Strategies for preliminary re-design of a LH2 Mach 5 cruiser concept originally conceived for Mach 8 mission

STRATEGIES FOR PRELIMINARY RE-DESIGN OF A LH2 MACH 5 CRUISER CONCEPT ORIGINALLY CONCEIVED FOR MACH 8 MISSION

N. Viola [1], D. Ferretto [1*], O. Gori [1], R. Fusaro [1], M. Marini [2], P. Roncioni [2], B. Çakır [3], A.C. Ispir [3], B.H. Saracoglu [3]

[1] Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy
* davide.ferretto@polito.it

[2] Centro Italiano Ricerche Aerospaziali, Via Maiorise, 81043, Capua (CE), Italy

[3] Von Karman Institute for Fluid Dynamics, Waterloosesteenweg 72, B-1640 Sint-Genesius-Rode, Belgium

ABSTRACT

This paper aims at presenting some aircraft design activities currently carried out in the framework of the H2020 MORE&LESS project. Specifically, benefitting of the latest outcomes of the H2020 STRATOFLY project, POLITO, CIRA and VKI are currently working at the re-design of the original Mach 8 waverider (MR3 vehicle concept) to derive a sustainable Mach 5 vehicle and mission concept. This paper presents the preliminary re-design of the Mach 5 waverider concept (MR5), keeping the same vehicle configuration and the same propulsive technologies (operating in different modes). The envisaged multidisciplinary methodology is here reported, focusing on the unavoidable links among aircraft and mission design, subsystems integration, aerothermodynamics and propulsion. First, the same configuration of the MR3 vehicle is considered, to evaluate the best solution in terms of propellant mass to be stored on-board. Then, a preliminary study on the possible modifications of the air-intake, to improve its performance in the supersonic range, is presented. Each configuration is validated through mission analysis. The capability to perform the Mach 5 mission is verified. However, further steps are needed to move towards a scaling down of the MR3 vehicle, while keeping the overall shape and proportion of the vehicle unchanged, to allow for a full exploitation of the outcomes of the STRATOFLY project.

Keywords: Aircraft and Mission Design, Aerothermodynamic, Airbreathing Propulsion

1 INTRODUCTION

High-speed flight has always been a crucial topic in the history of aeronautics, cyclically coming to the fore in the field of commercial aviation with mixed fortune and some honourable mentions. During the last two decades, several enabling technologies for high-speed flight have been developed all over the world with the aim of assuring technical feasibility, economic viability and environmental sustainability of the concept. In this context, in 2018, the European Commission funded the H2020 STRATOFLY project (STRATOspheric FLYing opportunities for high-speed propulsion concepts), to assess technical, economic and environmental challenges, of a Mach 8 cruiser, named MR3, conceived to fly at 30-35 km of altitude and to carry up to 300 passengers on antipodal routes (19000 km) in less than 3 hours. Even if the exploitation of liquid hydrogen as propellant can be considered as a cleaner and more efficient solution in terms of pollutant emissions and installed performance, the current state of the art in cryogenic storage technologies may superimpose hard constraints onto the mission, mainly because of the poor volumetric efficiency of the fuel. This is one of the main challenges currently addressed by the H2020 MORE&LESS project (MDO and Regulations for Low-boom and Environmentally Sustainable Supersonic aviation), funded by EC since 2021. The current project

aims at assessing the potential of several supersonic aircraft configurations (including a STRATOFLY-derived concept) and green fuels with the goal of proposing a sustainable model for supersonic aviation of the near future. In this context, the MR3 vehicle has been chosen as reference candidate to start the definition of an analogous concept, known as MR5, properly designed to cruise at Mach 5 instead of Mach 8.
This paper presents the preliminary re-design of a Mach 5 waverider configuration concept originally conceived to cruise at Mach 8, keeping the same vehicle configuration and the same propulsive technologies (operating in different modes). After a short introduction on the research context, the reference MR3 vehicle is presented along with its original mission. The list of high-level requirements to be considered for the re-design is also discussed. Then, the process to define the MR5 concept is described, starting from the evaluation of feasible design space, considering preliminary re-evaluation of the aero-propulsive characteristics of the aircraft throughout the mission, always keeping consistency with original MR3 configuration and layout constraints. This will allow defining the main characteristics of the vehicle, in terms of mass, dimensions and required performance. Moreover, ideas for the adaptation of the propulsive flow-path to match the lower-Mach lower-altitude flight environment, starting from the high-level requirements, will be provided. Ultimately, a mission simulation will be performed for concept validation and conclusions will be drawn together with identification of main future works to be performed within the frame of the project.

2 MULTIDISCIPLINARY DESIGN METHODOLOGY

STRATOFLY MR3 vehicle configuration is the result of research activities aimed at refining the promising MR2.4 waverider configuration. Benefitting from the heritage of past European funded projects and, in particular, from the LAPCAT II project, the waverider configuration has been adopted, improved and characterized 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 1a [1][2][3]. The reference mission profile (Figure 1b), initially based on the published MR2.4 reference trajectory [4], has been improved thanks to (i) the introduction of more detailed and reliable aerodynamic and propulsive databases [5], (ii) the optimization of the depletion strategy to minimize the variation of the centre of gravity position and (iii) the redesign of the Flight Control System.

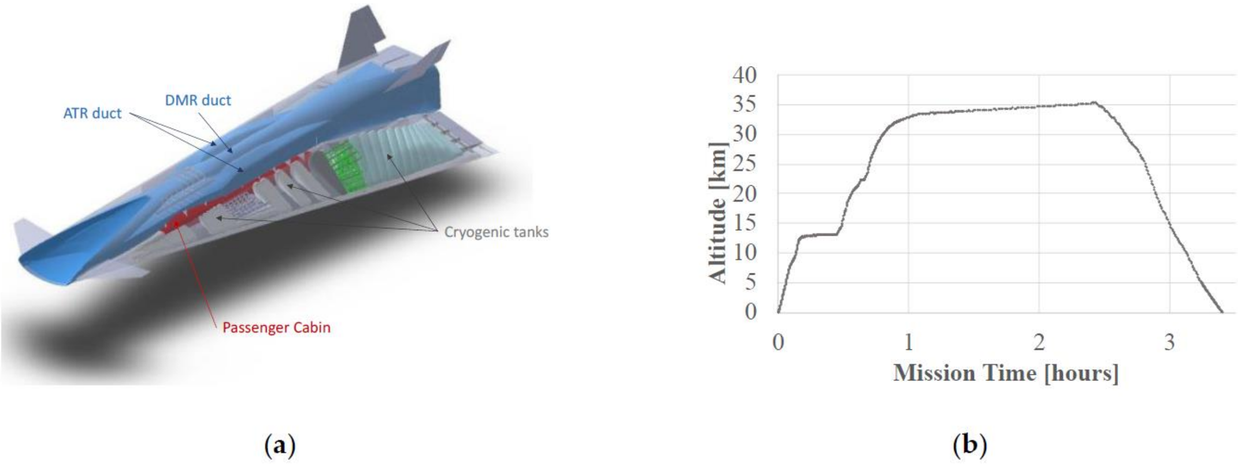


Figure 1: (a) STRATOFLY MR3 Vehicle; (b) Idealized Mission Concept

The mission profile can be further modified to be adapted for the Mach 5 mission. The first part of the mission remains unchanged, while the duration of the hypersonic climb is reduced, so that the vehicle can accelerate from Mach 4 to 5 and then continue with the Mach 5 cruise at an altitude of 25-28 km.
Then, a step-by-step approach is used to perform the re-design of the STRATOFLY MR3 vehicle, originally designed to cruise at Mach 8, which should be modified for a Mach 5 cruise.
Three main steps can be identified. First, the analysis is carried on considering the original STRATOFLY MR3 vehicle cruising at Mach 5, without any change in terms of aerodynamics or propulsion. Some evaluations on the propellant mass to be stored on board are also done in this preliminary phase.
Then, since the internal duct of the MR3 vehicle has been optimized for higher Mach numbers (up to Mach 8), some changes are required to improve the performance, since the vehicle is expected to fly mostly at lower

speeds during the mission. As a next step, a modified air-intake can be considered, which is optimized for the Mach 5 mission. Eventually, the next step is to proceed with a general re-design of the vehicle. However, due to the complexity of the topic, this step is currently under study and only a discussion on the possible future steps is provided here.

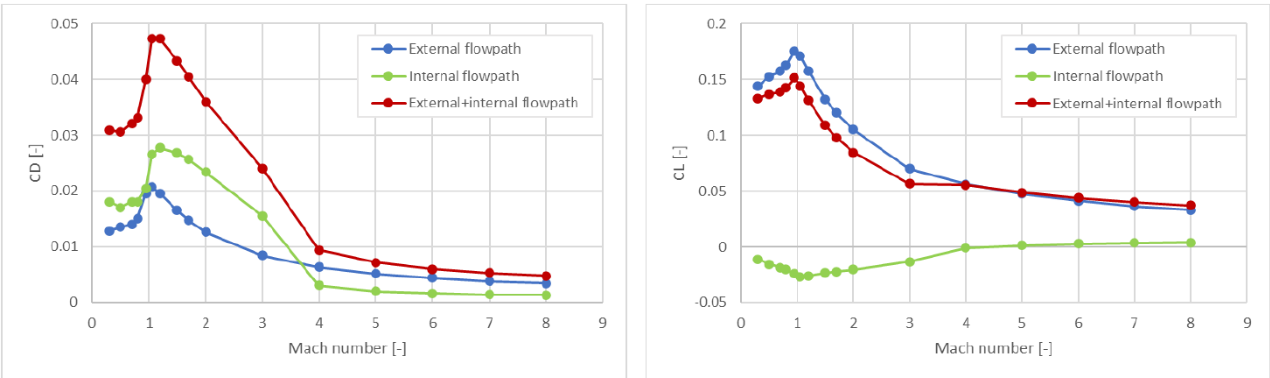
2.1 STEP1 : MR3 vehicle concept on a Mach 5 mission

Even though the STRATOFLY MR3 vehicle has been originally designed and optimised to cruise at Mach 8, the same vehicle has been initially considered for the Mach 5 mission, exploiting the existing aerodynamic and propulsive databases. For that reason, the aerodynamic and propulsive characteristics of the vehicle remain unchanged. Here, the main focus is placed on the verification of the vehicle performance along the mission, to evaluate which is the distance that can be covered. Since the original STRATOFLY vehicle has been conceived to fly on antipodal routes (i.e., 19000 km range), the same distance target is considered also for the Mach 5 version.

Moreover, some additional observations must be done on the fuel mass that can be stored on-board. Initially, the reference value of 180 Mg, derived from the STRATOFLY MR3 vehicle, is used. However, since the required fuel mass is highly dependent on the mission performance, this value is expected to change to better comply with the Mach 5 mission.

2.2 STEP2 : Air-Intake Aerodynamic improvements on the un-scaled concept

Following the analysis described in the previous section, further studies can be done to understand how to improve the aerodynamic performance. For example, it is possible to focus on the vehicle air-intake, which has been originally designed to optimally work at Mach 8. Due to the different mission, the intake should be properly modified, to better operate at lower Mach numbers. During this step, the overall external dimension and shape of the vehicle remain unchanged. However, it is possible to hypothesize to have an optimal air intake that can work well at Mach 5. It is important to consider that a fixed geometry air intake is designed to optimally work for a specific cruise Mach number, where there is no spillage and the internal flow path drag is minimised. If the flight Mach number is lower, there is an increase in spillage and in the internal drag and down-lift. In Figure 2, the drag and lift coefficients of the STRATOFLY MR3 vehicle are reported. It can be noticed that the air intake works well between Mach 4 and 8, since the additional drag and the down-lift of the internal flow-path are limited in this range.



(a) (b)

Figure 2: Drag (a) and Lift (b) coefficients for MR3 vehicle

However, this is not valid for lower Mach numbers. Here, the unstarting happens and it results in large values of air mass flow spillage, as can be seen from Figure 3. The spillage trend for different Mach numbers is reported in this figure, as obtained from CFD simulations considering both external and internal flow paths. The hypothetical spillage for the MR5 vehicle is also depicted. It has been obtained by an ad-hoc shift of the MR3 curve, that gives a working interval for the MR5 intake between Mach 3 and Mach 5 and a joining of the two curves at Mach equal to 2. This procedure has been verified by two-dimensional CFD simulations whose results are reported in Figure 4. It can be seen that the MR5 intake works better in the range from Mach=2 to Mach=5, while it shows the same efficiency for Mach<2 (Figure 4 b).

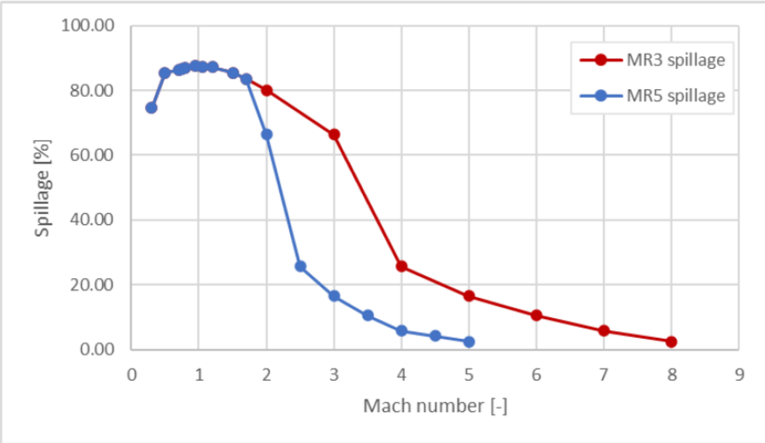


Figure 3: Spillage for MR3 and MR5 vehicles

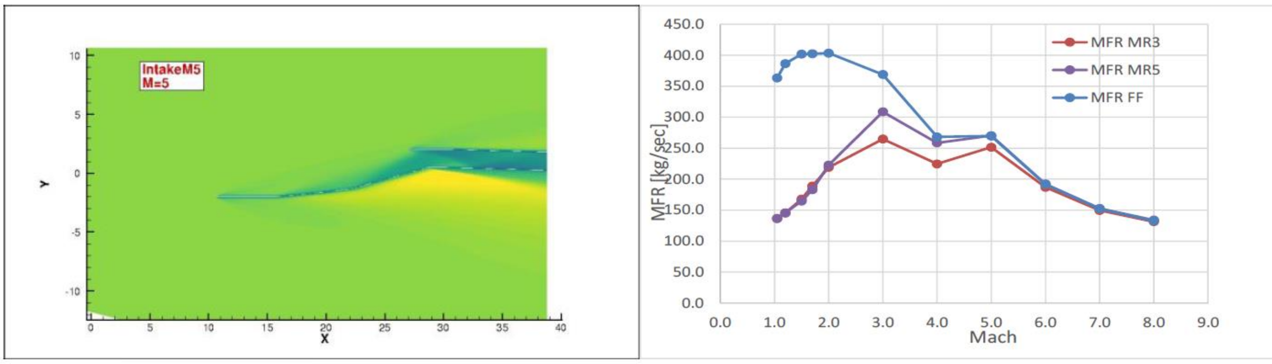


Figure 4: Mach number contour for 2D MR5 intake (a) and mass flow rates (MFR) (b)

From the values reported in Figure 3, it is possible to obtain a scaling factor of the internal flow path coefficients, which is shown in Figure 5.

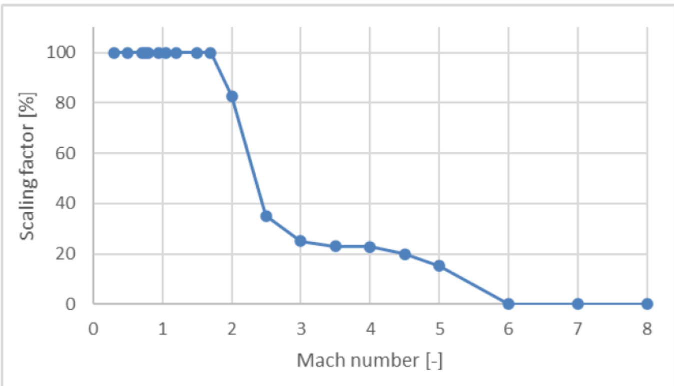


Figure 5: Aerodynamic coefficients scaling factor

Since the adaptation of the air intake affects only the internal flow-path, the scaling factor is applied to the aerodynamic coefficients of the internal duct. The comparison between the unmodified and the scaled version are reported in Figure 6, for the lift (a) and drag (b) coefficient. The drag coefficient decreases in the supersonic range from Mach 2 to Mach 5. Moreover, looking at the CL comparison, it can be noticed that the lift coefficient increases in the range from Mach 2 to 4. At Mach 5, however, the effect is the opposite. This is due to the intake original configuration which is characterized by an up-lift effect for this Mach number. If the scaling is applied, this effect is reduced, and the uplift generated by the intake is approaching zero.

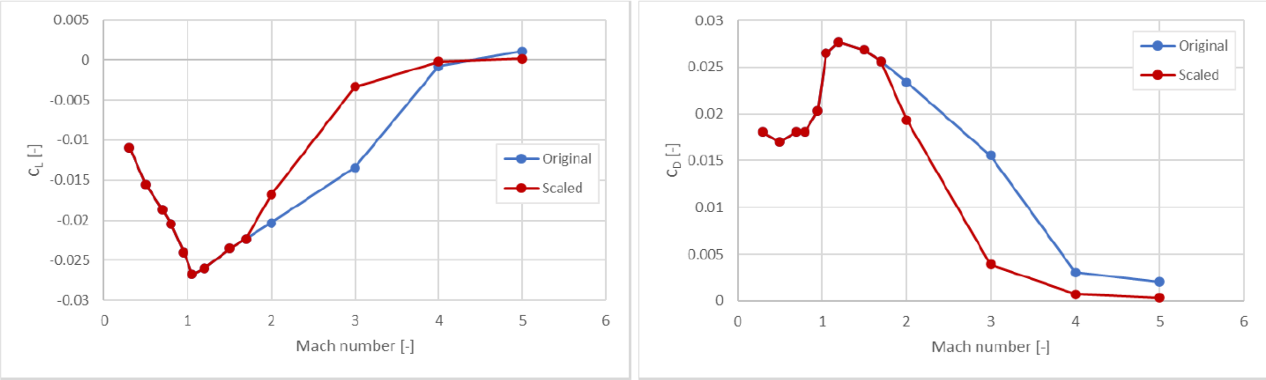


Figure 6: Aerodynamic coefficients comparison between original and scaled intake for internal flow path

2.3 Towards a scaled-down aircraft concept

The study on the preliminary scaling of the air-intake is the first step towards a general scaling-down of the entire aircraft. This further step, involving a multidisciplinary re-design of the vehicle, is just started and it is now under evaluation. However, some crucial aspects of this challenging task can be highlighted here.

First, due to the very large lifting surface of the vehicle, the lift generated during the mission and especially during the cruise phase at Mach 5 is too high. For that reason, the vehicle should fly at angles of attack lower than zero to balance its weight (from -0.9° to -1.2°, depending on the different cases). As a consequence, the vehicle flies in non-optimised aerodynamic and propulsive conditions. A reduction in the vehicle surface could be beneficial from that point of view.

Moreover, the re-design should be performed keeping the overall shape and proportions of the vehicle unchanged as much as possible. If this is done, indeed, the main outcomes of the STRATOFLY project (i.e., aerodynamic and propulsive database) can be exploited and used for the Mach 5 mission.

3 RESULTS

Detailed mission simulations are performed using the ASTOS software, to evaluate the vehicle performance during the mission. The reference mission Brussels to Sydney (BRU-SYD) has been evaluated, with a total distance flown of about 19000 km. The same vehicle configuration of the STRATOFLY MR3 concept has been considered [5]. The total mass of the vehicle is equal to 400 Mg, while the propellant mass is equal to 180 Mg. The maximum propellant which can be stored on-board can be evaluated considering the available volume for fuel and the cryogenic technology. Since the expected entry into service for the STRATOFLY MR3 vehicle is planned in 2050, a far-term cryogenic technology is considered. In this case, the storage density is equal to 90 kg/m3. The available volume on-board is equal to 2000 m3, which results in a maximum fuel mass of 180 Mg. This configuration is used for a first mission simulation. However, the results show that the fuel consumption during the Mach 5 cruise is very low, if compared to the Mach 8 one. As a consequence, the cruise phase can last longer and a maximum distance of more than 30000 km can be covered.

From this analysis it appears that a fuel mass of 180 Mg is too high for the Mach 5 mission and it should be reduced. A lower value can be selected, considering the state-of-art hydrogen storage capability. Currently, the most advanced cryogenic technology is characterised by a density of 70.72 kg/m3. Thus, the maximum fuel that can be hosted on-board is equal to approximately 140 Mg. For that reason, a second mission simulation is run considering this more realistic value for a near term usage, while all the other input are not changed.

Moreover, some additional consideration should be done for what concerns the aerodynamics. Using the complete aerodynamic database, the trim conditions have been evaluated for the STRATOFLY MR3 vehicle and used as an input for the simulation. However, during the STRATOFLY project it has been found that, due to the low aerodynamic performance at supersonic Mach numbers, the vehicle is supposed to fly unstable from Mach=0.95 to Mach= 3 to increase its aerodynamic efficiency as much as possible [5].

The resulting Mach and altitude profile are reported in Figure 7 (a), while the propellant mass variation over time is shown in Figure 7 (b). It can be seen that the reference mission BRU-SYD can be accomplished and a total propellant mass of 120.2 Mg is needed. The residual propellant mass at the end of the mission is then equal to 19.8 Mg.

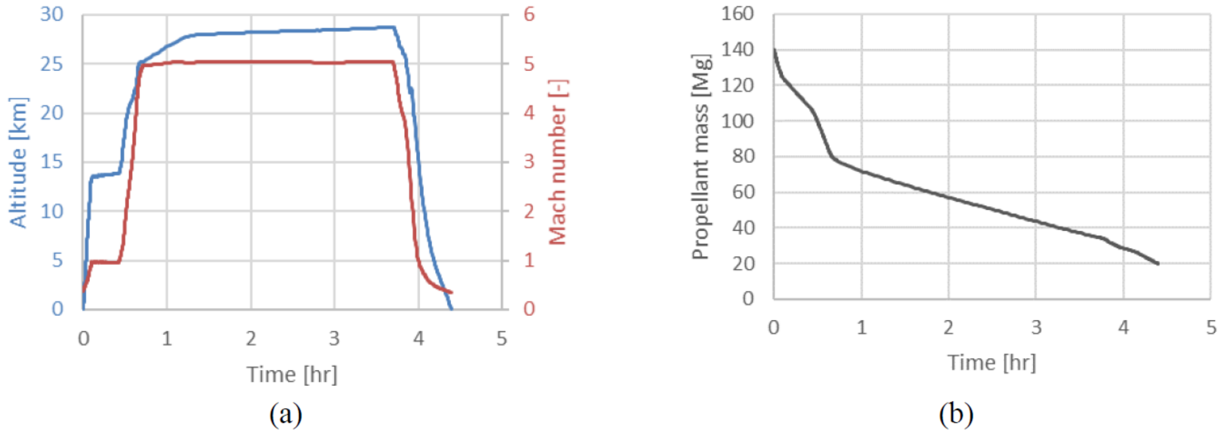


Figure 7: (a) Altitude and Mach profile; (b) Propellant mass variation for the Mach 5 mission

An additional mission simulation is performed considering the vehicle configuration with the scaled air-intake. Before proceeding with the simulation, the vehicle trimmed conditions can be evaluated again at each Mach number, exploiting the updated set of aerodynamic data. A comparison between the aerodynamic efficiency for the original and the scaled version is reported in Figure 8, at an angle of attack (AoA) equal to zero. As expected, the aerodynamic performance are considerably increasing in the supersonic range. The vehicle could now be able to fly stable and with a sufficiently high aerodynamic efficiency in the range from Mach=2 to Mach 5. Moreover, this plot clearly shows the Lift to Drag ratio reduction at Mach 5, since the up-lifting effect coming from the air-intake is not present anymore.

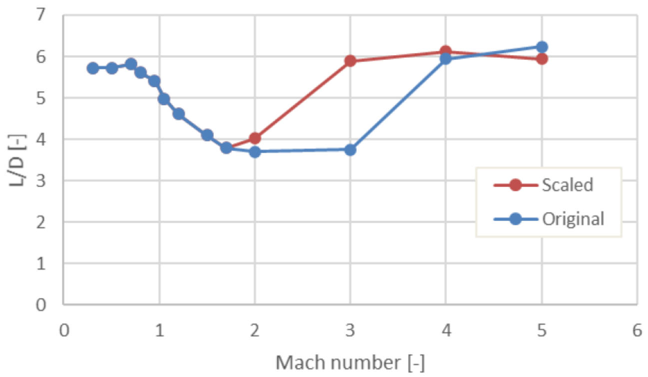
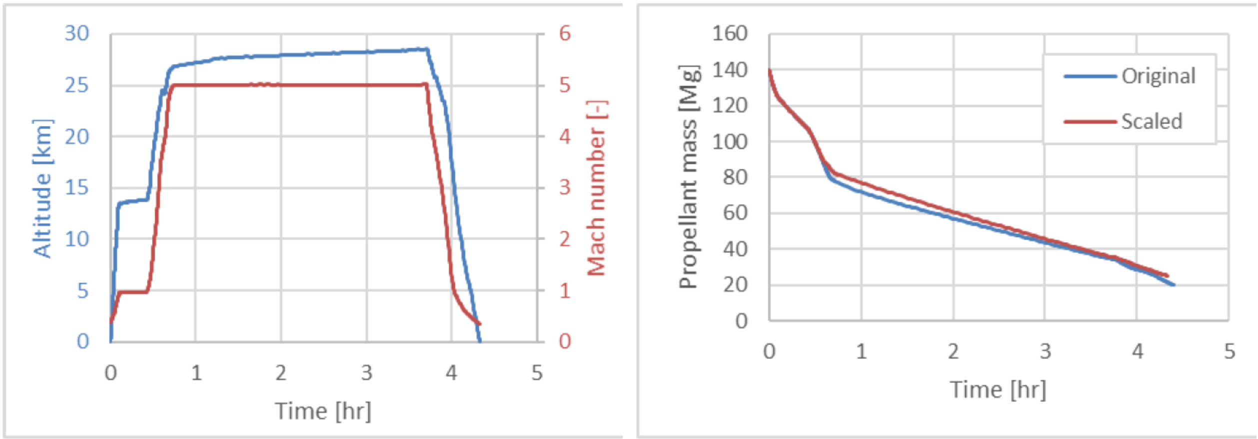


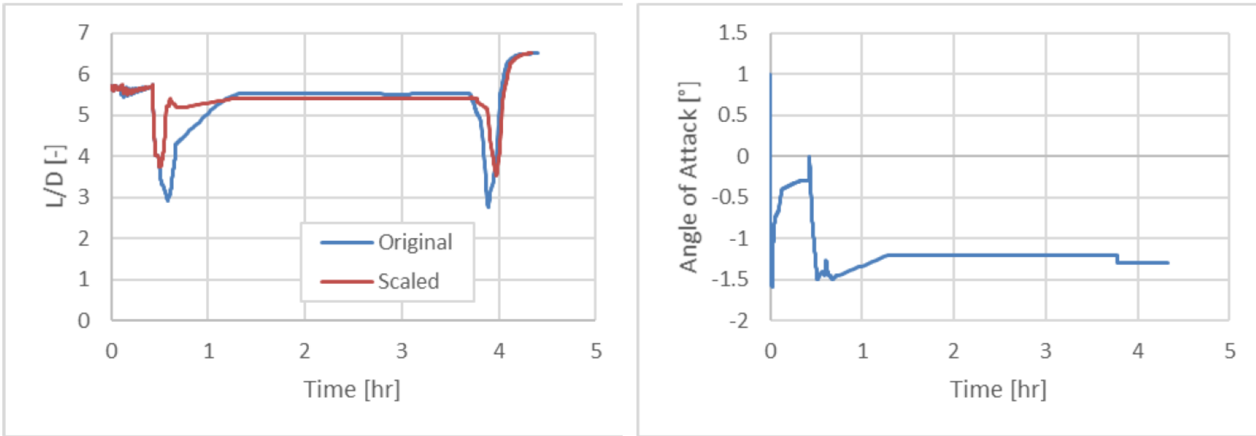
Figure 8: Lift to Drag ratio comparison between original and scaled version

The mission simulation is then run, considering the modified aerodynamic data. The resulting altitude and Mach profile are reported in Figure 9 (a). The propellant mass consumption during the mission is reported in Figure 9 (b), and it is compared to the previous case. The total amount of propellant needed to complete the BRU-SYD mission is now equal to 115 Mg and a reduction of 5.2 Mg is found with respect to the previous simulation. The main differences between the original and the scaled version are found during the supersonic climb. Here the modified air-intake is contributing to improve the aerodynamic performance (Figure 10 (a)) and, as a consequence, the propellant consumption decreases. The AoA variation during the mission is reported in Figure 10 (b). Due to the very large vehicle lifting surface, the AoA must be set to values below 0° to reduce the lift produced and to limit the altitude gain.



(a) (b)

Figure 9: (a) Altitude and Mach profile for scaled version; (b) Propellant mass vs time comparison between original and scaled version



(a) (b)

Figure 10: (a) Lift to Drag ratio comparison between original and scaled; (b) Angle of attack vs time for scaled version

4 CONCLUSION

This paper provides a description of the design activities carried out in the framework of the H2020 MORE&LESS project, exploiting the latest outcomes of the H2020 STRATOFLY project. The STRATOFLY MR3 vehicle, originally designed and optimised to operate at Mach 8, is considered to be adapted for a Mach 5 mission. The preliminary re-design of the vehicle has been described. Starting from the unmodified MR3 concept, different cases are considered depending on the amount of propellant carried on-board. The next step involves the preliminary modification of the air-intake to improve its performance in the supersonic range and to optimally work at Mach 5. At each step, the different concepts have been verified through mission simulation. The capability to perform long-haul routes is verified for all the concepts.

However, a complete re-design of the vehicle is required to better cope with the Mach 5 mission. Given the complexity of this task, which involves a multidisciplinary methodology (vehicle and mission design, subsystem integration, aerothermodynamics and propulsion), this process is currently under evaluation and it is not completed yet. Here some observations regarding the future work can be provided. In particular, the entire propulsive flow-path is expected to be re-designed and improved for the Mach 5 mission, moving towards a scaling-down of the entire vehicle. At the same time, this process is expected to lead to a new configuration which keeps the external shape and proportion of the vehicle unchanged as much as possible.

This is required to assess the potential of the STRATOFLY concept and to fully exploit the main outcomes of the STRATOFLY project.

5 ACKNOWLEDGMENT

The H2020 MORE&LESS Project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 101006856.

REFERENCE

[1] Viola, N.; Fusaro, R.; Gori, O.; Marini, M.; Roncioni, P.; Saccone, G.; Saracoglu, B.; Ispir, A.C.; Fureby, C.; Nilson, T.; et al. STRATOFLY MR3–how to reduce the environmental impact of high-speed transportation. In Proceedings of the AIAA Scitech 2021 Forum, 11 January 2021; p. 1877; doi:10.2514/6.2021-1877.

[2] Ferretto, D.; Fusaro, R.; Viola, N. Innovative Multiple Matching Charts approach to support the conceptual design of hypersonic vehicles. *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.* **2020,** *234*, 1893–1912, doi:10.1177/0954410020920037.

[3] Ferretto, D.; Fusaro, R.; Viola, N. A conceptual design tool to support high-speed vehicle design. In Proceedings of the AIAA AVIATION 2020 FORUM, 15–19 June 2020 Virtual Event; p. 2647, doi:10.2514/6.2020-2647.

[4] Langener, T.; Erb, S.; Steelant, J. Trajectory Simulation and Optimization of the LAPCAT MR2 Hypersonic Cruiser Concept. In Proceedings of the 29th Congress of the International Council of the Aeronautical Sciences, St. Petersburg, Russia, 7–12 September 2014; ICAS 2014 428.

[5] Viola,N.;Roncioni,P.;Gori, O.; Fusaro, R. Aerodynamic Characterization of Hypersonic Transportation Systems and Its Impact on Mission Analysis. *Energies* **2021**,*14*,3580. https://doi.org/ 10.3390/en14123580