional aircraft to the latter and widely interesting one of the hypersonic aircraft.

In the following we will delineate the main characteristics of a simple methodology for the conceptual design of spaceplanes carried out at the Aerospace Department (DIASP) of Turin Polytechnic.

Generality about the Conceptual Design Methodology

The aim of the above-mentioned methodology is achieved if this creates schemes with a level of definition so detailed that it makes them comparable, though they are not yet feasible. Figure 1 clearly shows the inputs to the methodology, the constraints, coming from the current technological level, and above all the design requirements. In Figure 1 we can also observe that the programs for the conceptual design essentially are based on:

- equations of the flight mechanics which join the desired performances (Requirements) with the main technical characteristics of the aircraft (unknown);
- weight estimation relationships (usually derived from statistical analysis) in which the weight (unknown) of the various subsystems forming the whole aircraft is related to the aforesaid main technical characteristics of the upcoming aircraft;

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• equations for the aircraft aerodynamic characteristics estimation (included in the performance estimation relationships) in correlation with the geometrical characteristics of the aircraft, usually by an empirical way;

• equations representing the performances of the propulsion system and its specific fuel consumption in function of the Requirements.

The management of all these equations is carried out by algorithms of optimization and/or methods of parametric analysis in order to obtain the solution (sometimes more than one) of the "design theme", that is the definition of the main technical aircraft characteristics, able to meet the design requirements.

In Figure 2 the development of our conceptual design methodology is schematically showed. The Designer, considering the requirements to meet, can hypothesize several architecture of the aircraft (Single Stage To Orbit or Two Stage To Orbit, aerodynamical shape, power plant layout,...); the architectures, the design requirements and the attempt values for some technical characteristics represent the input data to the program of calculus: according to these inputs the program generates the aircraft shape complying with the requirements, its aerodynamic characteristics, its performances, the weights of the aircraft subsystems, and finally the manufacturer empty weight and the maximum take-off weight.

Purpose of the subsequent paragraph is a more detailed explanation of our conceptual design methodology.

Computer Program

The flow-chart on Figure 3 schematically shows the organization of the conceptual design methodology: it begins by demanding some pieces of information about the mission profile which could be a standard mission, recorded on a data file, or it could be defined by the Operator; in this case he introduces the mission through a series of points and settles the three coordinates: time $t$ (passed after the take-off), altitude $z$ and Mach number $M$, for each of these points. Moreover, it is possible, for the Operator, to go on a
rough optimization of the mission in order to avoid extreme accelerations $a$; if we are in the case of an orbital mission, the program shows the flight profile to the Operator and verifies the respect of the typical "flight corridor": it expresses the acceptable range of altitudes versus the Mach number.

The Figure 4 shows an example of this graphical tool by which the program allows to modify, totally or partially, the mission profile.

The following step of the program is the definition of a preliminary attempt geometry (Figure 5): it presents the following two different ways to proceed:

1. it is possible to insert several detailed geometrical data if we want to study an already defined aircraft,

2. it is possible to assign few basic geometrical values; they consist of:
   - the indication of the main aerodynamical shape (wing body, lifting body or blended body),
   - the number and the type of tail unit and control surfaces,
   - an attempt value for the wing area.

From this step the program carries out a complete definition of the aircraft geometry; it makes use of empirical/statistical relationships and checks that, at the maximum speed, the whole aircraft is contained inside the Mach cone.

Now the program goes along to the definition of the propulsion system; it is possible to choose turbojet, ramjet, scramjet and rocket propulsion or many combinations of them.

Figure 6 shows that, at the insertion of the number and kind of engines, the program completes the aircraft architecture and hypothesizes some solutions of the propulsion system layout: it normally installs the rockets inside the fuselage and the airbreathing engines in such a way to comply with a request of their air intakes and nozzles.

We point out that a connection between the frontal area of the air intakes and the engine thrust exists as
well as between the frontal area of turbojets and of ramjets when the two types of engine are joined in a combined cycle engine. At this point the aircraft geometry, even though at an attempt level, is entirely defined.

Now the program proceeds in the evaluation of the aerodynamic characteristics, particularly of the $C_{D_0} = C_{D_0}(M)$ and of $C_L = C_L(M, \alpha)$ (Figure 7). The bases of this evaluation are the classical low Mach relationships (Data Sheets, Roskam method, etc...) and some of their extrapolations, at high Mach number, including values obtained by computational fluid-dynamics or by the experiments of an aircraft with configuration similar to the wing body, blended body or lifting body.

The definition of the geometrical, aerodynamical, weight and propulsion data, even though at an attempt level, allows to do some performance verifications.

1. The first verification is on the take-off, obviously if the aircraft is a first stage or a SSTO. This step verifies if the calculated balanced field length $BFL$ is shorter than a specified take-off runway $S_{TW}$; if the condition isn't satisfied the program lets the Operator to increase the available thrust of the working engines during the take-off phase.

2. The second verification is on the feasibility of the mission profile defined by the Operator. The program can proceed on the evaluation of the necessary fuel weight (included the liquid oxygen in the case of the rockets utilization) on the basis of the flight mechanics equations and of the engines specific fuel consumption $SFC$ (Figure 8). In every phase of the mission the program calculates the necessary thrust (this value allows evaluation of the fuel consumption) and compares it with the available thrust: when the last one results insufficient or extremely higher (even if at an only point of the mission) the Operator provides with a modification of the choices on the propulsion system or on the mission profile and then the program repeats the calculations (obviously only if necessary) from the beginning. At every mission phase a check on the attitude value $\alpha$ is also performed: if it exceeds the maximum the Operator has to modify the mission profile and or the wing area $S$; then the whole procedure restarts.

It is possible, now, to proceed toward the weight evaluation of the subsystems forming

Figure 3

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the whole aircraft. Like Figure 9 shows, we have got ready a set of Weight Estimation Relationships (WER's) collected from several sources\(^9,10,11\); these equations have needed some small calibration and some of them are obtained by an original elaboration. In order to check the consistency of the WER's we have tried to apply them to some hypersonic aircraft of which we know the weight list. The WER's depend on maximum take-off weight \( W \) and on empty weight \( W_e \) of the aircraft; so as we can see in Figure 3, the fuel weight, necessary for the mission, also depends on \( W \) so the program has to iterate on the value of \( W \) till to reach the convergence, since the \( W \) is fixed at the beginning by an attempt value.

3. The third verification is about the block fuel: if the internal volume is not enough to receive the fuel necessary for the mission, the program allows the Operator to increase the aircraft dimensions and then the entire procedure begins again.

4. The last two verifications are on the landing run-away length \( L \) and on the minimum radius \( r \) of turn during the approach phase; when these conditions are not satisfied the program allows the Operator to increase the wing area \( S \), restarting the entire procedure (of course without the not necessary steps which, for simplicity do not appear in the Figure 3 flow-chart).

When all the above-mentioned verifications (Figure 10) are satisfied we can consider the aircraft synthesis finished, of course for a given aerodynamic shape and a given propulsion configuration chosen by the Operator at the beginning. If the analysis is applied to a second stage vehicle, weights and characteristics defined by the program represent the input to the conceptual design of the first stage, which will be carried on it.

**Applications**

In order to validate the above presented computer program, we have tested it performing some applications: many of them were related to studies of hypersonic planes described in technical literature. For example in Figures 11, 12, 13, and 14 some results are reported; in particular Figures 11 and 12 concern a TSTO and Figures 13 and 14 two SSTO with different power plant. The results agree the available data.
regarding studies performed by Industries. These results, and many other here not reported because of shortness reasons, allow us to think we have reached our target.

References


19. Miscellanea of industrial reports.


<table>
<thead>
<tr>
<th>Component</th>
<th>Weight estimation relationships dependence</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing</td>
<td>( W_w = W_{0w} \left( \begin{array}{c} N_w \ V_w \ f \ \ S_{wex} \ T_F \ L_w \ T_w \end{array} \right) )</td>
<td>Product of the ultimate load factor of safety and the wing limit load produced by a 2.5 g subsonic maneuver</td>
</tr>
<tr>
<td>Tail unit</td>
<td>( W_{t} = W_{0t} (S_{vt}) )</td>
<td>Weight of the vehicle at landing</td>
</tr>
<tr>
<td>Body</td>
<td>( W_b = W_{fb} (U_{gb}, V_{gb}, L_F) )</td>
<td>Wing/body load distribution factor</td>
</tr>
<tr>
<td>Fuel tank</td>
<td>( W_f = W_{ft} (V_{ex}, V_{ih}) )</td>
<td>Body planform area</td>
</tr>
<tr>
<td>Landing gear</td>
<td>( W_g = W_{lg} (U_l) )</td>
<td>Exposed wing planform area</td>
</tr>
<tr>
<td>Surface control</td>
<td>( W_{sc} = W_{sc} )</td>
<td>Exposed wing root chord maximum thickness</td>
</tr>
<tr>
<td>Thermal protection</td>
<td>( W_{tp} = W_{tp} (S_{wex}, S_{vt}) )</td>
<td>Exposed total structural wing span</td>
</tr>
<tr>
<td>Hydraulics</td>
<td>( W_h = W_{h} )</td>
<td>Body width at wing-body juncture</td>
</tr>
<tr>
<td>Electrical</td>
<td>( W_{el} = W_{el} )</td>
<td>Vertical tail planform area</td>
</tr>
<tr>
<td>Electronics</td>
<td>( W_{av} = W_{av} )</td>
<td>Aircraft flight design gross weight = VTON - 4 WFUEL</td>
</tr>
<tr>
<td>Air conditioning</td>
<td>( W_{ac} = W_{ac} )</td>
<td>VTOL = take-off max weight, WFUEL = max fuel weight</td>
</tr>
<tr>
<td>Engines</td>
<td>From available data</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 8**

**Figure 9**

<table>
<thead>
<tr>
<th>Verifications</th>
<th>Actions</th>
<th>Comparison</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Take off</td>
<td>+ ( \Delta ) Thrust</td>
<td>BFL &gt; Required take-off, runway</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mission feasibility</td>
<td>Mission and/or</td>
<td>Available thrust &lt; Necessary thrust</td>
<td>Geometry modifying</td>
<td>( \Delta ) Thrust</td>
</tr>
<tr>
<td>Fuel volume</td>
<td>Geometry modifying</td>
<td>Incidence angle &gt; Maximum incidence</td>
<td>Mission and/or</td>
<td>( \Delta ) Thrust</td>
</tr>
<tr>
<td>Landing</td>
<td>Geometry modifying</td>
<td>Available tank volume &lt; Necessary fuel volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turn radius</td>
<td>+ ( \Delta ) ( S )</td>
<td>Turn radius &gt; Required turn radius</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 10**

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AIRCRAFT IDENTIFICATION NAME: SANGER type

Is the aircraft a Single Stage (1) or a Two Stage (2) ? 2
Mach of separation between first and second stage ? 6.5

FIRST STAGE DATA INPUT
Maximum take-off weight (attempt value N) ? 2565000
Wing area (attempt value m²) ??? 850

Select one of these aircraft configurations:
1- Lifting body
2- Wing body
3- Blended wing body

How many propulsive phases are forecast ? 2
Mach number at the end of the first phase ? 2.5
Kind of propulsion working during the first phase ? TURBOJET
Mach number at the end of the second phase ? 6.5
Kind of propulsion working during the second phase ? RAMJET
Maximum thrust of the turbojet engine (N) ? 383440
Number of turboramjet engines ? 6

Body wing location: low (1) or mid (2) ? 2
Is there the horizontal tail (Y/N) ? Y
Is the vertical tail canard (1) or normal (2) ? 2
Vertical tail location: wingtip (1) on the body (2) ? 1
Vertical tail single (1) or double (2) ? 2

FLIGHT CORRIDOR
Sanger type Aircraft

SANGER TYPE MISSION
Acceleration & Ramp angle vs Mach

THRUST, DRAG vs Mach

Mach number
0 1 2 3 4 5 6 7
Thrust, Drag [kn]

Available thrust
Necessary thrust
Drag

FIRST STAGE

AIRCRAFT COMPONENTS WEIGHT LIST
Wing
Tail unit
Body
Tank
Thermal protection system
Landing gear
Surface controls
Hydraulic system
Electrical system
Avionics
Environment conditioning system
AIRFRAME WEIGHT
GENERAL SYSTEMS WEIGHT
EMPTY WEIGHT (without engines)
Engines
EMPTY WEIGHT
FUEL WEIGHT
PAYLOAD (Second stage)
TOTAL WEIGHT

OUTPUT DATA
AIRCRAFT IDENTIFICATION NAME: FIRST STAGE SANGER type
Wing leading edge sweep-back ? 60.6 deg
Wing area = 1011 m²
Airfoil thickness at wing/body junction = 1.74 m
Maximum body width = 17.0 m
Body length = 90.0 m
Body internal volume = 2451 m³
Wing internal volume = 74.0 m³
Liquid hydrogen volume = 1525 m³
Field balanced length = 1105 m
Landing length = 1311 m
Turn radius = 934 m

Figure 11: First Stage of a TSTO
Figure 12: Second Stage of a TSTO

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ARTCRAFT IDENTIFICATION NAME: STS-2000 type

1. Is the aircraft a Single Stage (1) or a Two Stage (2)? 1
2. Maximum take-off weight (attempt value) (N) = 892,800
3. Wing area (attempt value m²) = 700

Select one of these aircraft configurations:
1. Lifting body
2. Wing body
3. Blended wing body

How many propulsive phases are forecast? 3
1. Mach number at the end of the first phase = 2.6
2. Kind of propulsion working during the first phase = TURBOJET
3. Mach number at the end of the second phase = 6.6
4. Kind of propulsion working during the second phase = RAMJET
5. Mach number at the end of the third phase = 24
6. Kind of propulsion working during the third phase = ROCKET
7. Maximum thrust of the turbojet engine (N) = 490,000
8. Number of turboramjet engines = 4

Select one of these rocket installed:
1. RD-0120 ........... 1962 N of thrust
2. Vulcain .......... 1120 N
3. Interim HoJol ....... 883 N
4. Flat A/NO ........... 600 N
5. Other

Number of rockets = 4
1. Body wing location: low (1) or mid (2)? 2
2. Is there the horizontal tail (Y/N)? N
3. Is the vertical tail canted (1) or normal (2)? 2
4. Vertical tail location: wingtip (1) on the body (2)? 1
5. Payload (in Newton) = 66,000

FLIGHT CORRIDOR
STS-2000 type Aircraft

STS-2000 TYPE MISSION
Acceleration & Ramp angle vs Mach

OUTPUT DATA
ARTCRAFT IDENTIFICATION NAME: STS-2000 type
1. Wing leading edge sweep-back = 73.5°
2. Wing area = 856 m²
3. Airfoil thickness at wing/body junction = 1.08 m
4. Maximum body width = 11.3 m
5. Body length = 73 m
6. Body internal volume = 1150 m³
7. Wing internal volume = 49.6 m³
8. Liquid oxygen volume = 180 m³
9. Liquid hydrogen volume = 1070 m³
10. Payload volume = 50 m³
11. Field balanced length = 1340 m
12. Lading length = 1166 m
13. Turn radius = 1565 m

Figure 13: Turbo-Ram-Rocket SSTO
Figure 14: Rocket-Ram-Rocket SSTO