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Simplified models for the preliminary aerodynamic characterization of high-speed vehicles to support mission analysis

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Abstract

This paper reports the use of simplified models for the evaluation of aerodynamic performance of high-speed vehicles, to support mission analysis during the conceptual design phase. These methods are applied to two reference vehicles: the waverider STRATOFLY MR3 and a Concorde-like configuration. The accuracy of each method is evaluated, then empirical corrections are implemented.

Keywords: MORE&LESS Academy, Multidisciplinary Aircraft Design, Waverider aircraft, Mission Analysis, High-speed Aerodynamic

1. Introduction

During the last decades, the interest for high-speed civil aviation has risen all over the aerospace community. Different projects are focusing on the design of high-speed civil passenger aircrafts, with particular emphasis on the environmental sustainability and social acceptance of such concepts. One of the latest projects is the H2020 MORE&LESS Project (MDO and REgulations for Low boom and Environmentally Sustainable Supersonic aviation), which has been funded by the European Commission. It started in January 2021 and it is supposed to last for 4 years. During the first part of the project, the focus is placed on the definition of the new supersonic aviation paradigm, in order to provide the project with a set of meaningful real case-studies to be further analysed. A wide range of the supersonic speed regime is considered. Moreover, the analysis is not only restricted to aircraft using traditional hydrocarbon fuels, but it moves beyond, addressing aircraft concepts exploiting alternative fuels, such as biofuels and cryogenic fuels. The idea of considering more case-studies with different configurations, performance and fuels fosters the enhancement of the flexibility of the tools, which, starting from the case-studies, are developed based on modelling activities and test campaigns as products that can be flexible enough to be applied to several vehicle concepts.

The ability to predict the aerodynamic characteristic of each case-study is a fundamental aspect of the preliminary design. The work presented in this paper contributes to improve the evaluation of the aerodynamic performance of a high-speed vehicle at the very first stages of the design, when higher fidelity aerodynamic analysis (such as CFD simulations) are not completed. Models already available in literature are considered as the basis for this activity. Then, they are used to evaluate the aerodynamic characteristics of two different aircraft configurations. To cover the entire high-speed range, two configurations are selected as references: the STRATOFLY MR3 vehicle (designed in the field of the H2020 STRATOFLY project, which main outcomes can be found in [1], [2], [3] and [4]) and the Concorde aircraft, which have been designed to cruise at Mach 8 and 2, respectively. Moreover, a scaled version of the MR3 vehicle, which is supposed to perform a Mach 5 cruise mission is currently being studied in the field of the More&Less project and it is also analysed here.

A more detailed description of the vehicles and the models considered is reported in Section 2, together with a discussion on the methodology used. The main results are presented and discussed in Section 3. Eventually, Section 4 draws the main conclusions and provides an overview of the possible future steps to be taken to further improve the results.

2. Methodology and reference vehicles

2.1 Methodology Overview

The methodology used in this study is summarised in Figure 1. First, simplified models for the preliminary evaluation of aerodynamic coefficients of high-speed concepts are considered. Different models are already available in literature and can be used for this analysis. Three models are selected: All-Body Hypersonic [5], Raymer [6] and Toreenbek [7]. They are tested to estimate the aerodynamic coefficient of specific reference vehicles. In particular, for this study, two types of high-speed vehicles are chosen as references: the STRATOFLY MR3 waverider configuration and the supersonic delta wing configuration of the Concorde. The coefficients are computed and then compared to the more accurate data, evaluated through CFD and/or flight data for such aircrafts. The main purpose of this comparison is to identify possible empirical corrections to the models, in order to better describe the aerodynamic behaviour of any other vehicle with similar configurations. Eventually, a preliminary aerodynamic database can be created and used to verify the vehicles concepts through mission analysis. This step can be useful to quantify the reliability of such models in estimating both the aerodynamic performance and ability to perform the reference mission.

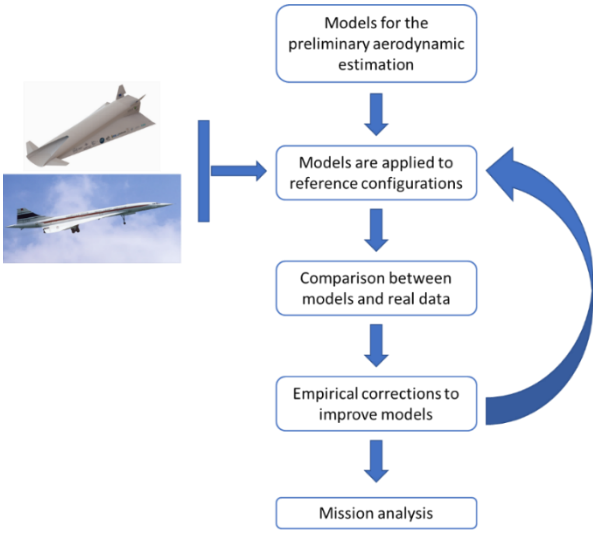

Figure 1 - Overview of the methodology

2.2 Aerodynamic models

The three models considered in the analysis are presented here. For each model an overview of the main assumptions and equations is reported.

2.2.1 All-body hypersonic model

The first model to be considered is the All-Body Hypersonic (ABH) Aircraft model, which is derived from [5]. It is referred to a specific aircraft configuration, composed as follows: a delta planform with an elliptical cone forebody and an elliptical cross-section afterbody, which forms a smooth transition surface from the end of the forebody to a straight-line trailing edge (Figure 2).

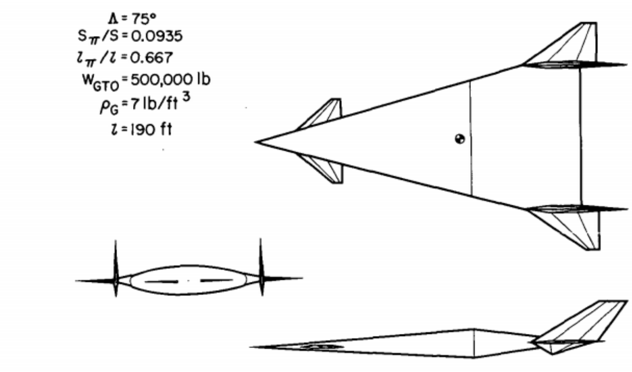

Figure 2 - All-Body Hypersonic Aircraft nominal configuration [5]

Three independent parameters can be identified to describe the basic configuration:

- Leading-edge sweep angle (Λ).
- Breakpoint length ratio ($\frac{l_\pi}{l}$), where l is the total body length and l_π is the position of the breakpoint between forebody and afterbody.
- Fatness ratio ($\frac{S_{max}}{S_{plan}}$), where S_{max} is the maximum cross-section area and S_{plan} is the total planform area.

An additional parameter, named as forebody cross-section ellipse ratio, can be defined (Figure 3):

$$\frac{a}{b} = \frac{\pi(l_\pi/l)^2 cot(\Lambda)}{S_{max}/S_{plan}} \tag{1}$$

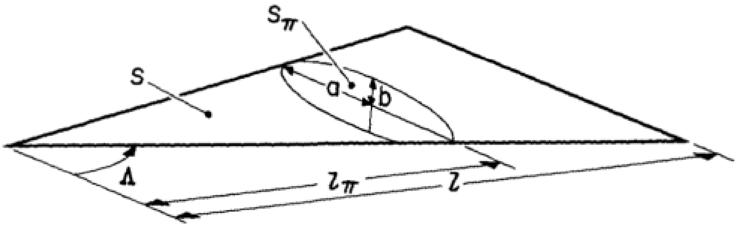

Figure 3 - Configuration parameters [5]

This model allows for the estimation of the lift and drag coefficients, considering not only the contribution of the body, but also the one given by any additional fin (i.e., Vertical tail, Horizontal tail and Canard).

The equations for the lift coefficient (C_L) are estimated by means of nonlinear relations, developed by curve fitting data for low aspect ratio delta wings and can be expressed as:

$$C_L = C_1 \cdot sin(\alpha) + C_2 \cdot sin^2(\alpha) \tag{2}$$

where the coefficients C_1 and C_2 are evaluated depending on the flight regime:

$$\begin{cases} C_1 = \dfrac{\pi \cdot AR}{2} - 0.355 \cdot \beta^{0.45} \cdot AR^{1.45}, & M \leq 1 \\ C_1 = \dfrac{\pi \cdot AR}{2} - 0.153 \cdot \ \beta \cdot AR^2 \quad , & M > 1 \; and \; \beta < {}^4/_{AR} \\ C_1 = \dfrac{4.17}{\beta} - 0.13 \quad , & M > 1 \; and \; \beta \geq {}^4/_{AR} \end{cases} \tag{3}$$

$$\begin{cases} C_2 = 0 \quad , & M \leq 1 \\ C_2 = linear\ interpolation\ with\ respect\ to\ \beta, & M > 1 \; and \; \beta < {}^4/_{AR} \\ C_2 = e^{[0.955-(4.35/M)]} \quad , & M > 1 \; and \; \beta \geq {}^4/_{AR} \end{cases} \tag{4}$$

The total drag coefficient (C_D) can also be evaluated, considering the contribution given by the Zero Lift Drag (C_{D0}) and the Induced Drag (C_{Di}).

$$C_D = C_{D0} + C_{Di} \tag{5}$$

The Induced Drag coefficient is derived in a similar way with respect to the lift coefficient and can be written as:

$$C_{Di} = K_m \cdot C_L \cdot tan(\alpha) \tag{6}$$

Where K_m is a coefficient which accounts for the rounded leading edge of the elliptic cone, evaluated through a comparison with experimental data:

$$\begin{cases} K_m = 0.25 \cdot (1 + M) if M < 3 \\ K_m \qquad\qquad if\ M \geq 3 \end{cases} \tag{7}$$

The zero lift drag coefficient C_{D0} is evaluated considering the different contributions of the body pressure drag ($C_{D\,pB}$), friction drag ($C_{D\,fB}$) and bluntness drag ($C_{D\,bB}$). The body pressure drag is assumed to be zero during subsonic flight, while for supersonic Mach numbers it is computed by numerical integration of the body pressure distribution. The body friction drag is evaluated using relations which are based on turbulent boundary layer for a flat-plate with empirical correction to account for higher thickness. The body bluntness drag is also assumed to be zero at subsonic conditions, while at M≥1 it is evaluated considering a given maximum radiation equilibrium temperature T_{le} and a given skin emissivity ε_{skin}.

$$C_{D0B} = C_{D\,pB} + C_{D\,fB} + C_{D\,bB} \tag{8}$$

2.2.2 Raymer model

The second model analysed is the Raymer model [6], which refers to a generic high speed aircraft configuration with a clear distinction between fuselage and delta wing (Figure 4). The contributions of the main parts of the aircrafts are considered to evaluate the aerodynamic coefficients: wing, fuselage, tails (horizontal, vertical and canards), air intake, nacelles, etc.

The lift coefficient C_L is written as a function of the angle of attack α:

$$C_L = C_{L\,\alpha} \cdot \alpha \tag{9}$$

Where $C_{L\,\alpha}$ is the lift-curve slope and it is evaluated differently according to the flight regime. Initially, the lift at zero angle of attack is supposed to be zero.

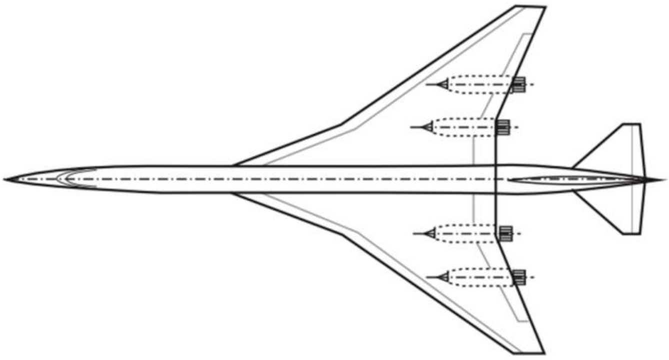

Figure 4 - Raymer model reference configuration

The total Drag coefficient (C_D) can be written as the sum of the Zero Lift (Parasite) Drag C_{D0} and the Induced Drag C_{Di}.

$$C_D = C_{D0} + C_{Di} \tag{10}$$

The component build-up method is used to estimate the parasite drag of each component. Three main contributions are considered: the Skin Friction Drag coefficient $C_{D\,f}$, the Miscellaneous Drag coefficient $C_{D\,misc}$ and the Leakage and Protuberance Drag coefficient $C_{D\,L\&P}$:

$$C_{D0} = \frac{\sum(C_{fc} \cdot FF_c \cdot Q_c \cdot S_{wet\,c})}{S_{ref}} + C_{D\,misc} + C_{D\,L\&P} \tag{11}$$

where $C_{f\,c}$ is the flat-plate skin-friction drag coefficient, FF_c is a component “form factor” which estimates the pressure drag due to viscous separation, Q_c is a factor which considers the interference effects on the component drag and $S_{wet\,c}$ is the wetted area of each component. The miscellaneous drag $C_{D\,misc}$ takes into account for the special features of an aircraft, such as flaps, un-retracted landing gear, unswept aft fuselage, etc. The $C_{D\,L\&P}$ is used to estimate the contribution for leakages and protuberances.

2.2.3 Torenbeek model

The last model analysed in this study is the Torenbeek model [7], which focuses on the supersonic flight only. It allows to estimate the aerodynamic coefficients for a generic aircraft configuration with a delta or arrow wing. First, the case of a flat plate wing is considered, where the basic aerodynamic properties can be evaluated with linearised theory. The aerodynamic forces of a wing are directly affected by the Mach component normal to the leading edge, which can be supersonic or subsonic. The flow past a flat delta wing is described by a parameter called leading edge flow parameter m:

$$m = \frac{tan\,\gamma}{tan\,\mu} = \beta \cdot cot\,\Lambda_{le} \tag{12}$$

where γ is the complement of the leading edge sweep angle Λ_{le}, $\mu = sin^{-1}(1/M_\infty)$ is the Mach angle and $\beta = \sqrt{{M_\infty}^2 - 1}$. If the leading edge is supersonic m>1, while m<1 for a subsonic leading edge. The lift coefficient C_L can be evaluated according to the value of m, considering the general equation $C_L = C_{L\,\alpha} \cdot \alpha$:

$$\begin{cases} C_L = \dfrac{4}{\beta}\alpha \\ C_L = \dfrac{2\,\pi\, m}{E'(m)\beta} \end{cases} \tag{13}$$

Where $E'(m)$ can be written as $E'(m) = 1 + (\pi/2 - 1)m^\eta$, with $\eta = 1.226 + 0.15\pi \cdot (\,1 - \sqrt{m}\,)$.

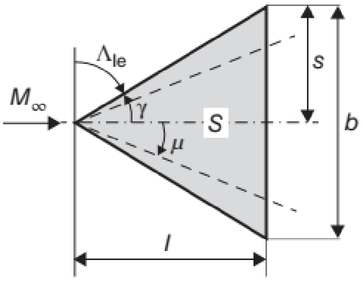

Figure 5 – Delta wing geometry [7]

The drag coefficient C_D can be evaluated as:

$$C_D = C_{D\,0} + C_{D\,i} = C_{D\,F} + C_{D\,WV} + C_{D\,VL} + C_{D\,WL} \tag{14}$$

Where:

- the zero lift drag coefficient $C_{D\,0}$, given by the skin friction drag coefficient $C_{D\,F}$ and the wave drag due to volume coefficient $C_{D\,WV}$.
- the induced drag coefficient $C_{D\,i}$, given by the vortex induced drag coefficient $C_{D\,VL}$ and the wave drag due to lift $C_{D\,WL}$.

2.3 Reference vehicles

The reference vehicles considered for the analysis are described in this Section. Two types of aircrafts are selected: the STRATOFLY MR3 and the Concorde.

2.3.1 STRATOFLY MR3 vehicle

The STRATOFLY MR3 vehicle (Figure 6) is characterized by a waverider architecture, with a dorsal-mounted propulsion plant duct, a canard and a V-Tail layout for directional stability and control. The integration of the propulsive system at the top of the vehicle allows maximizing the available planform for lift generation without additional drag penalties, thus increasing the aerodynamic efficiency, and it allows optimizing the internal volume. This layout guarantees furthermore 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. Specifically, STRATOFLY MR3 integrates 6 Air Turbo Rocket engines (ATR) that operate up to Mach 4 - 4.5 and one Dual Mode Ramjet (DMR) that is used for hypersonic flight from Mach 4.5 up to Mach 8. The propellant used for all the engines is liquid hydrogen.

Figure 6 - The STRATOFLY MR3 hypersonic cruiser

The external dimensions are characterized by an overall length of 94 m (excluding protruding rudders) and by a wingspan of 41 m. The planform area (excluding canards) is thus around 2491 m^2 with an overall internal volume arrangement of roughly 10000 m^3. Additional information on the vehicle design and configuration can be found in [8] and [9].

The STRATOFLY vehicle is supposed to perform the cruise at stratospheric altitude (30-36 km) at Mach 8. The complete aerodynamic database of the STRATOFLY MR3 vehicle has been evaluated by means of CFD [10] and can be used for this analysis. The vehicle is designed to host 300 passengers as payload. The propellant mass used as reference is 181.25 Mg and the take-off weight for the mission is equal to 400 Mg. The STRATOFLY MR3 vehicle has been originally conceived to cover antipodal routes with a distance flown up to 19 000 km. The reference trajectory considered in this analysis is the Brussels to Sydney mission.

During the first part of the mission the ATR engines are used up to Mach 4 – 4.5. At the end of this phase, the ATR engines are turned off and the DMR is activated to accelerate up to Mach=8 at an altitude of 32-33 km (hypersonic climb). Here, the cruise starts at a constant Mach number of 8 and at an altitude between 32 and 36 km. An overview of the complete trajectory is reported in Figure 7, where the main characteristics of the trajectory can be clearly identified.

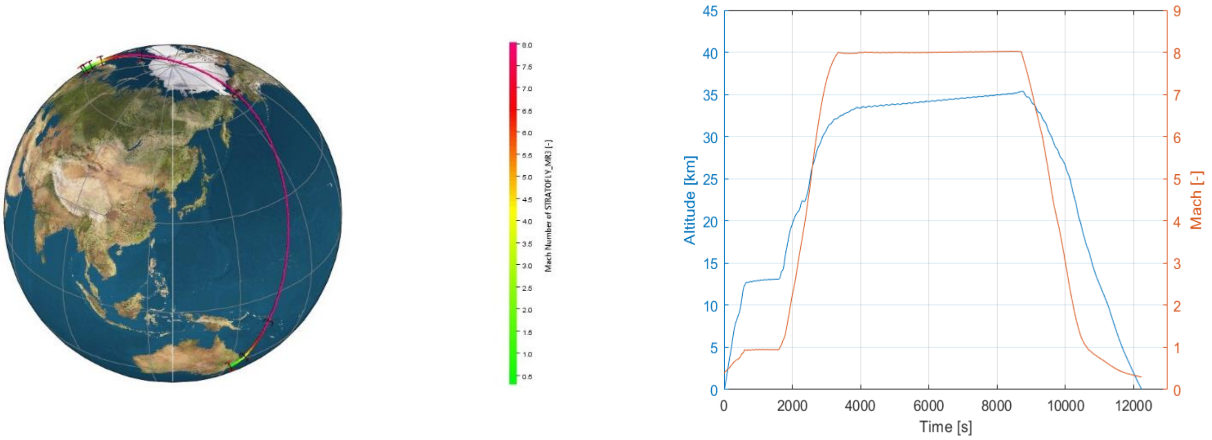

Figure 7 - Overview of complete MR3 trajectory BRU-SYD. Trajectory (left) is painted as function of Mach number.

Currently, a modified version of this vehicle is under evaluation in the field of the H2020 More&Less project, with the main aim of performing a Mach 5 cruise mission. The general idea is to exploit the STRATOFLY MR3 vehicle and adapt it for a Mach 5 mission. Since the aerodynamic investigation campaign could require a long time before completion, the aerodynamic models analysed here could be a good way to derive a preliminary aerodynamic characterization to be used for the mission analysis of the adapted concept.

2.3.2 Concorde vehicle

The Concorde aircraft (Figure 8) is a supersonic passenger airliner with a slender delta wing configuration, which operated from 1976 to 2003, when it was retired. It was designed to cruise at Mach=2.04 up to an altitude of 18 000 m. It could fly over a maximum range of about 6600 km and it could accommodate up to 128 passengers. The Concorde vehicle was powered by 4 Olympus 593 turbojet engines. The vehicle had an overall length of 62.1 m and a wing span of 25.56 m [11]. For what concerns the aerodynamic data, very few information can be found in literature for the Concorde. However, some data for the cruise conditions are reported in [12] and are used for this analysis.

Figure 8 – Concorde aircraft

3. Results

3.1 Models applied to the Concorde-like case study

The first reference vehicle to be analysed is the Concorde. The complete set of inputs required to perform this analysis is reported in Appendix. The three models analysed before are applied to a specific condition representing the cruise, which is at Mach 2 and at an altitude of 18 km. The angle of attack ranges from -2° to 8°. The aerodynamic coefficients are evaluated and plotted as C_L vs C_D, as can be seen in Figure 9. These data should be compared with the real aerodynamic data of the Concorde vehicle. However, only few data in cruise conditions are available and are selected from [12]. It is possible to notice that the model which better describes the shape of the curve is the Raymer model, especially at low angles of attack. This can be explained, considering that the Raymer model is referred to a general high-speed configuration, where the fuselage and the wing are clearly separated. The Concorde geometry is quite similar to the one considered within the Raymer model. However, some differences are also present. For example, the lift coefficient at zero angle of attack is considered to be zero, while this is not generally true for a generic aircraft. The Torenbeek model is equal to the Raymer in predicting the lift coefficient, since the same assumption are involved. However, it appears to be a little less precise in predicting the drag coefficient, which is overestimated at increasing angles of attack. The All Body Hypersonic model, instead, is defined for a configuration which is quite different from the one of the Concorde, and cannot be used to predict the aerodynamic coefficients.

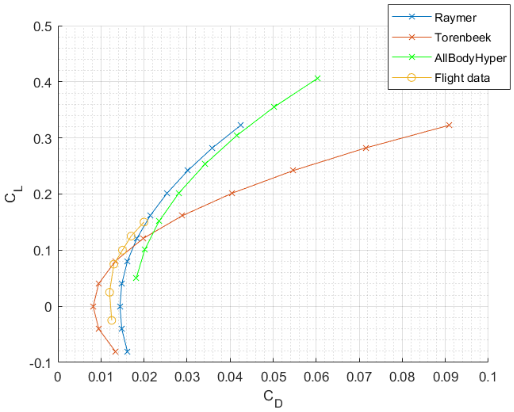

Figure 9 – Comparison between the C_L vs C_D evaluated with the three models and the real data

Then, the Raymer model is selected and used to derive a preliminary aerodynamic database to be used for a complete mission simulation. The reference mission is a generic long-haul flight, for example connecting Europe and North America, for a maximum travel distance of approximately 6500 km. The results of the simulation are reported in the following figures. The altitude and Mach profile are reported in Figure 10. It can be seen that the mission can be completed in less than 4 hours, cruising at Mach 2 with an altitude between 17 and 19 km. The total and propellant mass variation during the mission is reported in Figure 11. The angle of attack profile is reported in Figure 12, while the lift to drag ratio is shown in Figure 13.

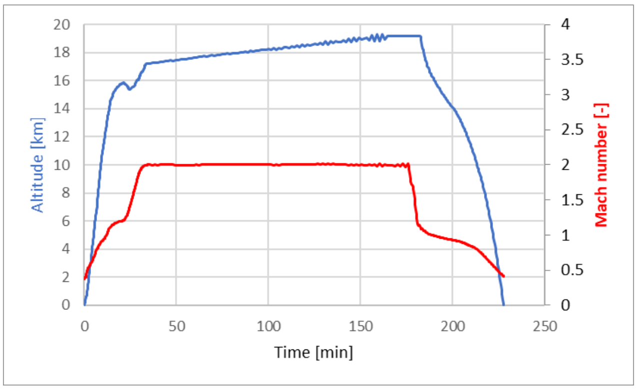

Figure 10 – Altitude and Mach profile for the Concorde-like mission

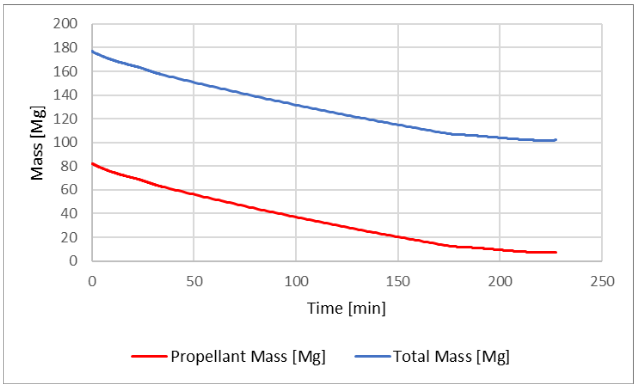

Figure 11 – Total and propellant mass variation during the Concorde-like mission

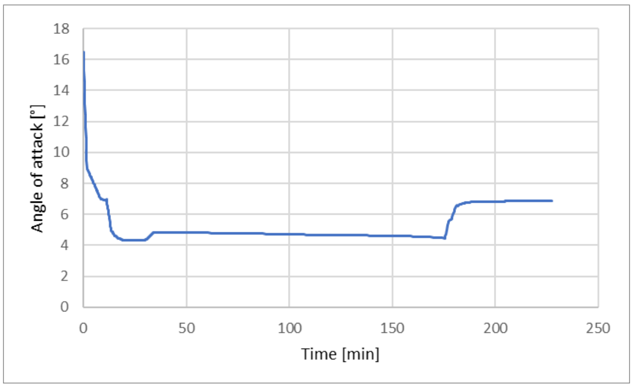

Figure 12 – Angle of attack variation during the Concorde-like mission

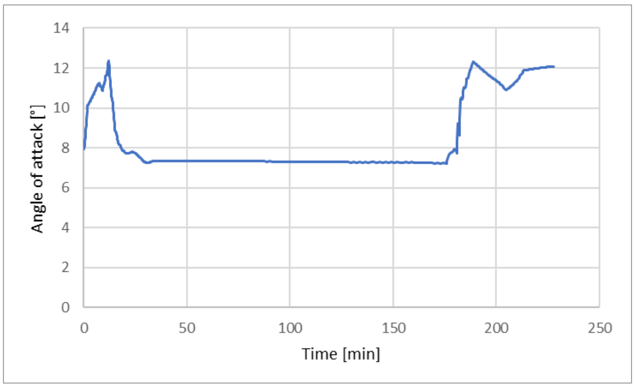

Figure 13 – Lift to drag ratio profile during the MR5 Concorde-like mission

3.2 Models applied to the STRATOFLY MR3 case study

As a second step, the STRATOFLY MR3 vehicle is analysed. In this case, the aerodynamic data available are not limited to a specific Mach number, but include the entire Mach range from Mach = 0.3 to 8. Moreover, a different approach should be followed for that case study. Here, the complete aerodynamic database of the vehicle is already available, which is one of the main outcomes of the H2020 STRATOFLY project. It is used as a baseline to compare the results obtained with each simplified model. Then, the model which better describes the aerodynamic behaviour of the vehicle is selected and tuned to further improve the prediction of lift and drag coefficients. The main goal is to exploit these results to predict the aerodynamic coefficient of the scaled version of the STRATOFLY MR3, which is re-designed for the Mach 5 mission.

First, C_L and C_D are evaluated at subsonic condition, for example at Mach 0.7. The results are reported in Figure 14, Figure 15 and Figure 16. It can be seen that both the Raymer and ABH model are not perfectly predicting the lift coefficient. However, this can be explained considering that the lift at zero angle of attack cannot be evaluated with these models, so a shift of the C_L curve is present. Instead, for what concerns the lift slope, the results of the ABH model are quite similar to the ones of the higher-fidelity data. The error computed with the Raymer model, instead, is higher. For what concerns the $C_{D,}$ the value predicted with the Raymer and ABH models are similar, but they are quite far from the real data.

The cruise condition at Mach 8 is also investigated and the results are reported in Figure 17, Figure 18 and Figure 19. All the three models are quite accurate in predicting the lift slope, with the ABH model being the most precise. There is still a shift between the models and the real data due to the lift at zero angle of attack being not evaluated. For what concerns the drag coefficient, both the Raymer and Torenbeek model tend to overestimate the drag. This can be explained by the fact that the configuration of the waverider is quite far from the one considered for these models, which is more similar to a typical aircraft. These methods are not able to catch the positive contribution to the aerodynamic performance given by this peculiar waverider configuration. On the contrary, the ABH model is underestimating the $C_{D,}$ which however is similar to the real data, especially for low angles of attack.

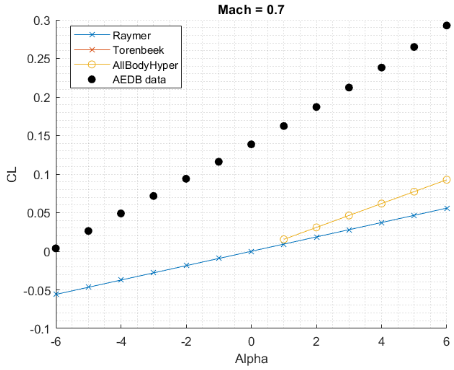

Figure 14 – C_L vs AoA at M = 0.7

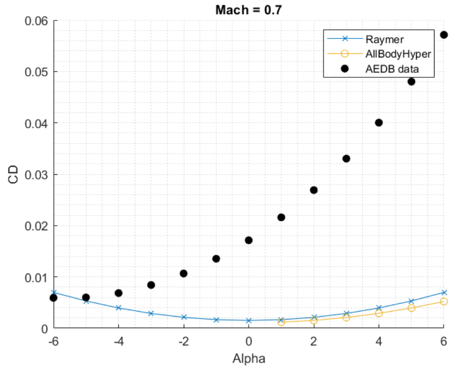

Figure 15 - C_D vs AoA at M = 0.7

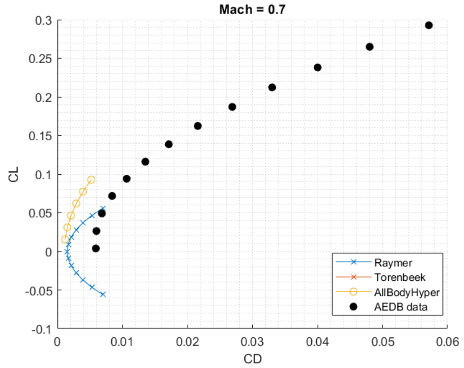

Figure 16 – C_L vs C_D curve at M = 0.7

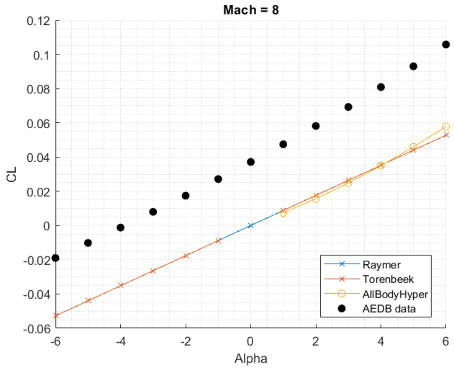

Figure 17 - C_L vs AoA at M = 8

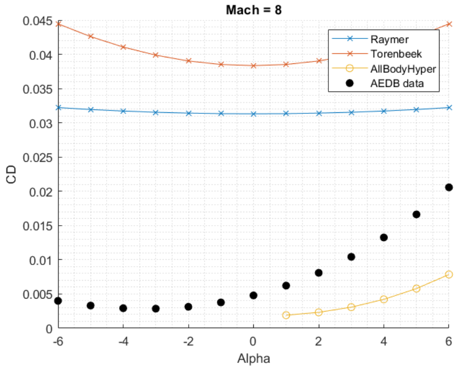

Figure 18 - C_D vs AoA at M = 8

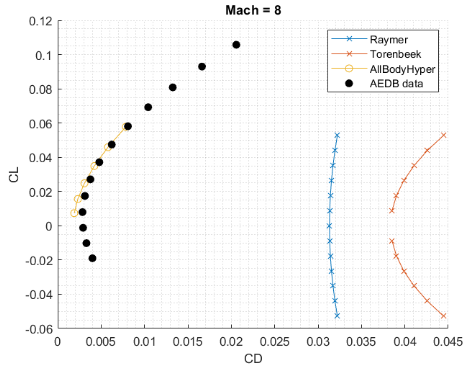

Figure 19 – C_L vs C_D curve at M = 8

Among those analysed, the All-Body Hypersonic (ABH) model is the one which better predict the aerodynamic behaviour of the Mach 8 waverider. Some corrections are needed to further improve the aerodynamic predictions of the model. Moreover, since the All-Body Hypersonic model is, in principle, defined only for positive angle of attacks, the range has been extended to negative values mirroring the coefficients with respect to $\alpha = 0°$.

First, the lift coefficient is analysed. Since the C_L at zero angle of attack (C_{L0}) cannot be directly predicted through the simple use of those models, an ad-hoc correction is introduced. For that reason, the hypothesis of considering the same C_{L0} from the MR3 database is done and the lift coefficient is evaluated again. The results for Mach 0.7, 1.5 and 5 are reported in Figure 20, Figure 21 and Figure 22, respectively. With the correction on the C_{L0}, the lift coefficient evaluated through the ABH model is very similar to the real one, especially for low angles of attack (i.e., $-2° \leq \ \alpha \leq 2°$), which is the range of interest for the typical mission.

Further corrections are applied to the model, so that the prediction of the drag coefficient C_D can be improved. The main focus is placed on the induced drag coefficient $C_{Di} = K_m(M) \cdot C_L \cdot tan(\alpha)$. The proposed corrections are first applied to the coefficient K_m:

$$\begin{cases} K_m = 1.3 & , \ M \leq 1 \rightarrow correction\ to\ curve\ slope \\ K_m\ is\ evaluated\ through\ interpolation\ for\ 1 < Mach < 3 \\ K_m = 1 & , \qquad M \geq 3\ \rightarrow no\ corrections \end{cases}$$

These changes allow for a better estimation of the curve slope. Additional corrections are considered for the general equation of C_{Di}:

$$\begin{cases} C_{Di} = 1.3\ \cdot C_L \cdot tan(\alpha + 4) & , \quad M \leq 1 \\ C_{Di}\ is\ evaluated\ through\ interpolation\ for\ 1 < M < 3 \\ C_{Di} = 1\ \cdot C_L \cdot tan(\alpha + 2) & , \quad M \geq 3 \end{cases}$$

The total drag coefficient for Mach = 0.7, 1.2 and 5, are reported in Figure 23, Figure 24 and Figure 25, respectively. The corrections work well both in subsonic and supersonic regimes, but they are less accurate for transonic.

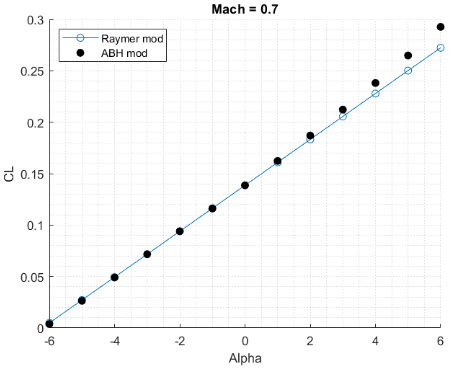

Figure 20 - C_L evaluated with correction to C_{L0} at M = 0.7

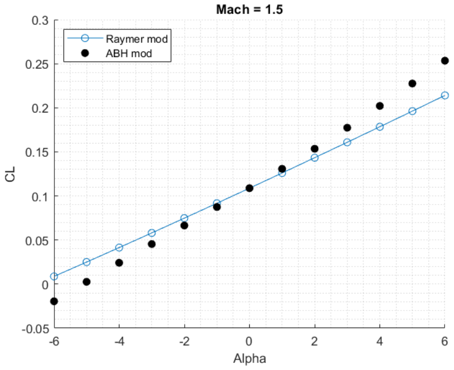

Figure 21 - C_L evaluated with correction to C_{L0} at M = 1.5

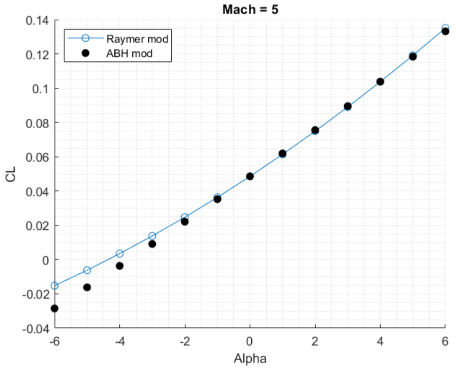

Figure 22 - C_L evaluated with correction to C_{L0} at M = 5

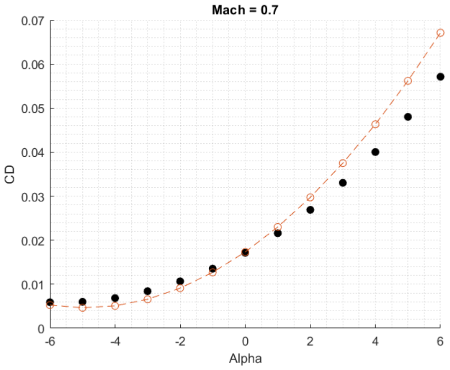

Figure 23 - C_D evaluated with corrections to C_{Di} at M = 0.7

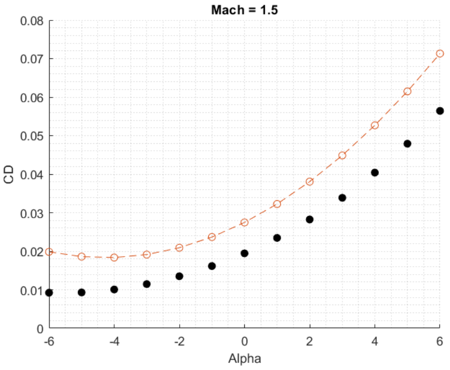

Figure 24 - C_D evaluated with corrections to C_{Di} at M = 1.5

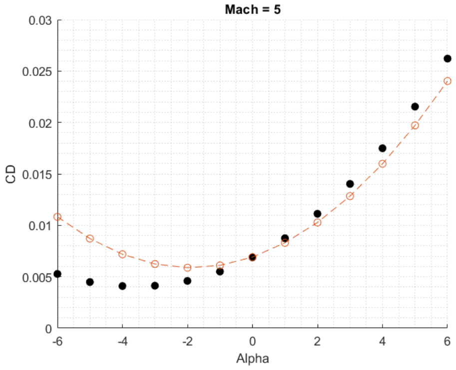

Figure 25 - C_D evaluated with corrections to C_{Di} at M = 5

3.3 Models applied to the Mach 5 scaled version

The equations described previously are used to estimate the aerodynamic performance of a scaled version of the STRATOFLY MR3 vehicle. The new vehicle concept is currently being studied in the field of the MORE&LESS project. The main aim is to redesign the original vehicle and to optimise it for a Mach 5 mission, instead of the hypersonic mission at Mach 8. The dimension of the scaled version, which is referred to as MR5, are reported in Figure 26, together with an image of the scaled vehicle. A complete aerodynamic database is derived for the MR5, for the Mach range between Mach=0.3 and Mach=5.

Input	*Value*	*Unit*
Mach Number	*5*	*-*
Planform Surface	*1696*	*m2*
Wing Span	*41*	*m*
Fuselage Length	*64*	*m*

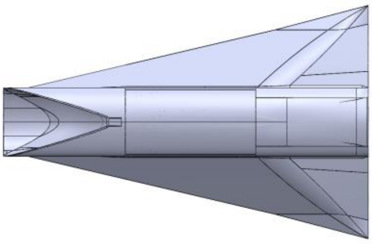

Figure 26 – Vehicle's geometry and visual representation

The lift coefficient at different Mach numbers is reported in Figure 27 and Figure 28, for angles of attack equal to -1° and 0°, respectively. These results are compared with the ones of the STRATOFLY MR3 database. It can be seen that the C_L is the same for the two cases for $\alpha = 0°$. This is due to the fact that the model do not provide the capability to evaluate the lift coefficient at zero angle of attack. Then, the same C_{L0} of the original vehicle is considered also for the scaled version. If the angle of attack is different from 0, the C_L evaluated for the scaled version is slightly different from the reference one, but the general trend is in good accordance with it.

The drag coefficient is also evaluated exploiting the ABH model and considering the proposed modifications. The results for angles of attack equal to -1° and 0° are reported in Figure 29 and Figure 30. Three cases are reported here. The first two are:

1. The yellow curve is referred to the drag coefficient of the MR3 aerodynamic database.
2. The blue curve represents the drag coefficient of the MR5 scaled vehicle, as evaluated with the

modified ABH model.

However, if a comparison between the two curves is considered, it can be seen that the evaluated drag coefficient shows a not negligible rise in the transonic regime and it is approximately three times larger than the reference value of the MR3. Typically, the C_D has its maximum value in this region, but it shows an unrealistic value for this case. However, this is something that could be expected, for example looking at how the C_D is modelled within the ABH model. For the transonic Mach numbers, interpolations are used to evaluate the C_D and that could lead to inaccurate results. For that reason, the results have been modified. In the range between Mach=1 and Mach=3, the curve is interpolated and the results are shown with a green line in Figure 29 and Figure 30.

In Figure 31 and Figure 32, the aerodynamic efficiency is reported for angles of attack equal to -1° and 0°. The maximum L/D is reached for subsonic Mach numbers. The Mach 5 cruise L/D is approaching 5 for an angle of attack equal to 0° and it is very similar to the theoretical maximum value in this condition.

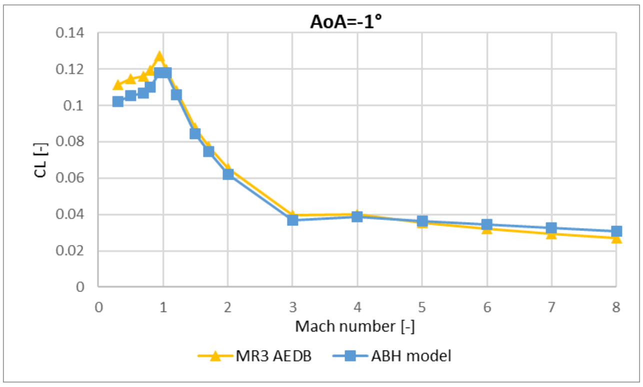

Figure 27 – Lift coefficient comparison between MR3 AEDB and MR5 ABH model at AoA=-1°

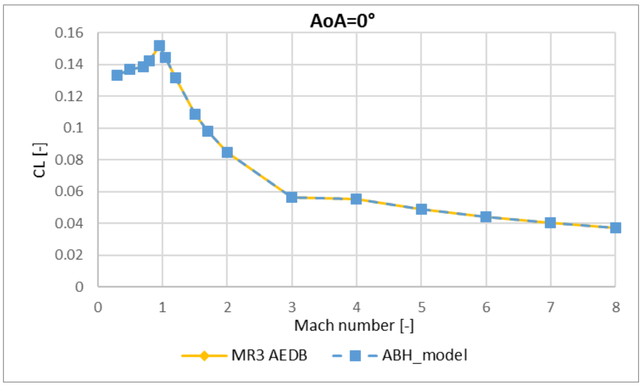

Figure 28 – Lift coefficient comparison between MR3 AEDB and MR5 ABH model at AoA=0°

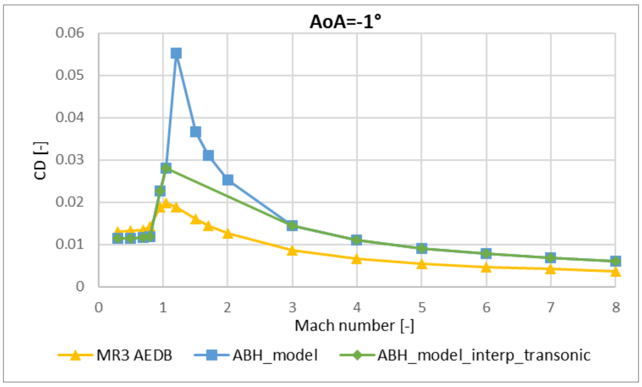

Figure 29 – Drag coefficient comparison between MR3 AEDB, MR5 ABH model and ABH model with interpolation in transonic range at AoA=-1°

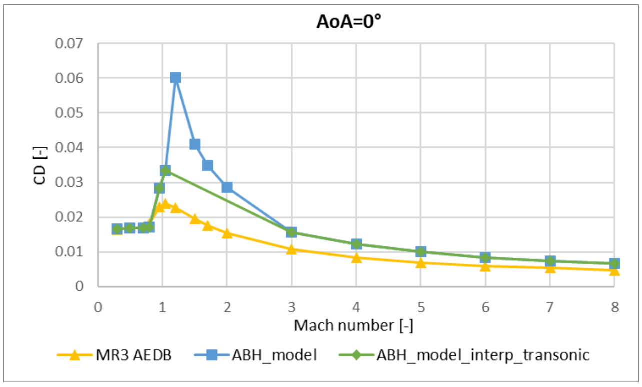

Figure 30 – Drag coefficient comparison between MR3 AEDB, MR5 ABH model and ABH model with interpolation in transonic range at AoA=0°

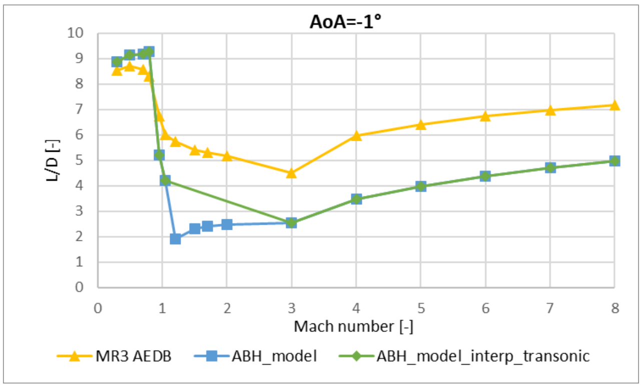

Figure 31– Lift to drag ratio comparison between MR3 AEDB MR5, ABH model and ABH model with interpolation in transonic range at AoA=-1°

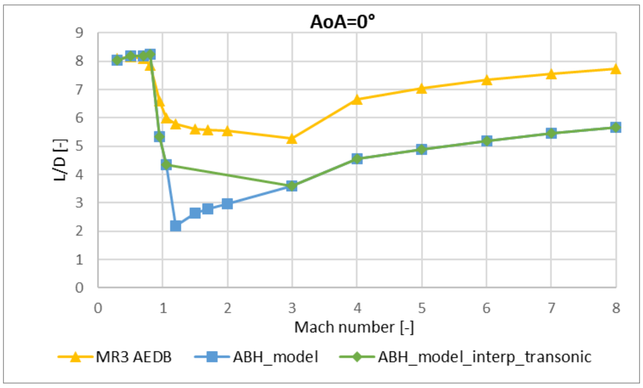

Figure 32– Lift to drag ratio comparison between MR3 AEDB MR5, ABH model and ABH model with interpolation in transonic range at AoA=0°

The final aerodynamic database can now be used for further analysis of the scaled MR5 vehicle. A simulation of the entire mission is performed. The same reference mission of the STRATOFLY MR3 vehicle is considered, with departure in Brussels and arrival in Sydney for a total range of 18 600 km. Moreover, the same propulsive database of the MR3 is considered, since no data are available at the moment for the scaled vehicle. The altitude and Mach profile of the mission is reported in Figure 33. The total and propellant mass variation during the mission is shown in Figure 34. The mission can be completed in approximately 4.5 hours. The propellant on-board at the beginning of the mission is equal to 95 Mg, while a total of 19 Mg are left at the end. The variation of the angle of attack during the mission is also reported in Figure 35, while the lift to drag ratio trend is shown in Figure 36. Negative angles of attack are used during the climb phases, even if limited in the range $-1.3° < \alpha < 0°$. During the cruise phases instead, the angle of attack is set constant and equal to 0°. Moreover, an aerodynamic efficiency of 5 is reached during the Mach 5 cruise, in line with the theoretical results presented before.

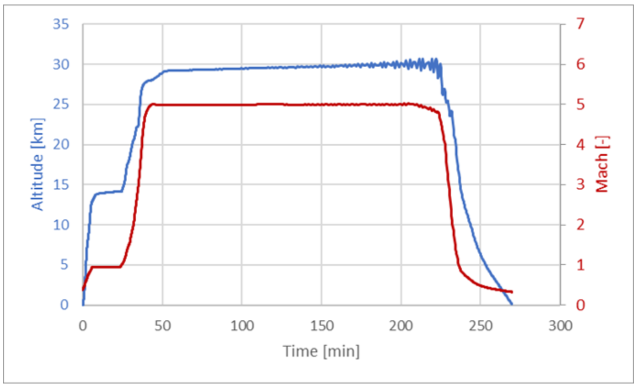

Figure 33 – Altitude and Mach profile for the MR5 mission

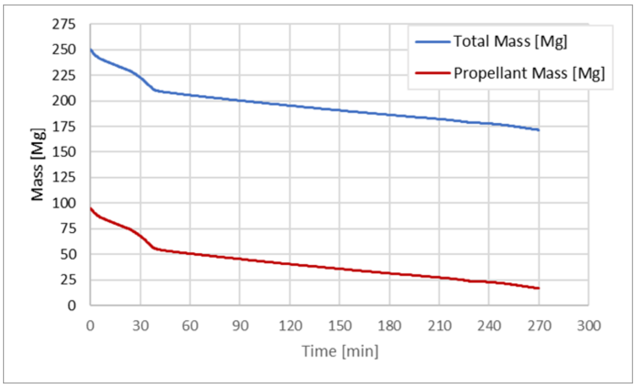

Figure 34 – Total and propellant mass variation during the MR5 mission

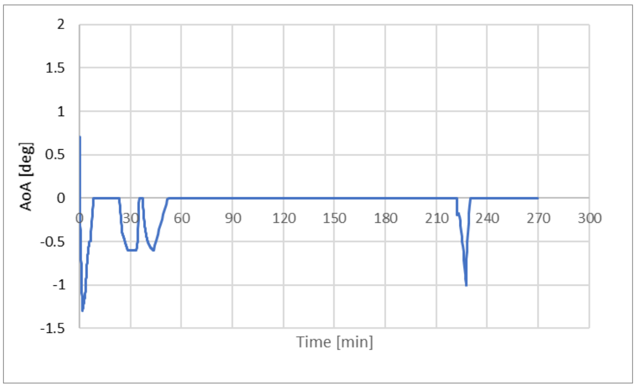

Figure 35 – Angle of attack variation during the MR5 mission

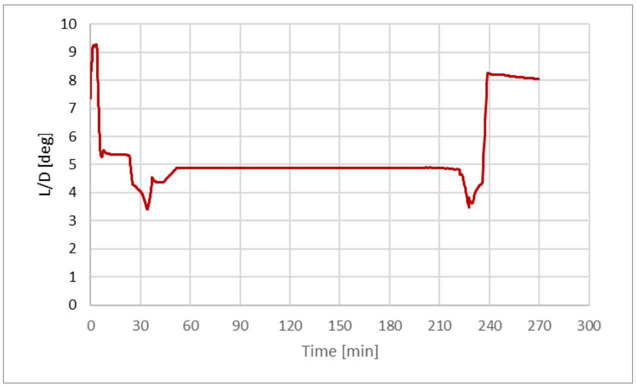

Figure 36 – Lift to drag ratio profile for the MR5 mission

4. Conclusions

The use of simplified models for the preliminary aerodynamic characterization of high-speed vehicles is described in this paper. Three aerodynamic models were selected from the literature and applied to two case studies: the Concorde-like and the STRATOFLY MR3 vehicles. The one which is able to evaluate the lift and drag coefficients most accurately is selected for each case study. Then, the model is further corrected to improve the aerodynamic characterization. This method allows for a preliminary estimation of the aerodynamic coefficients of a similar configuration, when higher fidelity analysis are not yet completed. These data can be exploited to perform a preliminary mission analysis, which can be used to verify the feasibility of the mission concept since the very first stages of the design, when no other data is available.

However, some additional analysis should be performed as soon as possible. First, for what concerns the Concorde-like case study, only the data at Mach 2 are available to test the models. This aspect limits the possibility to tune the models for the entire Mach range. However, the Concorde configuration is currently under study and a CFD campaign will be completed in the next future. As soon as the high-fidelity data will be available, a comparison will be performed to better quantify the accuracy of the preliminary models.

Something similar can be stated for what concerns the tuning of the waverider configuration. For this configuration it will be possible to directly verify the proposed corrections to the All-Body Hypersonic model for the Mach 5 vehicle configuration, once more accurate aerodynamic data will be available.

Eventually, additional mission simulations could be performed using higher-fidelity data and they could be compared with the ones presented in this paper.

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Appendix

The inputs required to perform the preliminary evaluation of the aerodynamic coefficients are reported in Table 1 for the Concorde and the STRATOFLY MR3.

Table 1 – Vehicles geometrical inputs

Input	Concorde	STRATOFLY MR3	Unit of measure
Total volume	396	1000	[m^3]
Planform surface	358.25	2491	[m^2]
Wetted surface	1079	5422	[m^2]
Exposed surface	278.86	1265	[m^2]
Wing span	25.56	41	[m]
Fuselage length	39.32	94	[m]
Fuselage diameter	3.1	11	[m]
Maximum cross-sectional area	40	210	[m^2]
Wing mean aerodynamic chord	14	14	[m]
Wing leading edge sweep angle	55	81	[°]
Wing trailing edge sweep angle	0	0	[°]
Wing thickness ratio	0.025	0.22	[ ]
Nacelle length	-	-	[m]
Nacelle diameter	-	-	[m]
Inlet length	-	26 [m]	[m]
Inlet diameter	-	8 [m]	[m]
Horizontal tail thickness ratio	-	-	[ ]
Horizontal tail surface	-	-	[m^2]
Horizontal tail leading edge sweep angle	-	-	[m]
Horizontal tail mean aerodynamic chord	-	-	[m]
Horizontal tail span	-	-	[m]
Number of Horizontal tail(s)	0	0	[ ]
Vertical tail thickness ratio	0.046	0.037	[ ]
Vertical tail surface	33.91	72.8	[m^2]
Vertical tail leading edge sweep angle	51	45	[°]
Vertical tail mean aerodynamic chord	7	9.4	[m]
Vertical tail span	11.32	8.5	[m]
Number of Vertical tail(s)	1	2	[-]

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