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# INTEGRATION OF AN INCREASING-FIDELITY AERODYNAMIC MODELLING APPROACH IN THE CONCEPTUAL DESIGN OF HYPERSONIC CRUISER

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**Abstract**

This paper deals with the integration of an increasing-fidelity aerodynamic modelling approach in the conceptual design of hypersonic cruiser. At this purpose, a dedicated methodology has been developed in the framework of the H2020 STRATOFLY project and applied to the STRATOFLY MR3, the Mach 8 waverider reference configuration. Considering the complexity of the concept to be analyzed at conceptual/preliminary design stage, a build-up approach has been adopted, incrementally increasing the complexity of the aerodynamic model, from the clean external configuration up to the complete configuration, including Propulsion Systems Elements and Flight Control Surfaces. In parallel to the aerodynamic analysis, detailed Mission Analyses are performed at each step, benefitting of the incremental versions of the Aerodynamic Database which are used as input. The application of the entire methodology to the reference case-study, allows to estimate design margins to be used at the different steps, to avoid unsolicited under/over-estimations of fuel mass and ranges.

**Keywords:** Aerodynamic Characterization; Aircraft Conceptual Design, Mission Analysis; Hypersonic civil transport, STRATOFLY MR3

## 1. Introduction

Hypersonic cruisers are currently considered as the far-term future of long-range civil aviation. The expected high-level performance are challenging engineers and scientists from around the world in different technological and operational areas. Despite the wide range of solutions which are emerging for these challenges, everybody agrees on the urgent need to improve the conceptual design stage, defining innovative and agile design methodologies able to capture all the most impacting design, performance and operational characteristics since the beginning of the process and implementing of multi-fidelity modelling strategies. The development of such an integrated methodology is one of the first outcome of the STRATOFLY Project, a Horizon 2020 Project funded by the European Commission in 2018. This project aims at assessing the potential of this type of high-speed civil transport to reach TRL6 by 2035, with respect to key technological, societal and economical aspects: thermal and structural integrity, low-emissions combined propulsion cycles, subsystems design and integration including smart energy management, environmental aspects impacting climate change, noise emissions and social acceptance, and economic viability accounting for safety and human factors. Future generation of high-speed civil aircraft make use of unexploited flight routes in the stratosphere, offering a solution to the presently congested flight paths while ensuring a minimum environmental impact in terms of emitted noise and green-house gasses, particularly during stratospheric cruise. In this context, the attention of the worldwide aerospace community is focusing on the development of high-speed aircraft, which will integrate these newly developed technologies to guarantee faster, safer, and more environmentally sustainable future aviation. However, to achieve this goal and thus guaranteeing top-level performance, holistic design methodologies for high-speed aircraft shall be defined. This methodology should cope with the high level of integration of the airframe and crucial on-board subsystems, with the high number of disciplines and with the presence of innovative multifunctional subsystems. Only a dedicated multi-disciplinary integrated design approach could realize this, by considering airframe architectures embedding the propulsion systems as well as meticulously integrating crucial subsystems. To implement a rapid but reliable aircraft conceptual design process, the definition of the general layout of the aircraft cannot prevent from being anticipated and supported by a detailed aircraft general performance analysis as well as from the design and sizing of the main subsystems. However, the final goal of the conceptual design phase remains the same: providing an

assessment of the feasibility of vehicle and mission concepts from both the technical and operational standpoints. Many best practices and guidelines for aircraft conceptual design are available in literature [1][2][3], suggesting typical workflows to draft a vehicle configuration and to evaluate the impact of requirements on the vehicle architecture and performance. In these processes, special attention is devoted to the identification or development of tools able to depict the design space at a glance, meeting stakeholders' expectations with design feasibility criteria [4][5][6]. For high-speed vehicles, the proper definition of the basic performance (e.g. mass, thrust and lifting surface) is crucial for the selection of a reference design point (or a region of points) to be considered as the baseline for the next development phases. It is also important to notice that nowadays, the high-speed air and space transportation systems are experiencing a revolution on the design process, which is resulting in highly innovative and integrated concepts, able to push the performance barrier beyond the limits. This is especially visible in the case of hypersonic civil transportation systems, such as the STRATOFLY MR3 concept, where the need to meet a set of challenging technical and operational requirements may impose the adoption of highly integrated waverider configurations [6][7][8][9].
In this context, this paper aims at suggesting an incremental approach towards the integration of increasing-fidelity aerodynamic modelling techniques within an agile design methodology, including vehicle and systems design activities as well as mission analyses. The integrated design methodology developed in the framework of the H2020 STRATOFLY Project, is reported in Fig. 1. To manage the conceptual design of highly integrated waverider configurations for hypersonic civil aircraft, the authors suggest proceeding through an incremental path, in which each step brings together multidisciplinary analyses at the same level of details. The mission analysis, traditionally considered as a final concept validation is here assured of a discipline role, allowing for more accurate estimation of nominal ranges, fuel mass, fuel reserves, external heat loads, etc…
Therefore, mirroring the integrated design methodology reported in Figure 1, the paper consists of three main sections, one per each design iteration. Throughout the paper, the development and refinement of the STRATOFLY MR3 Mach 8 cruiser is adopted as common example.

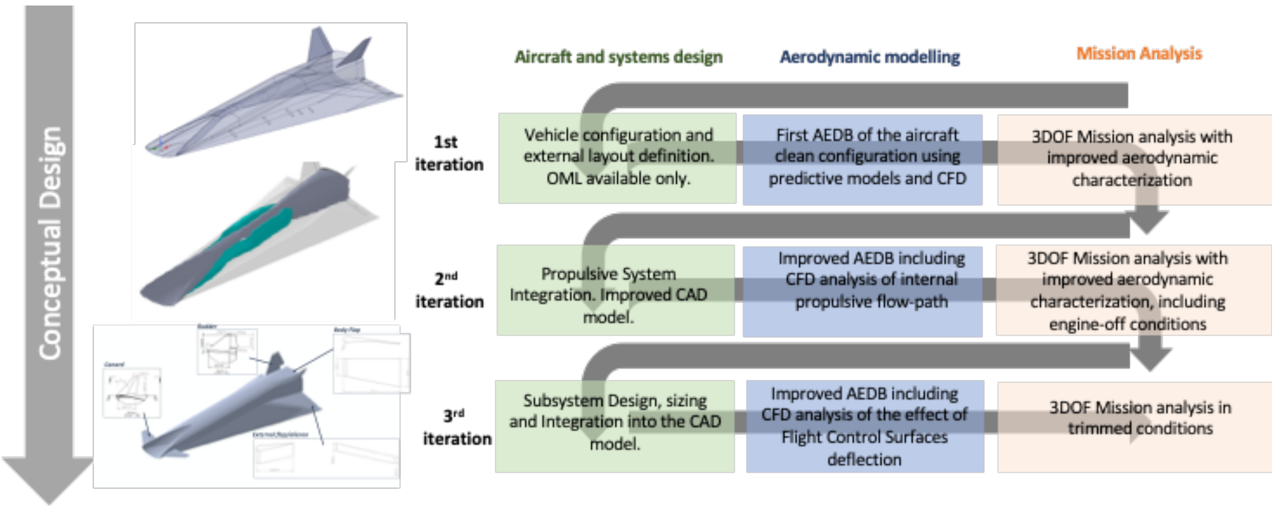



*Figure 1 - Integrated Conceptual Design Methodology*

After this short introduction, Sections II, III and IV describe each single step of the methodology, directly showing the implementation to the STRATOFLY MR3 vehicle and mission concept. However, it is important mentioning that the iterations reported in Figure 1 are usually forerun by an initial step 0 iterative design, that is usually characterized by the elicitation of the high-level requirements and the estimation of the most important performance and geometrical characteristics of the aircraft together with the identification of a reference mission profile. At this stage, the unavailability of CAD models with an adequate level of detail prevents the aerodynamic characterization of the vehicle through CFD codes. Complementary, it is worth noting that the complexity of the high-speed vehicle configurations hampers the exploitation of purely statistical approaches for the aero-propulsive characterization. Therefore, simple but quite accurate engineering tools have been recently developed to predict the aerodynamic and propulsive performance of a new vehicle design on the basis of a limited set of input data. These engineering tools are able to provide the mission analysis routine with a simple aerodynamic characterization of the aircraft in all speed regimes to allow for a first 3-degree-of-freedom mission analysis. Considering the poor dataset and the low-fidelity aerodynamic modelling, adequate margin policy shall be adopted. Section II starts from the following step, when a preliminary CAD model is becoming available, together with a quite accurate description of the vehicle external layout. This allows for a better aerodynamic characterization of the vehicle, thanks to the possibility of exploiting more complex engineering tools and preliminary CFD analysis. These set of analyses enables the generation of a first Aerodynamic Database (AEDB). At this stage, the AEDB is only representative of the so called "clean configuration", but it is fundamental because it contains the characterization of the aircraft aerodynamic performance throughout the mission.

One of the major limits of the analyses carried out in the first step of this methodology consists in the fact that they do not consider the high-level of integration which characterizes these types of vehicles. For hypersonic cruisers such as STRATOFLY MR3, it is crucial to estimate the impact of the integrated propulsive subsystem since the beginning. As it is extensively reported in Section III, the sizing of the low and high-speed propulsive ducts and their integration into the CAD model, allows for a crucial update of the AEDB. From the mission analysis standpoint, this second iteration is fundamental to properly simulate the aircraft behaviour when the engine is switched-off, which usually happens during the gliding descent phase towards the landing airport. However, this is not sufficient yet to perform a reliable 3-degree-of-freedom mission analysis. To achieve this goal, it is fundamental to move to the last conceptual design loop, when details on the most important subsystems become available, as the Flight Control Subsystem. Following a build-up approach, the AEDB is improved with the additional contributions coming from the deflection of the control surfaces. Complementary, the integration of all the major subsystems into the CAD model allows for a proper weight and balance characterization which, together with the complete AEDB, allows to carry out a first static stability analysis. This analysis allows for the identification of stability and trim maps which are essential to complete a reliable mission analysis.

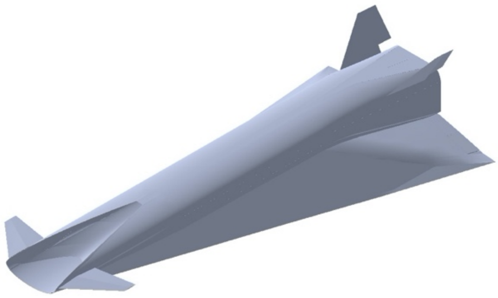
The integrated design methodology presented in this paper and validated during the H2020 STRATOFLY Project, is considered crucial and enabling for a wide range of high-speed vehicle design. In addition, it is worth noting that the methodology validation with the STRATOFLY MR3 vehicle configuration allows for the upgrades of aerodynamic predictive models specifically tailored for highly integrated waverider configurations together with the improvement of design margin philosophy. These results can be considered as an important step forward for the scientific community, allowing for very fast and reliable conceptual design phases of future high-speed civil transportation systems.

## 2. 1st Iteration: external aerodynamic characterization by means of corrected Inviscid CFD

### 2.1 Aircraft and System Design: STRATOFLY MR3 external configuration

STRATOFLY MR3 vehicle is the result of the research activities carried out by several international partners in the framework of the Horizon 2020 STRATOFLY Project funded by the EC since June 2018. Benefitting of the heritage of past European funded projects and of the LAPCAT II project led by ESA [1], the waverider configuration has been adopted and in-depth investigated throughout all flight phases. STARTOFLY MR3 is a highly integrated system, where propulsion, aerothermodynamics, structures, and on-board subsystems are strictly interrelated to one another, as highlighted in Figure 2.

STRATOFLY MR3 design is driven by its peculiar mission concept, which can be summarized as follows: STRATOFLY MR3 shall be able to fly along long-haul routes reaching Mach 8 during the cruise phase at a stratospheric altitude (h > 30000 m), carrying 300 passengers as payload. Figure 2 shows STRATOFLY MR3 external configuration. STRATOFLY MR3 has a waverider configuration with the engines and related air duct embedded into the airframe and located at the top. The integration of the propulsive system at the top of the vehicle guarantees different advantages. First, the available planform for lift generation is increased without additional drag penalties, thus increasing the aerodynamic efficiency. Then, the internal volume is also optimized. Furthermore, this layout guarantees to expand the jet to a large exit nozzle area, without the need to perturb the external shape, which would lead to extra pressure drag. However, it is important to notice that Figure 2 represents an already well-shaped and defined layout. Most probably, at the beginning of the conceptual design process, when only the major geometrical and performance characteristics have been defined, a CAD model is not available or sufficiently detailed to undergo a first set of CFD analyses. Presumably, only sketches and a preliminary limited dataset are available. This means that in the very preliminary phases of the design, semi-empirical analytical formulations are used both for the aerodynamic characterization of the vehicle, as well as for the mass breakdown and main mission performance predictions [6][9].



| Parameter | Value | Unit of Measure |
|---|---|---|
| Length | 94 | $m$ |
| Wingspan | 41 | $m$ |
| Wing surface | 1365 | $m^2$ |
| Aspect ratio | ~1 | - |

*Figure 2 – STRATOFLY MR3 external layout and main dimensions*

## 2.2 Aerodynamic Modelling

Considering that the external vehicle layout has already been clearly defined, numerical aerodynamic modelling can be performed. At this stage, the aerodynamic modelling consists in the investigation of the clean configuration, which encompasses the external vehicle layout, the empennages and relative undeflected control surfaces. In this case, a compromise between accuracy of the numerical models and available resources (manpower, computational resources and available budget) should be found. Based on the experience gained in the H2020 STRATOFLY project, the authors suggest performing inviscid CFD simulations on half vehicle configuration and then applying viscous effects corrections. These corrections can be estimated through engineering formulations, which are widely available in literature. However, for the STRATOFLY MR3 configuration, the viscous corrective factors have been improved with respect to literature, to better cope with waverider configurations. As far as the inviscid CFD is concerned, a Eulerian unstructured grid of about one million of cells (half configuration) has been generated by means of ICEMCFD-TETRA grid generator (Figure 3). The number of cells has been selected to guarantee a good compromise between calculations time and accuracy. It is important noticing that Supersonic/Hypersonic Panels Method (Surface Impact Method tool), based on classical Modified-Newtonian, Tangent-Wedge and Shock-Expansion Theories are widely used in these preliminary design stages. Even if these theories and tools provide a valuable support for the aerodynamic characterization of high-speed vehicles throughout the supersonic and hypersonic speed regimes, they cannot be used to predict the behaviour of such vehicles along the transonic and subsonic phases. Therefore, inviscid CFD simulations have been preferred and main results are reported in Figure 4Figure 3.

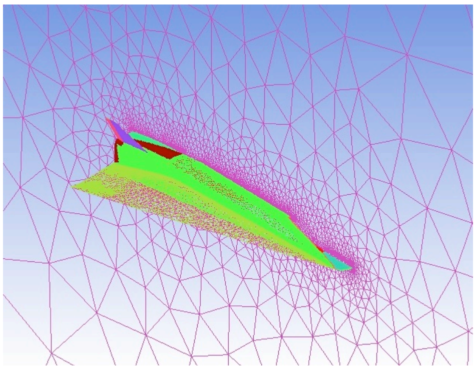
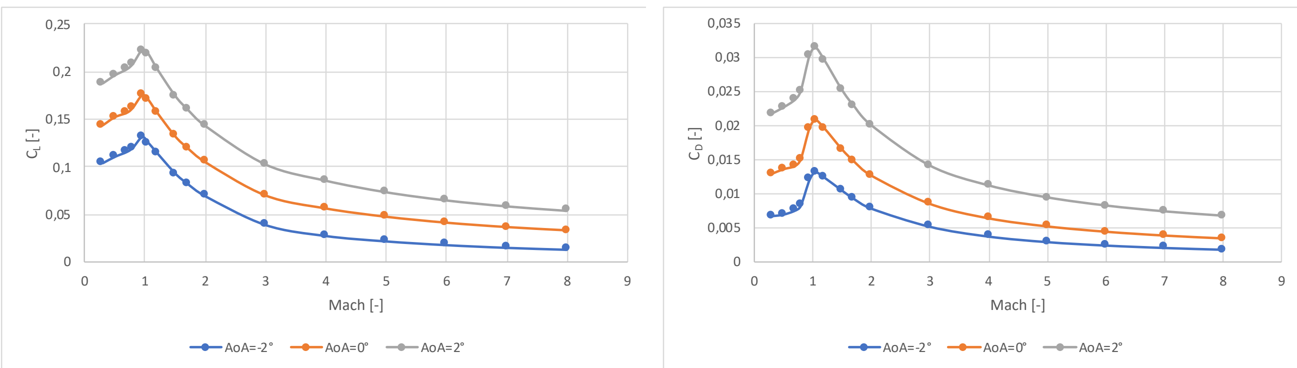


*Figure 3 – Inviscid Grid. Half body and symmetry plane. Cells = 1M*




(a) (b)

*Figure 4 – Lift (a) and Drag (b) coefficients for the External Clean Configuration from inviscid CFD*

As previously suggested, it is important to correct the results obtained from the inviscid CFD with viscous corrections. Engineering formulations are widely available in literature ([10][11][12]) and can be generalized as it follows:

$$(\Delta C_D)_{visc_{ext}} = \alpha * \frac{1}{[Log(Re)]^{2.58}} * \frac{1}{(1+\beta * M^2)^{\gamma}} * \frac{A_{wet}}{A_{ref}}, \quad (1)$$

The parametric formulation reported in Eq. (1) allows for the estimation of the viscous effect by correcting the turbulent flat plate theory (represented by the term $\frac{1}{[Log(Re)]^{2.58}}$, see [10]) with (i) the factor $\frac{1}{(1+\beta * M^2)^{\gamma}}$ which takes into account the compressibility effect [11], (ii) the wetted and the reference areas ratio and (iii) the parameter $\alpha$ which shall be customized depending on the vehicle configuration. It should also be noticed that the discrepancy between the two methods is expected to increase for higher angles of attack. In the original formulation which was used to support the Space Ship 2 Aerodynamic Characterization [12], the values suggested for these parameters are as follows: $\alpha = 0.455$ $\beta$=0.144 and $\gamma = 0.65$. However, in order to better cope with waverider configurations like STRATOFLY MR3, the authors suggest using $\alpha = 0.43, \beta = 0.31$ and $\gamma = 0.37$. It is worth noting that these modified parameters have been defined thanks to a dedicated viscous CFD simulation campaign.
The comparison between the inviscid and viscous drag coefficient is reported in Figure 5, for different Mach numbers.

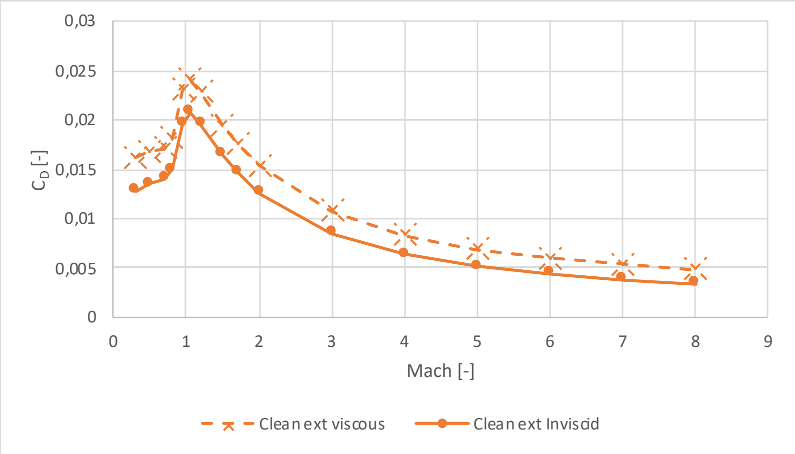



*Figure 5 – Drag coefficients for the External Clean Configuration. Comparison between inviscid CFD results and viscous correction*

## 2.3 Mission Analysis

Thanks to the results reported into the previous subsection, a first mission simulation can be run, thanks to the support of in-house developed or commercial tools, such as ASTOS. The possibility to exploit a preliminary Aero-database which includes the effect of Mach numbers and angle of attack guarantees a more accurate prediction of the vehicle performance throughout the mission. Consequently, the availability of a preliminary Aero-database allows for a more accurate estimation of fuel masses, flight time and flight distances. The results obtained for the STRATOFLY MR3 vehicle clean configuration are reported in the following Figures. In Figure 6, altitude and Mach profiles are reported in function of the mission time (which is of about 3 hours). The Lift to Drag ratio is shown in Figure 7. In Figure 8Figure 7, the Mach number is also reported as a function of the distance flown. Please, consider that at this stage, the mission simulation is rather focused on the verification of the vehicle take-off mass (in this case 400 t), the fuel mass (180 t) and the cruise aerodynamic efficiency (close to 7 as from theoretical predictions). Therefore, the hypersonic cruise is terminated when the overall fuel mass is depleted (see Figure 9), and the descent phase is assumed unpowered. According to this first mission analysis, STRATOFLY MR3 vehicle is able to meet its initial set of requirements, being able to complete a 18904 km flight (Brussels to Sydney route) in 3 hour time.

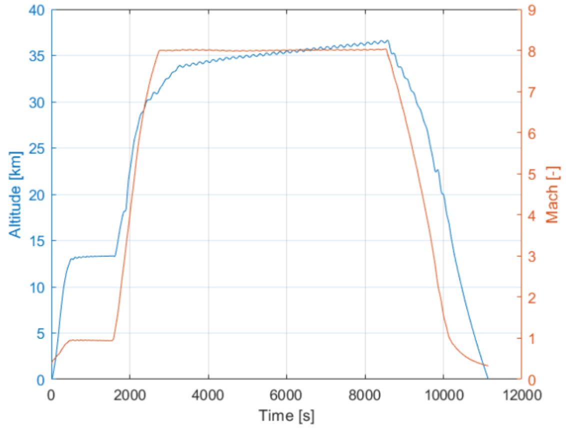



*Figure 6 - Altitude and Mach vs Time profile for clean external configuration*

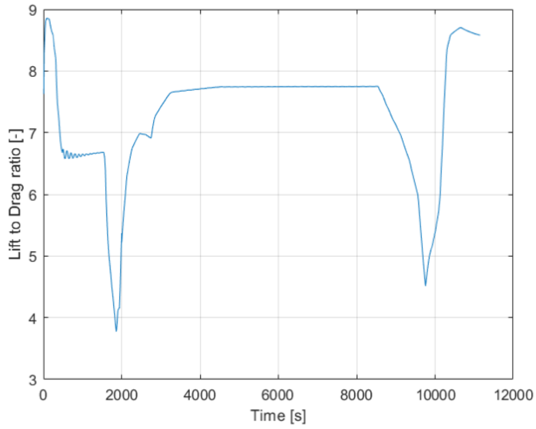



*Figure 7 - L/D vs Time profile for clean external configuration*

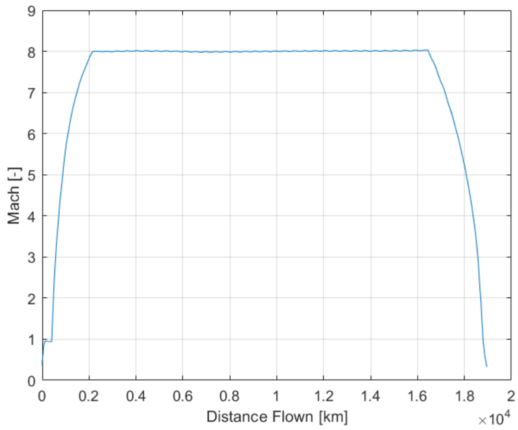



*Figure 8 – Mach number vs Distance flown for clean external configuration*

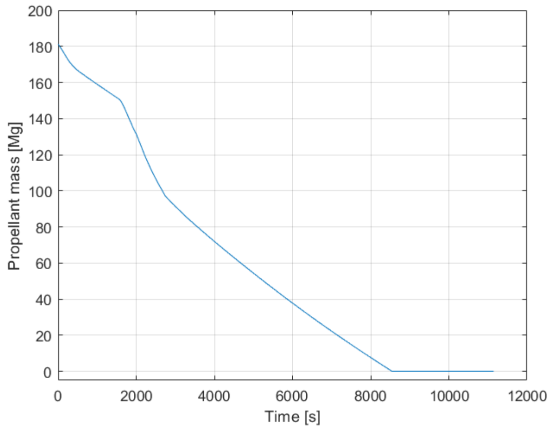



*Figure 9– Propellant mass vs Time for clean external configuration*

However, as it is clarified in the following sections, these results cannot be used to validate either the vehicle or the mission concepts, because additional and more detailed investigations shall be carried out. Considering the highly integrated vehicle layout and the bulky internal flow-path, it is fundamental to estimate its impact into the aerodynamic characterization. As it is clearly reported into the next section, the integration of the propulsive flow-path clearly affects the aero database and consequently the mission analysis.

## 3. 2nd Iteration: complete aerodynamic characterization, including the integrated propulsive flowpath

### 3.1 Aircraft and System Design: STRATOFLY MR3 integrated propulsive flowpath

Figure 10 shows the details of the integrated propulsive flowpath, which runs through the entire propulsive duct. Indeed, during the first part of the mission, STRATOFLY MR3 uses the Air Tubo-Rocket engines (ATR). The air turbo–rocket is a particular case of turbine–based combined cycles cycle engines, which brings together elements of the turbojet and rocket motors and provides a unique set of performance characteristics. This engine offers a high thrust–to–weight ratio and specific thrust over a wide range of speed and altitude, constituting an excellent choice as an accelerator engine up to high–supersonic speeds. However, when approaching Mach 4.5, the ATRs are no more able to sustain the vehicle and the DMR is activated to accelerate it up to Mach=8. Dual Mode Ramjet engine (DMR) is the high-speed engine which can be operated in both ramjet and scramjet modes. To improve the overall vehicle efficiency, the 6 ATR engines and the single DMR have been integrated inside the vehicle. However, considering the huge propulsive ducts, it is important to include the evaluation of the internal flowpath contribution to the overall vehicle aerodynamic performance.

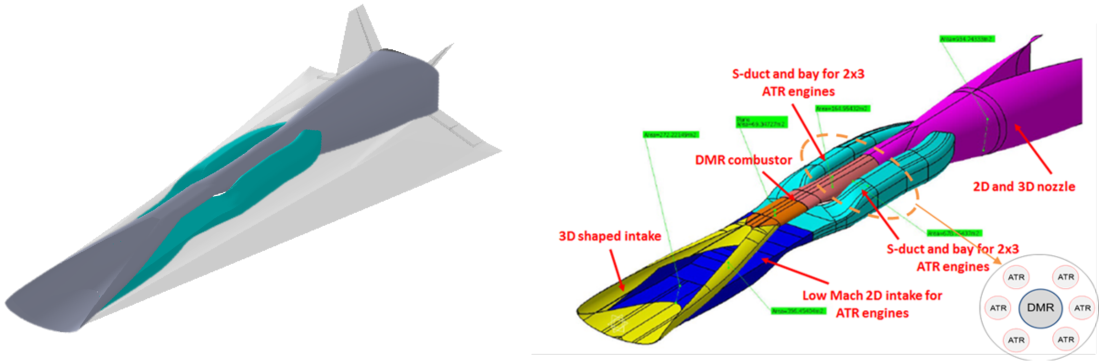
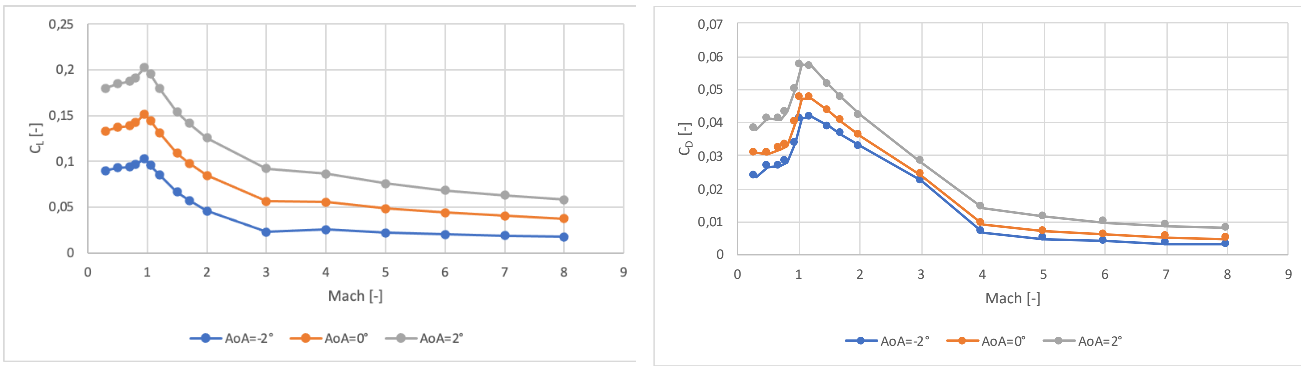



*Figure 10 – Integrated ATR and DMR propulsive flowpath*

## 3.2 Aerodynamic Modelling of the internal propulsive flow-path

Once the details of the propulsive flow-path have been disclosed, a new set of aerodynamic investigations have been carried out following the same approach reported into the previous section. Also in this case, the results of the inviscid CFD (see Figure 11) have been complemented with viscous corrections.




(a) (b)

*Figure 11 – Lift (a) and Drag (b) coefficients for the External Clean Configuration at different angles of attack*

However, the viscous correction formulation for the external vehicle surface (reported into the previous section) is not immediately applicable to the internal flow-path. In this case, the authors derived a new semi-empirical correlation which is graphically reported in Figure 12. A comparison between the inviscid and viscous total drag coefficient is reported in Figure 13. As it is clearly visible from Figure 14, the application of this new viscous correction shows that the flow-path substantially contributes to the overall aerodynamic forces, especially in subsonic, transonic and low supersonic speed regimes, in terms of additional drag and down-lift both mainly due to the intake.

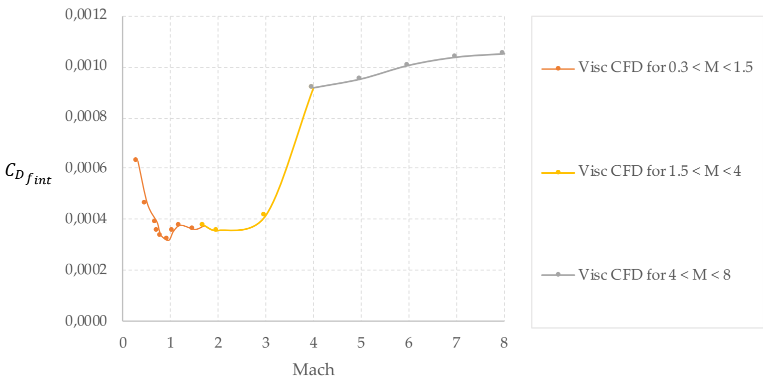



*Figure 12 – Semi-empirical correlation to evaluate internal viscous flow-path correction*

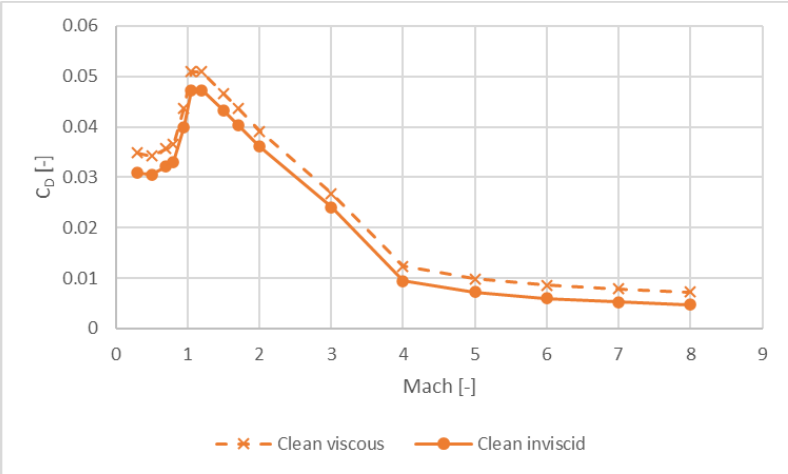



*Figure 13 – Comparison between inviscid and viscous drag coefficient for the external + internal configuration*

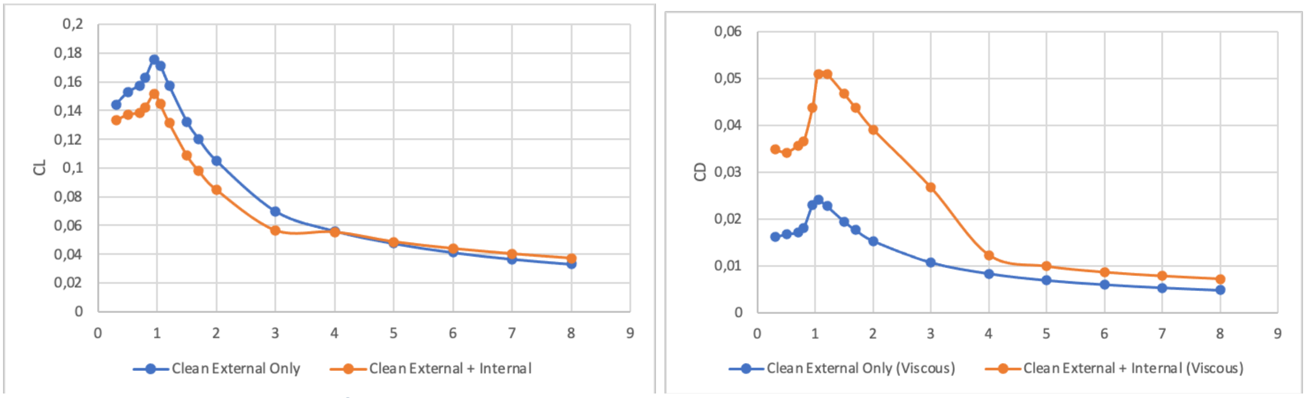



*Figure 14 – Comparison between external only and external + internal contributions*

## 3.3 Mission Analysis

During the second iteration, the contribution of the internal flow-path is included and integrated onto the AEDB. Since the internal duct is open when the engines are not active, this allows for a more realistic evaluation of the engine-off conditions. The internal flow highly affects the overall aerodynamic performances of the vehicle. A further simulation is run to evaluate the effect on the mission and on the maximum distance flown. The ascent and cruise phase are not affected by these changes in the AEDB, while the last part of the mission is quite different with respect to the previous case. The open internal duct highly affects the vehicle performance and the rate of descent becomes higher. The comparison between the resulting Mach profiles and the ones of the previous simulation is reported in Figure 15 and Figure 16. Because of the reduced aerodynamic efficiency (Figure 17) during the descent phase, the distance flown is decreasing. The overall distance is now reduced to 18244 km, which is not sufficient to reach Sydney from Brussels. However, this range still allows to cover long-range routes.

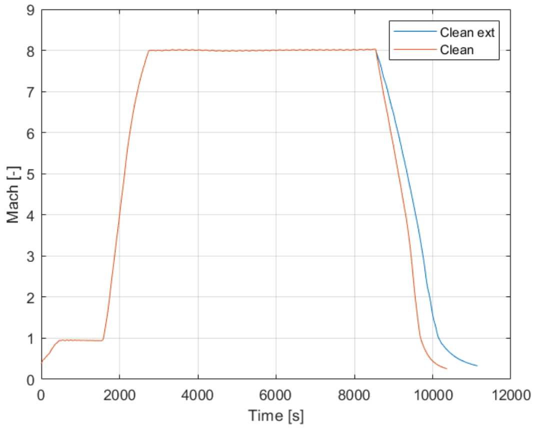



*Figure 15 – Mach vs Time comparison for external only and external + internal clean configuration*

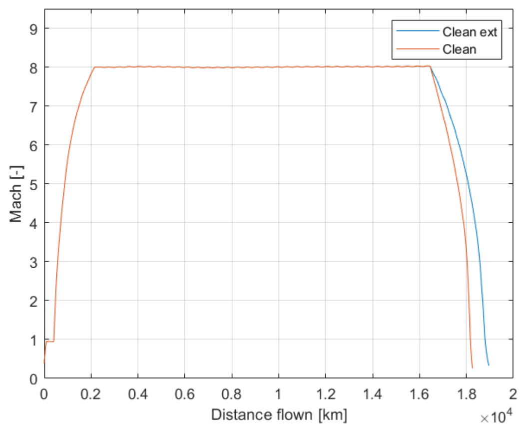



*Figure 16 – Mach vs Distance flown comparison for external only and external + internal clean configuration*

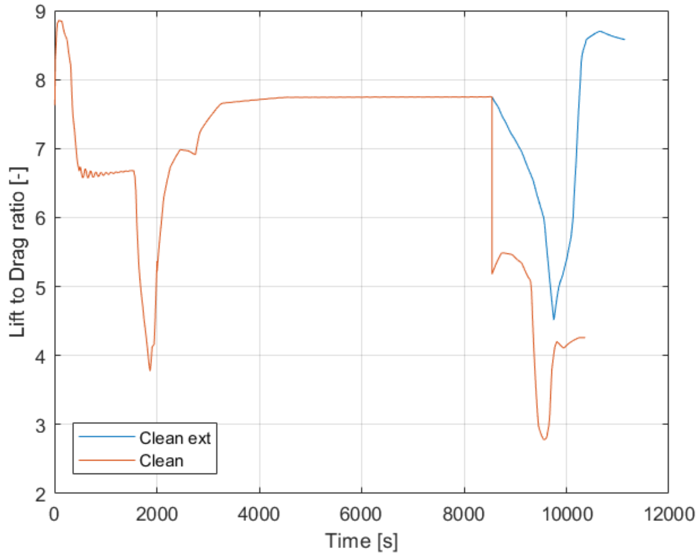



*Figure 17 – Lift to Drag comparison between external only and external + internal clean configuration*

## 4. 3rd Iteration: Flight Control Surfaces (FCS) and trim analysis

### 4.1 Aircraft and System Design

Once the main vehicle design has been assessed, the Flight Control Surfaces have been properly designed through several iterations, involving both design and sizing activities as well as preliminary aerodynamic investigations. Figure 18 shows the most recent Flight Control Surfaces configuration which encompasses a canard at the front of the vehicle, two pairs of flap/aileron on the wing surface, two body flaps on top of the rear fuselage and two rudders on the fins.

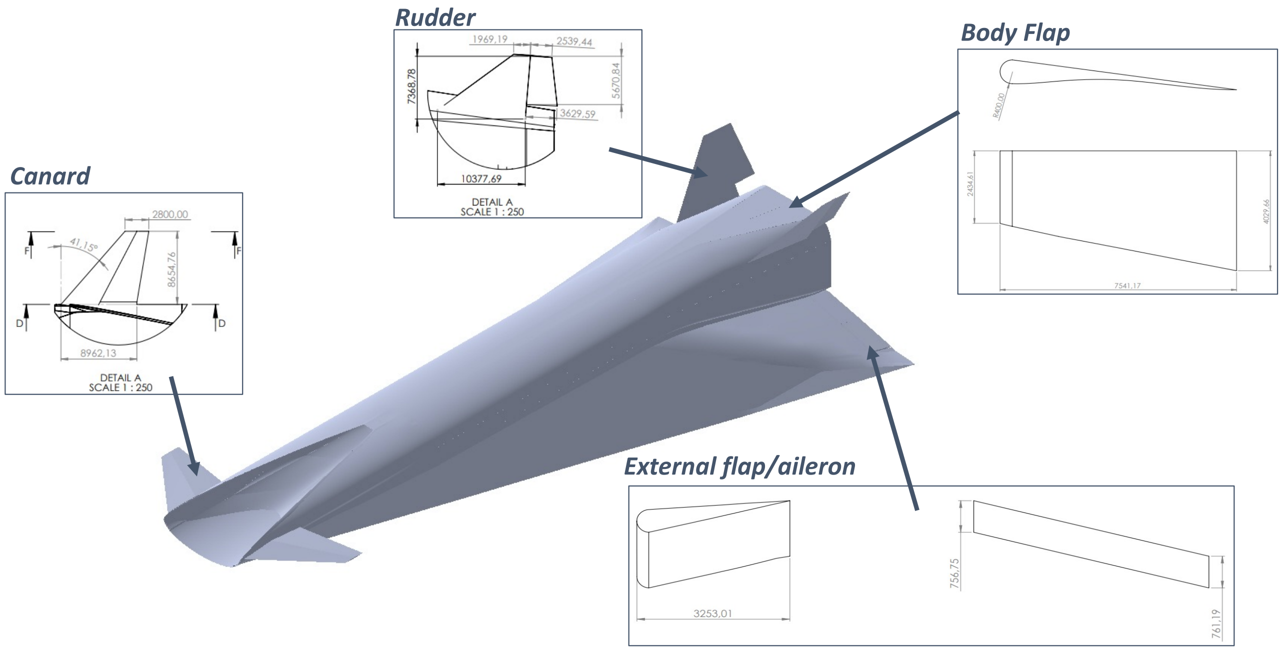
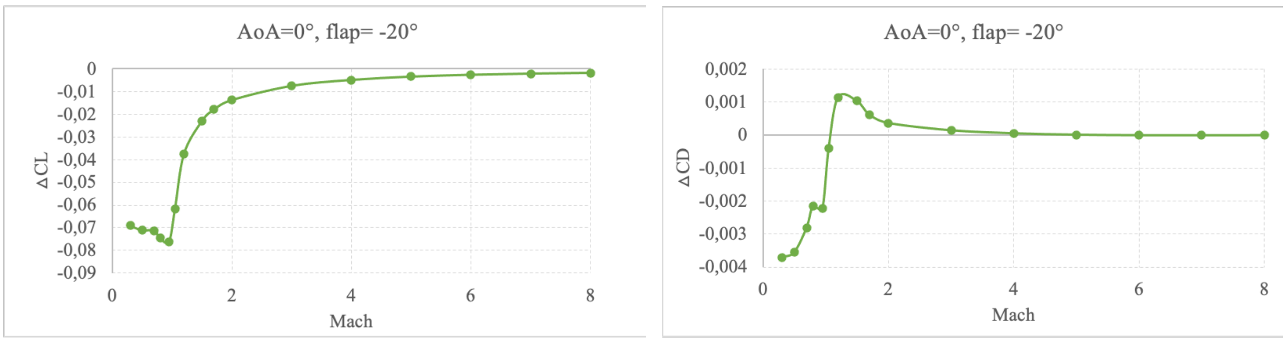



*Figure 18 – Flight Control Surfaces*

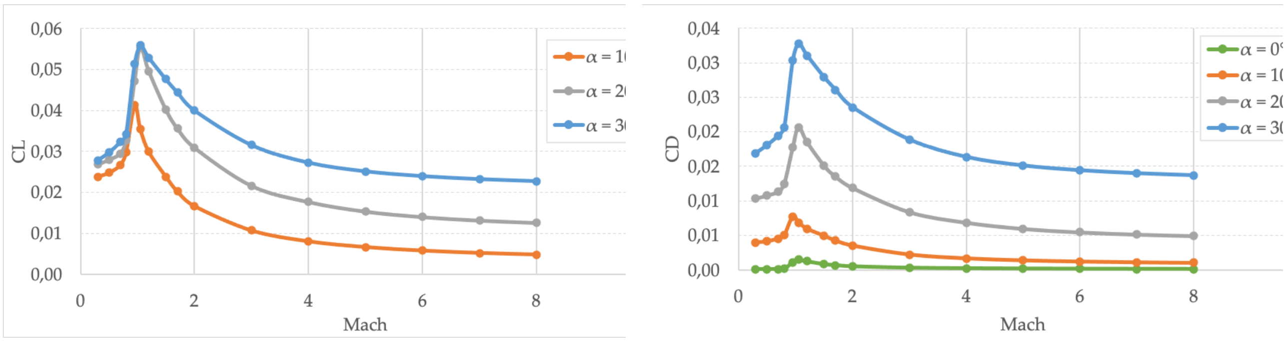
## 4.2 Aerodynamic Modelling

The effect of control surfaces is considered through a simplified approach (inviscid calculations) and simplified configuration selecting only the parts of the vehicle of interest. For example, for the effect of flaps, a wing-flap configuration is used. For the canard, which are place at the front of the vehicle, a stand-alone one is sufficient. As far as the body-flap is concerned, a more complex configuration has been generated, accounting for both the rear part of the fuselage and the vertical tail. Viscous corrections are not considered since the delta values (with respect to the clean configuration) are used. The resulting lift and drag coefficient due to the deflection of the control surfaces are reported in Figure 19, Figure 20 - $\Delta C_L$ (a) and $\Delta C_D$ (b) due to the canard effect at several angle of attack and Figure 22.



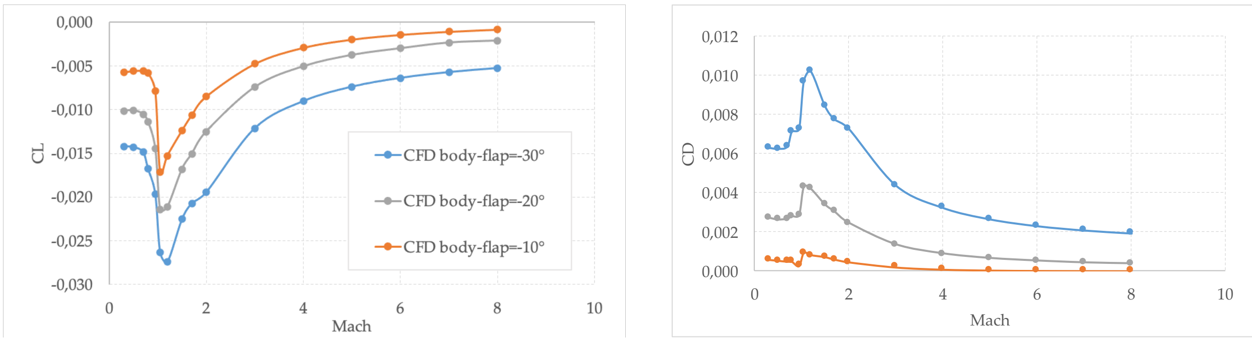

(a) (b)

Figure 19 - $\Delta C_L$ (a) and $\Delta C_D$ (b) due to the flap effect at AoA=0° and flap=-20°.




(a) (b)

Figure 20 - $\Delta C_L$ (a) and $\Delta C_D$ (b) due to the canard effect at several angle of attack




(a) (b)

*Figure 21* - $\Delta C_L$ (a) and $\Delta C_D$ (b) due to the body-flap effect at several deflections

## 4.3 Mission Analysis

During this last iteration, the AEDB is completed with the additional contribution of the flight control surfaces, namely the canards, flaps and bodyflap. Then, the most updated AEDB is used to perform the longitudinal static stability and trim analysis. This analysis cannot be performed in ASTOS while computing the trajectory. For that reason, a Matlab script is created to evaluate the complete set of stable and trimmed conditions for the STRATOFLY MR3 vehicle. The detailed CAD model is used to evaluate the shift of the CoG position throughout the mission (Figure 22). Then, the trim conditions can be evaluated for a given CoG position at each Mach number. The use of the trimmed AEDB is crucial to better asses the vehicle performance during the entire mission. There is an important impact on the mission analysis, mainly due to the reduced aerodynamic efficiency for the entire Mach range. The aerodynamic efficiency reaches the maximum value of 7, during cruise conditions at Mach=8. However, the Lift to Drag ratio is very low at supersonic Mach numbers, as can be seen in Figure 23. A further analysis is carried on, to understand if a relaxation of the trim conditions in supersonic flight can lead to some improvements in aerodynamic performance. For that reason, the trim conditions are evaluated again from Mach 0.95 to 3, allowing for static instability in this range. Since this guarantees an increase in aerodynamic efficiency, the final AEDB is built considering the unstable conditions from Mach 0.95 to 3 and the stable conditions for all the other Mach numbers, and then used to perform the mission simulation.

The Lift to Drag ratio for engine-off is reported in Figure 24 . As expected, the aerodynamic efficiency decreases with respect to the engine-on case.

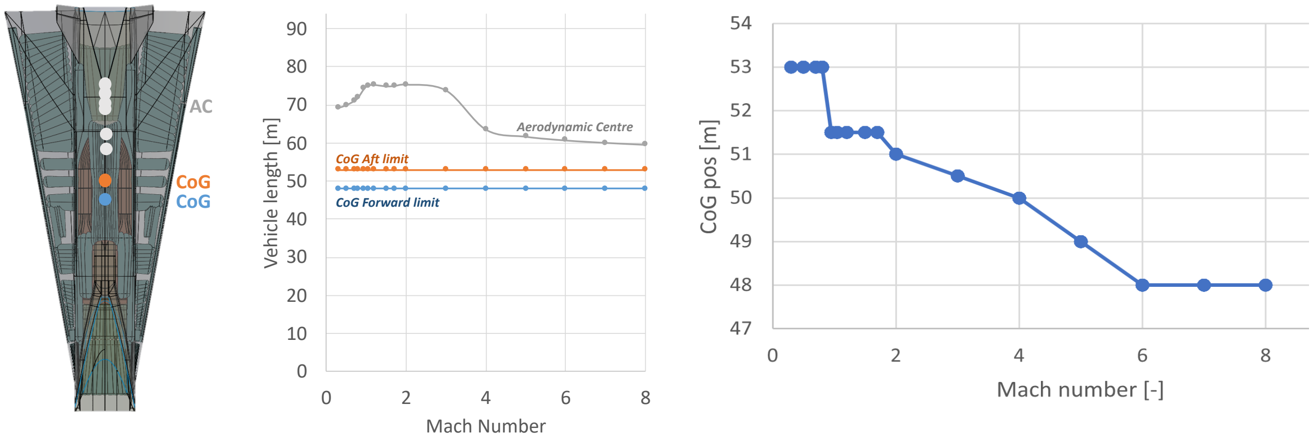



*Figure 22 – Aerodynamic Centre and CoG location throughout the mission*

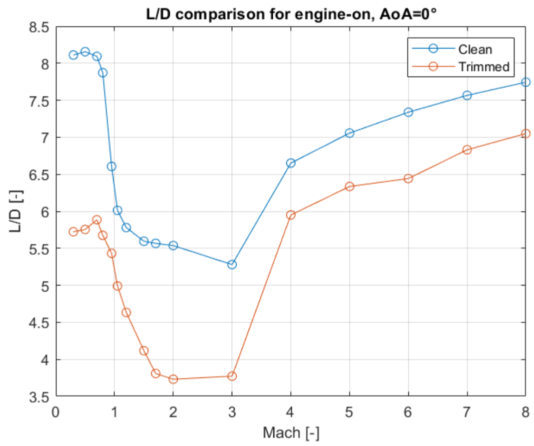



Figure 23 - Lift to Drag comparison between clean and trimmed configurations in engine-on conditions

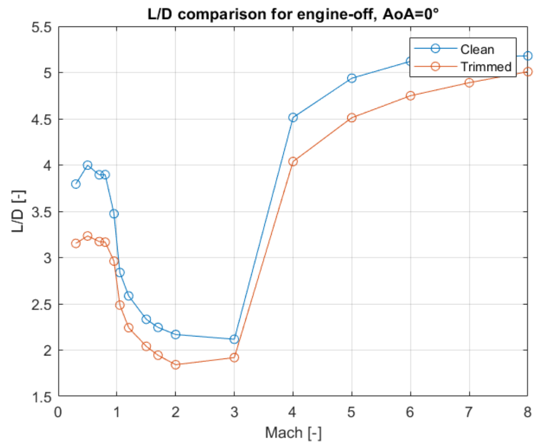



Figure 24 - Lift to Drag comparison between clean and trimmed configurations in engine-off conditions

Eventually, the mission simulation can be run considering the complete version of the AEDB. The resulting Mach profiles are reported in Figure 25 and Figure 26, and compared to the clean configuration results. The reduced aerodynamic performance negatively affects the entire supersonic and hypersonic climb phase. The time needed to reach the cruise conditions at Mach 8 is increasing from approximately 2750 s (clean configuration) to 3650 s (trimmed configuration). Therefore, the fuel consumption is also increasing during the mission as can be seen in Figure 27 and Figure 28. As expected, the maximum distance that the vehicle can cover is reduced to 14039 km and prevent the STRATOFLY vehicle to complete the BRU-SYD route.

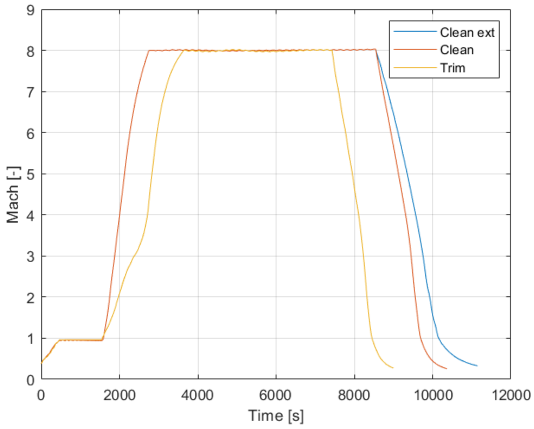



*Figure 25 – Mach vs Time comparison for Trim and Clean configurations*

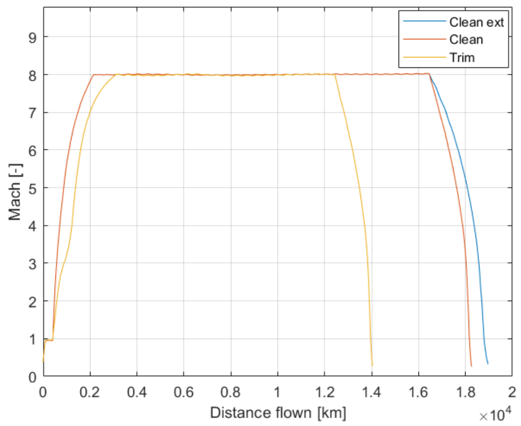



*Figure 26– Mach vs Distance Flown comparison for Trim and Clean configurations*

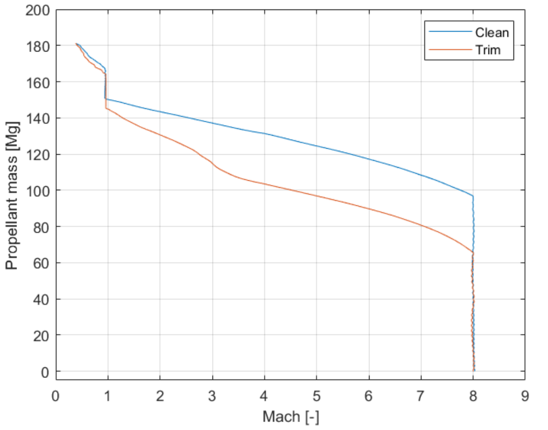



*Figure 27 – Propellant mass vs Mach number comparison between Clean and Trimmed configuration*

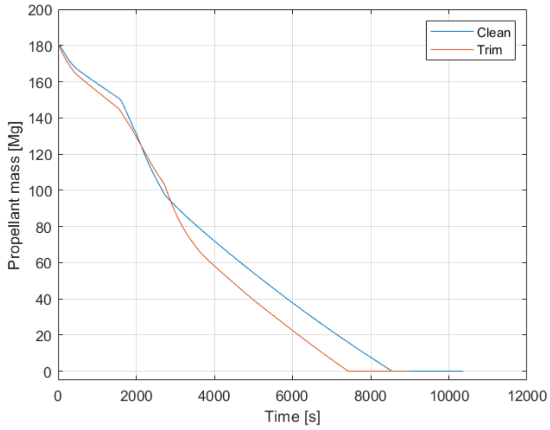



*Figure 28 – Propellant mass vs Time comparison between Clean and Trimmed configuration*

## 5. Results Analysis

The different level of accuracy considered for each iteration, resulted in a more reliable evaluation of the vehicle performance. The main focus is placed on the maximum distance which the vehicle can cover during the mission. A summary of these outcomes is reported in Table 1, where the third column contains the error obtained in computing the distance with respect to the most reliable results available.

*Table 1 - Mission analysis results at each iteration*

| Iteration | Distance Flown [km] | Margin |
|---:|---:|---:|
| 1 | 18958 | +35 % |
| 2 | 18261 | +30 % |
| 3 | 14039 | +0 % |

It is clear that the contribution of the deflected control surfaces is extremely important for the STRATOFLY vehicle, since it highly affects the overall mission, limiting the capability to cover distances above 14 000 km (i.e., antipodal routes). The estimation of the maximum distance flown can be as high as the 30% of the actual value, if the effect of the deflected control surfaces is not considered.

Eventually, a possible reference route, which copes with the distance limitations for the STRATOFLY vehicle, has been identified: the Brussels to Tokyo Narita (BRU-NRT) mission. An example of the mission trajectory is reported in Figure 29, where the line is coloured by Mach number. It is worth noticing that the entire mission occurs over water, in order to avoid that the vehicle could fly over populated areas at Mach greater than one.

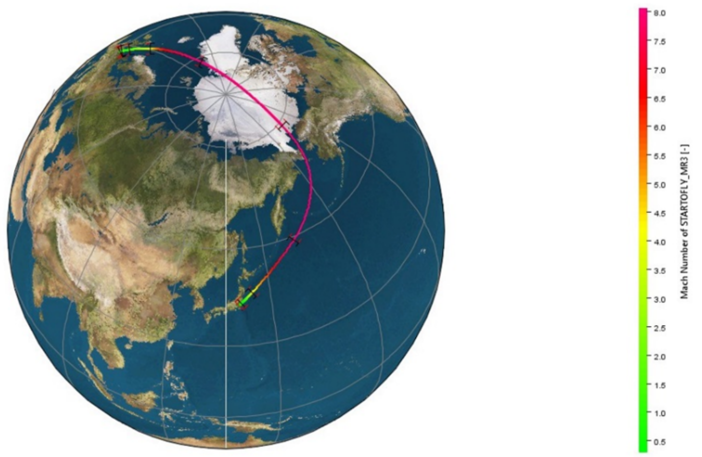



*Figure 29 – Overview of the Brussels to Sydney mission*

The resulting altitude and Mach profiles are reported in Figure 30. Figure 31 shows the Mach profile versus the distance flown during the mission. The final distance is equal to 12 245 km, a value which is lower than the maximum 14 039 km found before. This means that the mission can be accomplished with the initial fuel on-board and the residual fuel mass is equal to 10.45 Mg, as reported in Figure 32.

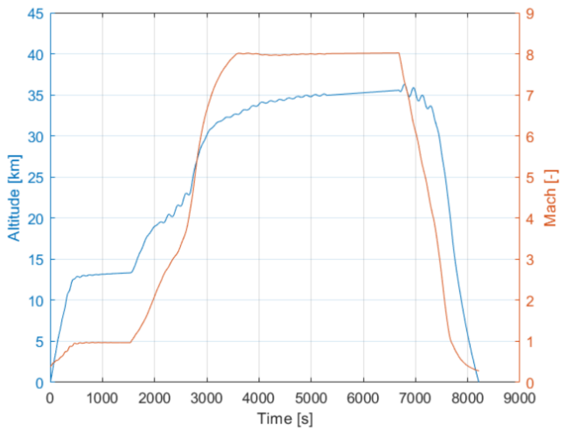



*Figure 30 – Altitude and Mach profile for the BRU-NRT mission*

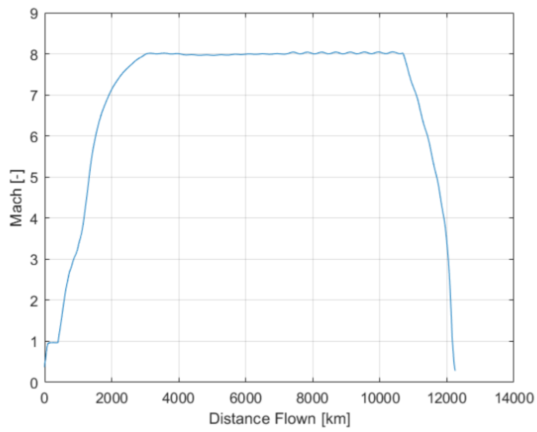



*Figure 31 – Mach vs Distance flown for the BRU-NRT mission*

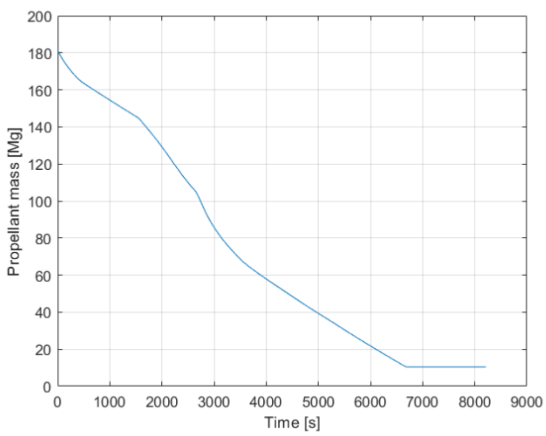



*Figure 32 – Propellant mass vs Time for the BRU-NRT mission*

## 6. Conclusions

This paper deals with the integration of an increasing-fidelity aerodynamic modelling approach in the conceptual design of hypersonic cruiser. At this purpose, a dedicated methodology, developed in the framework of the H2020 STRATOFLY project and applied to the STRATOFLY MR3, is here disclosed. The Mach 8 waverider reference configuration has been thoroughly analysed following an increasing fidelity approach, and a Complete aero database has been disclosed. Considering the complexity of the concept to be analyzed at conceptual/preliminary design stage, the build-up approach has proven to be the best solution to guarantee continuous validation of the vehicle and mission concepts thanks to the extensive Mission Analysis simulation campaigns.

The paper significantly contributes to the field of high-speed aircraft design methodologies, for different reasons. First, it unveils a complete and accurate aerodynamic database for a waverider with dorsal mounted engines configuration. It also discloses new corrective factors for the viscous contribution to drag from subsonic to hypersonic speed regimes. Eventually, it clearly shows the effect of the incremental accuracy of the aerodynamic database onto mission concept definition. In details, one of the most important outcomes of this paper is the complete aerodynamic database, which improves and extends the existing findings for waverider configurations, including the impact of highly integrated dorsal mounted propulsive flow-path and of the Flight Control Surfaces deflections. Moreover, it is worth underling the novelty of the method used for the characterization of the database for what concerns the viscous contribution to drag: the paper suggests the exploitation of inviscid CFD analysis coupled with new viscous corrective factors. These corrective factors are new semi-empirical parametric formulations, obtained thanks to detailed CFD analyses and specialized for both external vehicle surface and internal propulsive flow-path. In addition, the paper clearly shows the impact of incremental accuracy of the aerodynamic analysis onto mission concept definition. Eventually, it is important to notice that the application of the entire methodology to the STRATOFLY MR3 case study allows for the estimation of design margins on the achievable range which might be adopted in future to improve the accuracy of the results coming from the very first iterations of the design process.

## 7. Copyright Statement



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