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# Concept of Operations and Mission Analysis of STRATOFLY MR3 vehicle

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## Abstract

Hypersonic transportation systems will be a game-changer for the future of aviation sector. For this reason, important effort is placed on the development of high-speed civil aviation concepts among the aerospace community, with a particular focus on the environmental sustainability and social acceptance of such concepts. A new aircraft concept, the STRATOFLY MR3 vehicle, has been studied in the field of the H2020 STRATOFLY project. This paper reports the analysis which has been performed to define the reference mission and related concept of operations for the STRATOFLY MR3 vehicle. Eventually, a detailed mission simulation has been carried on, to verify the vehicle performance and the feasibility of the concept.

**Keywords**: H2020 *STRATOFLY MR3, hypersonic aircraft, waverider concept, mission analysis.*

## 1. Introduction

The worldwide incentive to reconsider commercial high-speed transport urges Europe to quantitatively assess the potential of civil high-speed aviation with respect to technical, environmental and economic viability in combination with human factors, social acceptance, implementation and operational aspects. High-speed commercial flights could be significantly beneficial for long-haul routes to virtually shrink the globe and shorten the time of flight of one order of magnitude for antipodal destinations, thus revolutionizing the present idea of business trips and touristic travels. The satisfaction of this need can however be seriously hampered by the goal of reaching complete decarbonization of aviation by 2050, unless innovative technological solutions are investigated, developed and eventually integrated and validated in operative aircraft. In fact, the higher is the speed of flight, the higher is, generally, the consumption of fuel and consequently emissions, unless breakthrough technologies can intervene to break down this obvious conclusion. In order to allow for a decarbonisation of air travels by 2050, new solutions need to be designed for the various ranges of flight routes, thus leading to different aircraft configurations and enabling technologies for short, medium and long-haul range missions.

As far as long-haul flights are concerned, the targets of zero $CO_2$ emissions and shorter times of flight urge to seek for new solutions in terms of propellant, aircraft configuration and technologies. To shorten the time of flight and to fulfil the requirement of long-haul routes, high speed air-breathing propulsion shall be considered, innovative aircraft configuration with high aerodynamic efficiency shall be targeted and liquid hydrogen, that guarantees complete decarbonization, shall be exploited as not drop-in fuel, thanks to its high specific energy content. Shorter time of flights and long-haul routes are the two crucial mission requirements that have led to a new concept of aircraft that has been named STRATOFLY MR3. STRATOFLY MR3 vehicle is one of the main outcomes of the H2020 STRATOFLY project ( [1], [2], [3] and [4]). It builds up on the heritage of previous studies, which have led to

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LAPCAT MR2.4 as reference aircraft configuration for high-speed long-haul civil passenger transport aircraft ( [5], [6]).

After the introduction, section 2 contains a description of the STRATOFLY MR3 vehicle, then in section 3 an overview of the reference mission is reported. Section 4 gives an overview on the STRATOFLY MR3 Concept of Operations, while Section 5 contains the details and results of the final mission simulation. Eventually main conclusions are drawn.

## 2. STRATOFLY Reference Vehicle

The concept of a hypersonic aircraft makes sense only for long-haul routes with ranges up to antipodal destinations, since long-haul routes maximize the benefits of a hypersonic cruise at Mach 8. For medium-haul routes, the amount of time spent during the cruise phases becomes too short.

Simply based on the Breguet range equation, if the design is driven by the mission requirement of long-haul routes, higher ranges can be achieved thanks to higher values of L/D, in combination with a lower specific fuel consumption, a better propulsive system efficiency and a greater ratio of initial mass with respect to final mass.

Therefore, to match the mission requirement of long-haul routes the waverider configuration has been selected for the STRATOFLY MR3 vehicle to guarantee higher L/D values (L/D > 6). Moreover, liquid hydrogen is exploited as propellant for its higher specific energy, which leads to lower specific fuel consumption and increased propulsive efficiency. Additionally, light weight bubble structures are considered to allow for higher ratios of initial mass with respect to final mass.

The second crucial mission requirement of shorter time of flights (the time of flight shall be shortened of one order of magnitude with respect to current values) leads to the exploitation of high-speed air-breathing engines up to ramjet and scramjet modes of operations. 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.

It is worth remembering that the use of liquid hydrogen guarantees the complete decarbonization, thus fulfilling another top mission requirement.

Therefore, it can be easily stated that STRATOFLY MR3 vehicle is driven by its peculiar mission, which can be summarized as follows: STRATOFLY MR3 shall be able to fly along antipodal route (R > 16000 km) reaching Mach 8 during cruise at a stratospheric altitude (h > 30000 m) carrying 300 passengers as payload. Fig 1 (a) shows STRATOFLY MR3 external configuration.

(a) (b)

**Fig 1. STRATOFLY MR3 (a) external and (b) internal configuration**

As already mentioned, STRATOFLY MR3 has a waverider configuration with the engines and related air duct embedded into the airframe and located at the top, as can be seen in Fig 1 (b). The integration of the propulsive system at the top of the vehicle allows to maximize the available planform for lift generation without additional drag penalties and to optimize 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. Main technical data about STRATOFLY MR3 are reported in Table 1.

**Table 1.** STRATOFLY MR3 main technical data

| Technical data | Value | Unit |
|---|---|---|
| Length | 94.7 | m |
| Wing span | 41.1 | m |
| Overall volume | 10000 | $m^3$ |
| Height | 17 | M |
| Maximum take-off gross weight | 400 | Mg |
| Fuel weight | 181.25 | Mg |
| Maximum thrust at take-off | 2334 | kN |
| Thrust during cruise | 400 | kN |

## 3. STRATOFLY MR3 reference mission

The nominal scenario of the mission performed by STRATOFLY MR3 is described in this chapter, focusing on the different mission phases and identifying the related *start/end* conditions and constraints for each phase.

The STRATOFLY MR3 vehicle is supposed to cover antipodal routes, with an estimated maximum range of around 19000 km. The reference mission considered here is the Brussels to Sydney. It is derived from the LAPCAT II project, where the trajectory of the LAPCAT MR2.4 vehicle was studied [7]. The mission can be generally divided into 11 phases, which are listed below and depicted in Fig 2.

1. Pre-departure
2. Taxi
3. Take-off
4. Subsonic climb
5. Subsonic cruise
6. Supersonic climb
7. Hypersonic climb
8. Hypersonic cruise
9. Descent
10. Final approach
11. Landing

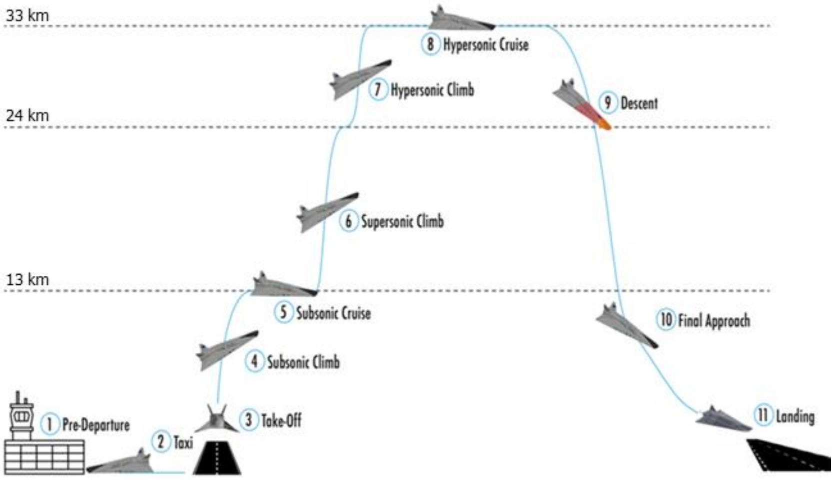


**Fig 2.** STRATOFLY MR3 reference mission

The *pre-departure* phase starts when the crew reaches the aircraft. It involves the tests and procedures needed to check if the system is ready for the departure. The interfaces between ground systems and aircraft shall be opened and operating in order to allow fuelling, water charging and other needed procedures. The phase ends when the boarding is completed and the aircraft is authorised to leave the parking area. Then, the *taxi* starts, when the aircraft leaves the parking area and reaches the take-off runway. The phase ends when the engines are operating at maximum power to perform take off.

During *take-off* phase, the vehicle accelerates on the runway until the minimum speed required to lift-off is reached. The phase ends when the hypothetical obstacle is cleared. The STRATOFLY MR3 is supposed to operate within the present airport infrastructure. The runway length required to complete the take-off should be lower than 4000 m. The subsonic climb is required to reach a Mach number equal to 0.95 and an altitude of approximately 13 km. However, since the current aviation regulation prohibit the supersonic flight over land, a *subsonic cruise* is required to move away from inhabited areas and avoid the sonic boom while flying over land.

Once the aircraft is over the ocean, it is possible to transitions through and fly faster than the speed of sound. The duration of this phase is directly dependent on the departure site and its distance from the ocean. A constraint on the distance flown from the departure airport is introduced to fulfil this requirement: a distance of 400 km is considered as a maximum value. The Brussels airport satisfies this requirement, however each other airport located at a distance lower than 400 km from sea can be considered.

The aircraft continues its mission performing a *supersonic climb* up to a Mach number of 4 at an altitude of about 24 km. This is the condition which corresponds to the switch from one propulsion system (ATR) to the other (DMR). From Mach 4 to Mach 4.5 the thrust generated by the DMR only is not sufficient. For that reason, during this part of the flight the DMR is used together with the ATR engines. The *hypersonic climb* phase is required to increase altitude and speed up to the cruise conditions, at an altitude of about 32 km and a Mach number of 8.

The *hypersonic cruise* is the longest phase of the mission. The Mach number is kept constant, while the altitude is slightly increasing from 32 to 36 km. At the end of the hypersonic cruise, the *descent* phase starts. Initially, this phase is initially conceived to be performed in engine-off conditions, as it was for the LAPCAT MR2.4 concept. However, this option is later discarded, since an unpropelled flight could cause accelerations which are too high for the passengers on-board. For that reason, the engines are kept active during the descent. The vehicle decelerates and decreases its altitudes, while moving towards the landing airport. In the proximity of the airport the vehicle performs the *final approach* and *landing.*

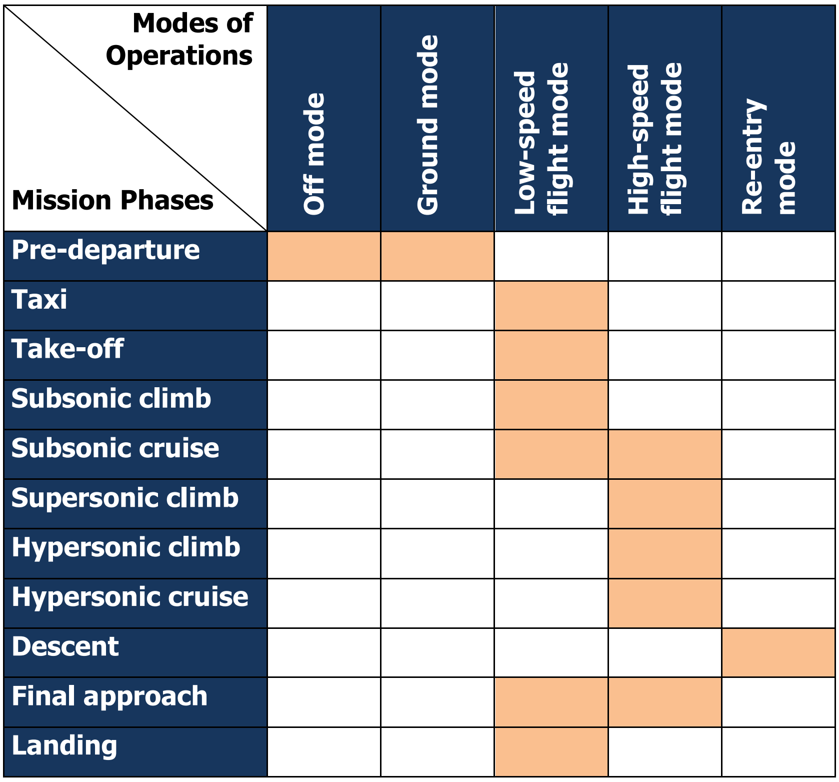
## 4. STRATOFLY MR3 Concept of Operations

Once the STRATOFLY MR3 reference mission is defined, it is important to describe how the system will work during the mission phases in order to meet mission objectives. First, this activity is performed from an overall system point of view. Then, it is also done for each of the different subsystems. Here, only the *system level mode of operations* are considered, to give an overview of the way the system works during the mission. Five different modes of operations are identified and reported in Table 2.

The Phases/Mode Matrix is also reported in Fig 3. The first two modes of operations, *off mode* and *ground mode,* are related to the phases in which the aircraft is still on ground. *Low-speed mode* and *high-speed mode* are related to the situation in which the aircraft is performing the climb/cruise phases. In particular, the *low-speed mode* refers to the subsonic phases, while the high-speed mode is related to the supersonic and hypersonic phases. The *re-entry mode* is instead related only to the descent phase, in which the engines are active at low power and the aircraft shall survive the high external heat flow during the atmospheric re-entry.

**Table 2.** Mode of operations

| Modes of Operations | Description |
|---|---|
| Off mode | The overall system is turned off. |
| Ground mode | Only components aimed to provide energy, maintain the internal environment and check the state of the system are active. Interfaces with on-ground facilities are also active. |
| Low-speed flight mode | All the subsystems aimed to allow the flight and control the vehicle are active; other active components are those related to internal energy production and internal environment management. |
| High-speed flight mode | Sinergy between propulsion, propellant, thermal protection and energy management subsystems is needed to allow the flight and survive the external environment characterized by high speed and high heat flow. Other active components are aimed to control the flight and manage internal environment. |
| Re-entry mode | All the subsystems needed to control the vehicle during flight, produce energy, manage internal environment and survive external environment are active. Engines are active to avoid too high rates of descent. |



| Modes of Operations / Mission Phases | Off mode | Ground mode | Low-speed flight mode | High-speed flight mode | Re-entry mode |
|---|---|---|---|---|---|
| **Pre-departure** | ▨ | ▨ | | | |
| **Taxi** | | | ▨ | | |
| **Take-off** | | | ▨ | | |
| **Subsonic climb** | | | ▨ | | |
| **Subsonic cruise** | | | ▨ | ▨ | |
| **Supersonic climb** | | | | ▨ | |
| **Hypersonic climb** | | | | ▨ | |
| **Hypersonic cruise** | | | | ▨ | |
| **Descent** | | | | | ▨ |
| **Final approach** | | | ▨ | ▨ | |
| **Landing** | | | ▨ | | |

**Fig 3.** System level Phases/Modes Matrix

## 5. STRATOFLY MR3 mission simulation results

Mission simulation is performed using the software ASTOS 9.17 by Astos Solutions GmbH. Different inputs are required to define the vehicle and its performance, such as vehicle geometry, aerodynamic database and propulsive database. For what concern the aerodynamic database, in the field of the STRATOFLY project, simplified CFD simulation campaigns have been performed which guarantee reliable results without excessively compromising the available resources. Moreover, a longitudinal stability analysis is carried on, which allows to generate a complete trimmed aerodynamic database to be used for mission analysis. A detailed overview of the aerodynamic characterization can be found in [8]. Similarly, the propulsive database has been generated for various flight altitude, Mach number and air-fuel mixture ratio. The propulsion system is optimized to produce higher thrust while reducing the fuel consumption if compared to the previous LAPCAT MR2.4 project. [9]

Each flight phase can be defined in ASTOS, to provide a complete characterization of the mission concept. The time duration and/or final constraints can be defined for each phase. It is also possible to specify which engine is active. Moreover, angle of attack (AoA) and throttle are the two parameters which are used to control the vehicle throughout the simulation. The angle of attack is set to vary in the range -2°/+2°, while the throttle can vary between 0 (engine-off conditions) and 1 (full thrust). The vehicle initial conditions, as set in ASTOS, are reported in Table 3. It must be noted that the simulation starts at the end of the take-off phase, since the runway acceleration at take-off cannot be properly simulated in ASTOS. An initial velocity of 128 m/s is set to ensure lift-off and to guarantee the stability of the simulation.

**Table 3.** Initial conditions for mission simulation

| Initial condition | Value |
|---|---|
| Latitude | 50.9 deg |
| Longitude | 4.49 deg |
| Altitude | 0 m |

| | |
|---|---|
| Velocity | 128 m/s |
| Heading | -15 deg |

The results of the reference trajectory simulation are reported in the following figures. The Brussels to Sydney mission can be completed with a total travel time of approximately 3h 30min. An overview of the complete trajectory is reported in Fig 4, where the main characteristics of the route can be clearly identified. Since it is necessary to avoid flying over land due to the sonic boom requirements, the vehicle cannot follow the shortest trajectory towards the destination airport in Sydney. During the first part of the cruise, it flies over the arctic region towards the Bering strait, between Asia and North America. Then, the aircraft continues to cruise over the Pacific Ocean towards Sydney. A detailed view of the first part of the mission is reported in Fig 5. At the end of the subsonic climb phase, the vehicle is still over land, even if it is few kilometres away from the sea. A shorter subsonic cruise could be considered from that point on, instead of the 400 km one. However, this value is kept unchanged, so that the results can be valid for other departure airport which are at a maximum distance of 400 km from the sea.

Fig 6 show the descent phase, which is performed over the Pacific Ocean. During this phase, the trajectory is modelled to avoid that the vehicle flies over land at a Mach number greater than one. For that reason, the aircraft performs a right turn in the vicinity of the Sydney airport, where it reaches subsonic speed.

**Fig 4.** Overview of complete trajectory BRU-SYD**.** Trajectory characterized by Mach number.

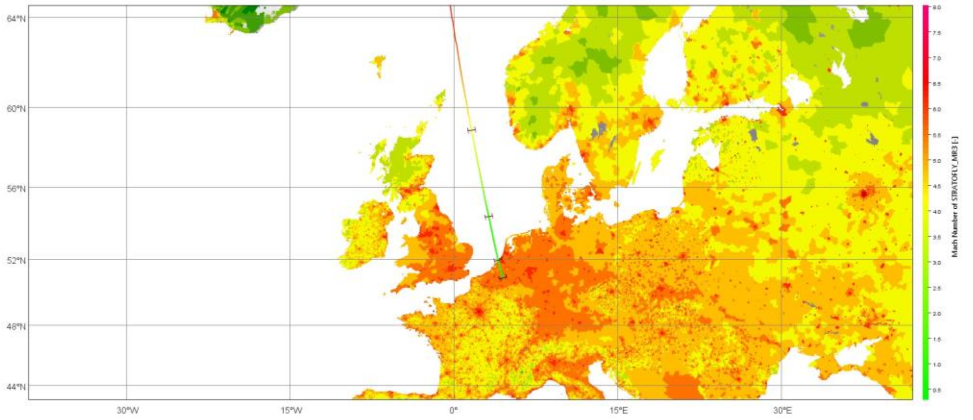


**Fig 5.** View of take-off in Brussels and climb between Norway and Britain. Trajectory characterized by Mach number. Map colours show the population density

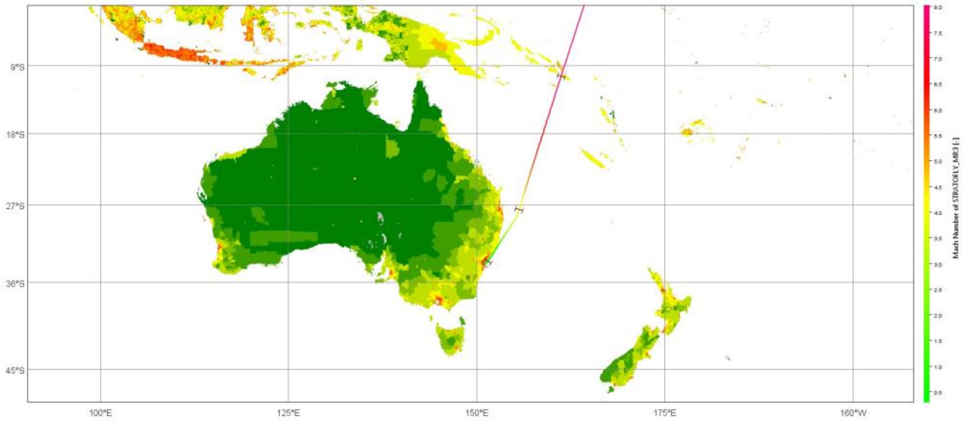


**Fig 6.** View of the arrival and landing in Sydney airport. Trajectory characterized by Mach number. Map colours show the population density

The altitude and Mach profile of the STRATOFLY MR3 vehicle are reported in Fig 7, while the Mach number versus the distance flown is shown in Fig 8. It can be noticed that a total distance of almost 19000 km can be covered by the STRATOFLY MR3 vehicle concept.

The time required to perform the different phases is reported in Table 4. A total time of 55 minutes is required to reach the cruise conditions, while approximately 90 minutes are spent to complete the cruise phase. The time required to complete the descent and to reach the destination airport is equal to 59 minutes.

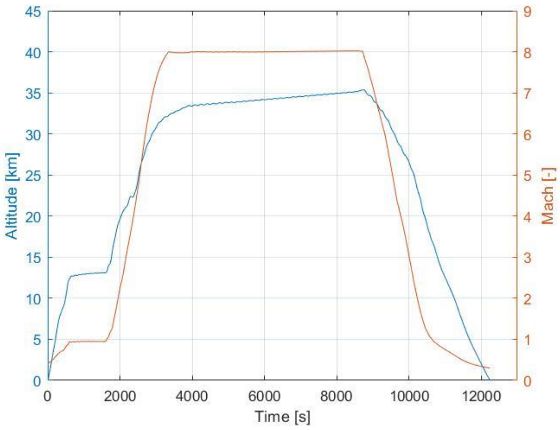


**Fig 7.** Altitude and Mach vs Mission Time

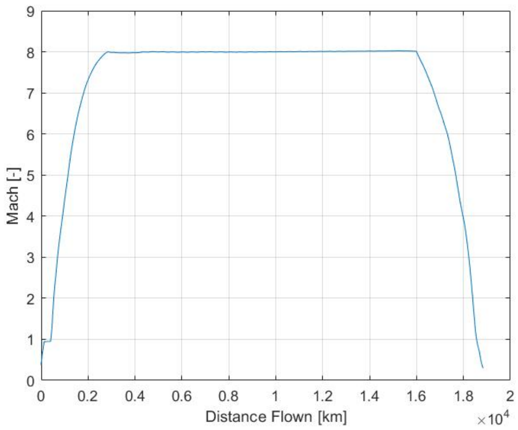


**Fig 8.** Mach number vs Distance Flown

**Table 4.** Overview of the time required to complete each phase

| Phase | Phase time [min] | Total mission time [min] |
|---|---|---|
| Subsonic climb | 10 | 10 |
| Subsonic cruise | 16 | 26 |
| Supersonic climb | 13 | 39 |
| Hypersonic climb | 16 | 55 |
| Hypersonic cruise | 90 | 145 |
| Descent | 59 | 204 |

The total amount of propellant mass employed for the mission is equal to 179 Mg, with about 2 Mg of propellant that are left at the end. The variation of the vehicle mass and the propellant mass with time is shown in Fig 9.

The lift to drag ratio profile is reported in Fig 10. The L/D is maximised during cruise and it is equal to 7, a value that satisfies the aerodynamic performance requirement which is defined at the beginning of the project (L/D>6). The L/D lowest value (L/D≈3) is found during the supersonic climb. This drop in the aerodynamic performance has a direct impact on the duration of the climb phase, which becomes longer than expected.

The thrust and mass-flow profiles are reported in Fig 11, for the ATR (continuous line) and DMR (dotted line). The highest thrust level is required during the climb phase, so that the vehicle is able to accelerate and gain altitude. During cruise, the equilibrium conditions is guaranteed and the thrust is equal to the drag. Low thrust is required during descent: here, the throttle is only used to produce enough thrust to avoid a too steep descent, which would result in too large values of rate of descent. The rate of climb and descent (ROCD) is reported in Fig 12. Here, the comparison between the engine-on and the engine-off descent is also shown. The blue line is referred to the mission with the powered descent, while the orange line shows the rate for the gliding descent. The rate of climb (ROC) reaches a maximum value of almost 30 m/s, during the first part of the climb phase. During descent, the maximum rate of descent (ROD) is limited to -20 m/s. It can be noticed how the ROD increases significantly (up to -60 m/s) in case the engines are not used during the descent. For that reason, the propelled descent is considered for the STRATOFLY MR3 mission.

The variation of the angle of attack during the mission is shown in Fig 13. Angles lower than zero are needed throughout the entire mission. If the AoA is different from zero, the vehicle flies in non-optimal condition from the point of view of the aerodynamic and propulsive performance. However, the use of low AoAs is required to avoid that the vehicle generates too much lift due to its large lifting surface, which would result in a fast gain and/or loss of altitude and in an increase of the ROCD.

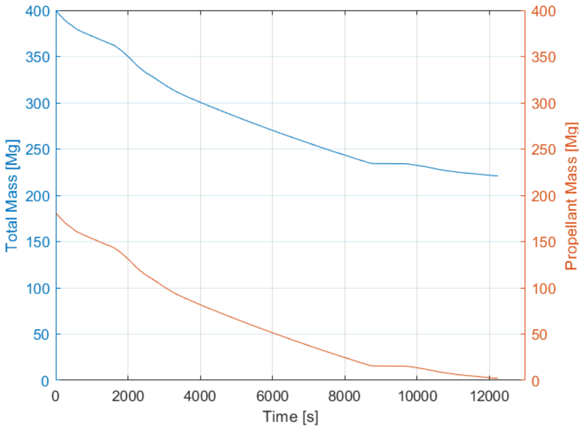


**Fig 9.** Total and propellant mass vs time

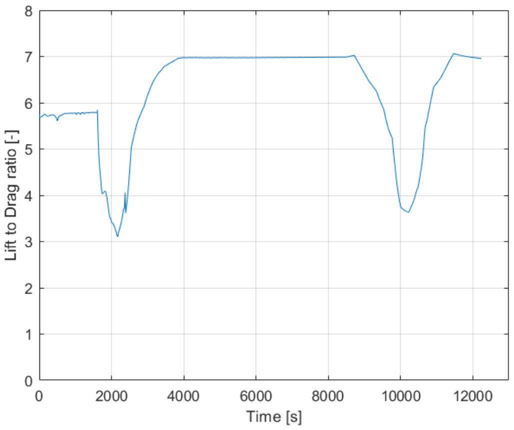


**Fig 10.** Lift to Drag ratio vs Mission Time

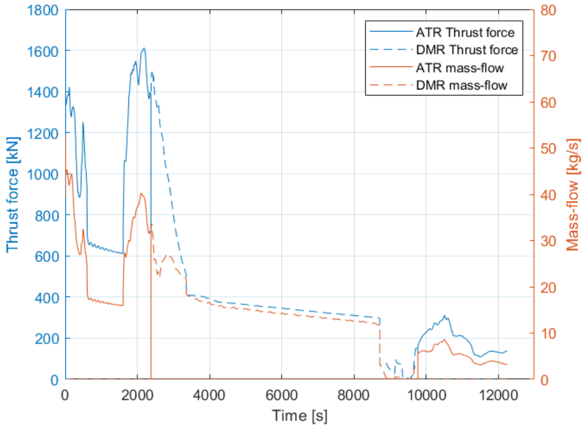


**Fig 11.** Thrust force and Mass-flow vs Mission Time

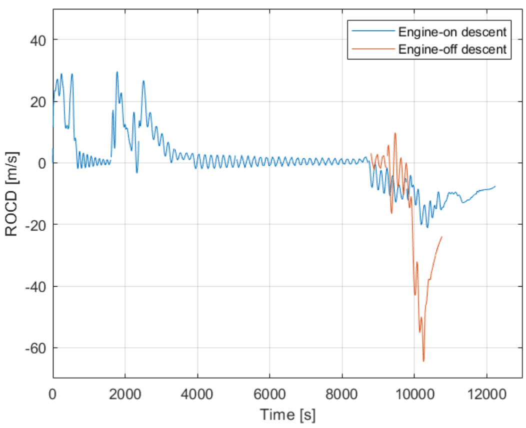


**Fig 12.** Rate of Climb/Descent vs Mission Time for engine-on and engine-off descent

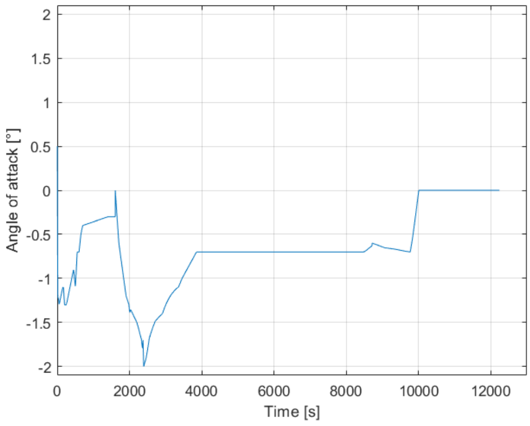


**Fig 13.** Angle of Attack vs Mission Time

## 6. Conclusions

This paper provides technical insight on concept of operations and mission analysis activities, performed in the field of the H2020 STRATOFLY project for the STRATOFLY MR3 Mach 8 waverider concept. Based on the main outcomes of the previous LAPCAT II project, long-haul routes, with a range greater than 16 000 km are considered. In particular, the route from Brussels to Sydney is defined as the reference mission. Moreover, any possible constraint which could affect the mission is evaluated. For example, the present regulation which prohibits to fly supersonically over land is considered. For that reason, almost the entire route is performed over the ocean, apart from the initial and final subsonic segments.

Mission and vehicle concept validations are carried out, exploiting the mission simulations. The STRATOFLY MR3 vehicle concept is proven to be successfully able to complete its mission and meeting all the high-level requirements, given the vehicle layout and the aerodynamic and propulsive databases. Notably, the STRATOFLY MR3 hypersonic cruiser is able to cover the Brussels-Sydney route (of about 19000 km) in 3h 24min using around 181 tons of liquid hydrogen.

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