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# Trajectory and Flight Mechanics Analysis of the HEXAFLY-INT Experimental Flight Vehicle

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## Abstract

In the context of a funding by the *European Space Agency* (ESA) and the *European Commission* (EC) within the 7th Framework Program, the *High-Speed Experimental Fly Vehicles – International* (HEXAFLY-INT) project has the main objective to perform a flight validation of hypersonic technologies enabling future trans-atmospheric flights.

The *Experimental Flight Test Vehicle* (named EFTV) is planned to be launched by the Brazilian VBS43 launcher, equipped with a S43 rocket engine which will perform a suborbital trajectory with an apogee at 90 km. After the release at 55km, the EFTV will perform a pull-out manoeuver bringing it to a levelled flight at an altitude of about 30km, where the experimental phase will start in hypersonic cruise at approximately Mach 7. This maneuver, combined with a lateral one, will be accomplished thanks to the onboard GNC algorithms, making the EFTV capable to perform a fully autonomous flight by using the aerodynamic control surfaces only.

Generally speaking, the Flight Mechanics analyses are essential to investigate the open-loop vehicle flyability properties (trimability, controllability, etc.). Using this kind of analyses, the reference trajectory to be tracked by the GNC can be defined through a procedure capable to optimize a desired cost function along the trajectory itself respecting, at the same time, assigned constraints.

The EFTV mission requirements – in terms of objectives and constraints – have been considered, as inputs, in the process of the trajectory generation. The aim of this paper is to describe the process of the EFTV trajectory generation and, in addition, to perform a dispersion analysis taking into account all the available uncertainties about vehicle mass, aerodynamics, measurement errors, etc.

**Keywords**: *high-speed, trajectory, vehicle design, flight testing, flight mechanics*

## Nomenclature

AoA – Angle of Attack
CLA – Centro de Lançamento de Alcântara
CGS – Cold Gas System
CoG – Centre of Gravity
D – Drag force
Dof – degree of freedom
EC – European Commission
EFTV – Experimental Flight Test Vehicle
ESM - Experimental Support Module
FPA – Flight Path Angle
GNC – Guidance Navigation and Control
HEXAFLY – High-Speed Experimental Fly Vehicle
L – Lift force
LRF – Layout Reference Frame
M – Mach number
MCI – Mass, Centre of Gravity, Inertia

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MRC – Moment Reference Centre
Re – Reynolds number
RMS – Root Mean Square
SM – Static Margin

*Greek*
$C_{m\alpha}$ – Slope of the pitch moment coefficient
$\delta$ – Trim deflection
$\Delta PGPS$ – GPS position error
$\Delta VGPS$ – GPS velocity error
$\Delta x$ – longitudinal CoG shift
$\Delta z$ – vertical CoG shift
$\chi$ – Track angle
$\Delta\chi$ – Track angle error

## 1. Introduction

The HEXAFLY-INT project aims at in-flight testing an experimental vehicle above Mach 7 to verify its potential for a high cruise efficiency during a free-flight [1]. The feasibility for a 3m long vehicle was demonstrated during the European L0 precursor project HEXAFLY [2]. Its realization is now being enabled on an international scale underlining the need for global cooperation in case of a future deployment of a high-speed cruiser.

The entire HEXAFLY-INT mission is depicted in Fig. 1. The *Experimental Flight Test Vehicle* (EFTV) and ESM assembly (Fig. 3) will be launched by a sounding rocket, the Brazilian VBS43 equipped with 8 tons solid rocket motor, in a suborbital trajectory having an apogee at about 90km and Mach 8. The vertical launch is planned from the Centro de Lançamento de Alcântara (CLA) in Brazil.

After the release at apogee from the launcher, the attitude of the mentioned assembly is controlled at high altitudes by means of a *Cold Gas System* (CGS). Indeed, the EFTV will perform the early descent flight docked to the ESM and it will undock at about 55 km altitude; then it will pull up to perform a hypersonic cruise at approximately Mach 7 and at an altitude of about 30km. The EFTV mission timeline is reported below:

- ESM/EFTV Separation
- pull-out maneuver
- Heat flux peak
- g-load peak
- experimental window
- controlled and Stabilized Flight
- gliding Phase
- splash-down/Impact

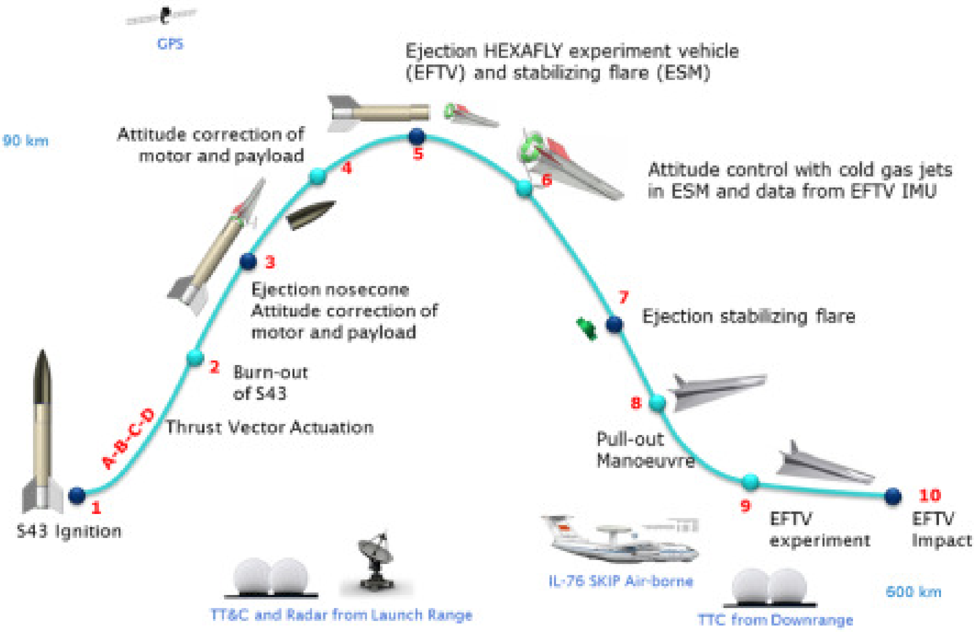

**Fig. 1** HEXAFLY-INT mission phases.

## 2. EFTV flight simulator

Simulations of EFTV flight are carried out through a 3Dof simulation model where AoA and bank angle are given as input commands. The vehicle state is then represented by the following six quantities:

- Speed
- Flight path angle
- Heading angle (from North in clockwise direction)
- Latitude (geodetic)
- Longitude
- Altitude

Clearly, the values of geodetic latitude and heading angle are converted in geocentric latitude and heading angle from East in counter clock wise direction before starting simulations as a 3Dof model require.

The 3Dof simulator is part of the process described in Fig. 2 where the trajectory design and verification process is shown. As a matter of fact, the results of trajectory analysis and verification are used to continuously refine the trajectory optimization and guidance design.

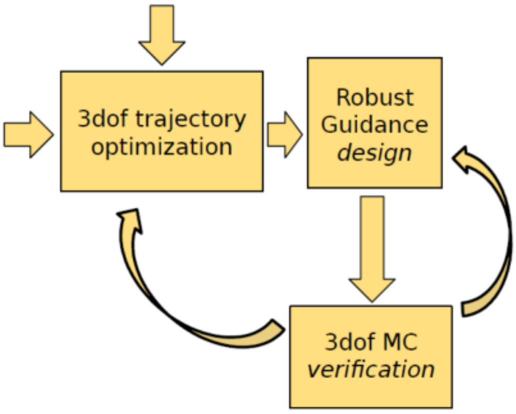

**Fig. 2** Trajectory Design & Verification process.

## 3. EFTV configuration

The EFTV is shown in Fig. 3. It is a hypersonic glider 3.29m long and with a wing span of about 1.23m.

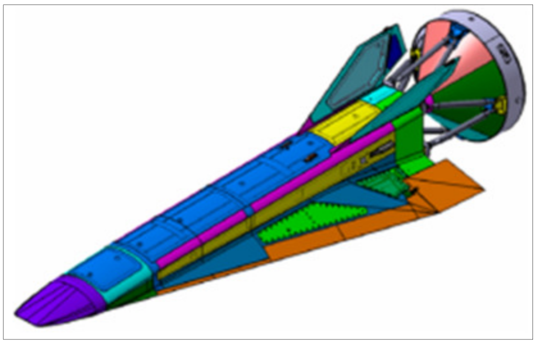

**Fig. 3** EFTV and ESM view.

The vehicle is equipped with two elevons (0.4m long and 0.32m wide), which can be commanded independently of each other, and a couple of fixed vertical fins to improve lateral-directional stability characterized by a 68.5deg sweep angle and a 54deg angle between the two fins in the transversal plane.

The 3dof EFTV flight simulator accepts, as MCI information, only the mass while the centre of gravity position is used for the computation of both trim elevon deflection and static margin, which are added as outputs of the simulator. The assumed mass is 462 kg while [1.4819, -0.0001, -0.008] m is the given CoG position in the *Layout Reference Frame*, LRF (Fig. 4). The MRC (*Moment Reference Centre*) is positioned at [1.455 0 0.12] m (57% EFTV length), again in LRF.

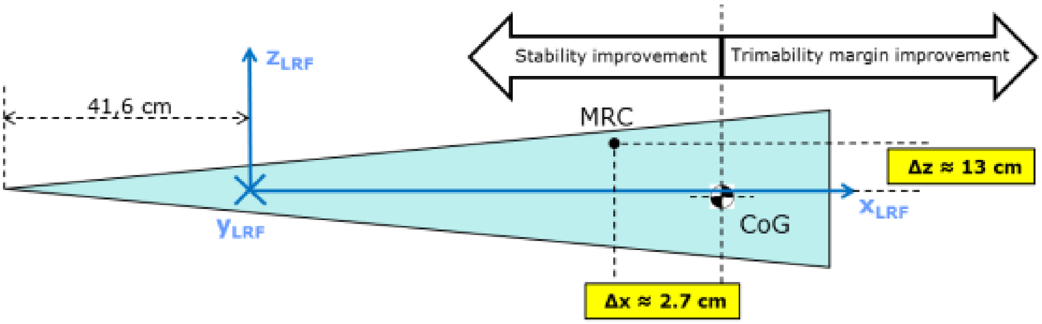

**Fig. 4** EFTV MRC and CoG positions in LRF.

## 4. Initial and terminal EFTV flight conditions

The initial EFTV state is reported below:

- Speed: 2321.7 m/s;
- Flight path angle: -19.5 deg;
- Heading angle (from North in clockwise direction): 56 deg;
- Latitude (geodetic): 0.2469 deg;
- Longitude: -40.627 deg;
- Altitude: 55 km (separation from ESM).

The simulation ends at Mach 2 as the controlled phase of EFTV flight is down to Mach 2.

## 5. Mission objectives and constraints

The EFTV flight has the objective of performing a flight above Mach 7, with maximum aerodynamic efficiency, in a specified altitude range and in a quasi-levelled flight (i.e., with small flight path angle).

Specific constraints are defined for the lateral manoeuvre, driven by safety and telemetry reasons. All these information led to the definition of objectives and constraints of the trajectory and they are collected below in Table 1.

The structural limitations are represented by the maximum heat flux, dynamic pressure, vertical load factor and hinge moment. These values are strongly dependent on the mass value.

**Table 1.** EFTV trajectory constraints.

| Trajectory | Variable | Constraint | Type |
|---|---|---|---|
| Vertical | Vertical Load Factor, $N_z$ [g] | <8 | Mandatory |
| | Dynamic pressure, $P_{dyn}$ [kPa] | <65 | |
| | Heat flux [kW/m$^2$] | <760 | |
| | Aerodynamic efficiency, E=L/D [-][3] | >4 | |
| | Mach number, M [-][3] | 7<M<8 | |
| | Flight Path Angle, FPA [deg][3] | >-3 and <3 | Optional |
| | Altitude [km][3] | >27 and <33 | |
| | Trim deflection range, $\delta$ [deg][4] | >-20 and <5 | Mandatory |
| | Static Margin, SM [-] | >0 | |
| Horizontal | Final Track angle, $\chi$ [deg] | -48 | |
| | Final Track angle error, $\Delta\chi$ [deg] | <1 | |
| | Final Track angle derivative error, $\Delta\chi_{dot}$ [deg/s] | <0.01 | |
| | Distance from Fortaleza [km] | <600 | |

## 6. EFTV Reference Trajectory

In this section, the process of EFTV trajectory generation is described. Starting from the trajectory objectives and constraint previously defined, the reference trajectory is designed and subsequently verified through a dispersion analysis, i.e. taking into account all the uncertainties applicable to 3Dof simulators (see sec. 7).

### 6.1. Trajectory generation procedure

An optimization procedure has been employed for the generation of the reference trajectory. This semi-automatic tool is based on the Matlab® optimization routine named "fmincon" where the objective function and inequality constraints have been defined coherently with the Table 1.

A first longitudinal optimization is performed to ensure that the main EFTV survival requirements are met, then a lateral optimization is performed in order to guarantee the compliance to the position requirements. Finally, a new longitudinal optimization is repeated to perform a fine tuning of the angle of attack command thus guaranteeing a better requirements' satisfaction.

In other words, the trajectory optimization process can be defined as the problem to find commands for AoA and bank angle commands which minimize:

- the RMS of FPA during the experimental window (longitudinal trajectory optimization sub-procedure),
- the RMS of bank angle (lateral trajectory optimization sub-procedure)

For what concerns experimental window, it is worth noting that the mission requirements don't give a clear indication about the beginning and the end of this phase of flight, in which the trajectory has to comply with specific mission requirements. For this reason, it has been decided to set:

- the beginning of experimental window just after the peaks of heat flux and dynamic pressure, when EFTV reaches an almost horizontal condition after the initial fall and consequent pullout maneuver (about 40-50 s since ESM/EFTV separation);

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[3] In the experimental window.

[4] Range of definition of the used aerodatabase.

- the end of the experimental window at Mach 5, conventionally considered the limit for hypersonic regime.

### 6.2. Vertical Trajectory

The vertical trajectory is composed by four different phases, detailed hereafter.

***Flight Segment 0: Pull-Out maneuver***

In the initial part of trajectory, the EFTV penetrates rapidly and steeply into the atmosphere. Consequently, the peaks of some very important quantities (such as dynamic pressure, heat flux, load factor and hinge moment) are reached very soon, within the first 40-50 seconds.

Furthermore, these peaks are very dangerous being hard constraints for them (Table 1), therefore the best choice is to fly at high angle of attack.

***Flight Segment 1: Leveled flight***

In this phase, the EFTV flight is almost leveled and the Mach number changes between 7 and 8. According to the mission requirements, the EFTV should fly with an aerodynamic efficiency greater than 2.5, in a given Mach number range and, possibly, within a given range of altitude and with a flight path angle lower enough (Table 1) in the abovementioned experimental window.

In Fig. 5 the aerodynamic efficiency is reported against AoA for several Mach number, at a Reynolds number of $10^6$.

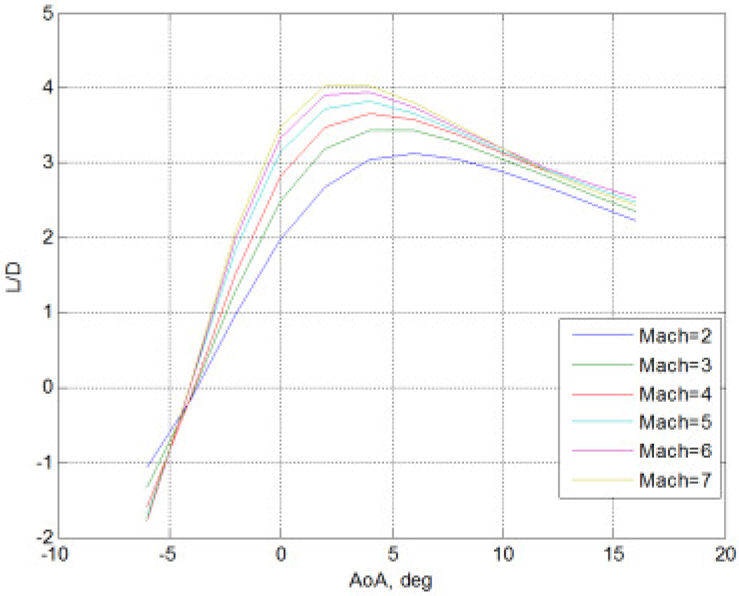

**Fig. 5** Aerodynamic efficiency against AoA and Mach (Re=$10^6$)

As it can be seen, for Mach number between 5 and 7 (range of interest for the beginning of the EFTV flight), the highest efficiency is obtained at low angles of attack.

***Flight Segment 2: Gliding***

In this phase the Mach number decreases from 7 to 2. There are no specific mission requirements after the experimental window and also the structural limitations are not a concern in this phase.

The unique constraint is the one related to the vehicle static stability (through the Static Margin, SM) along the trajectory. Furthermore, a high downrange is desirable.

***Flight Segment 3: Deceleration***

In this termination phase, the Mach number decreases from 2 until the EFTV splash-down event. In this segment, EFTV is not controlled by GNC; anyway this phase is beyond the scope of this paper.

The AoA reference (nominal) signal coming from the optimization procedure is reported in Fig. 6. As already mentioned, the experimental window starts at 50s and ends at M=5 (210s).

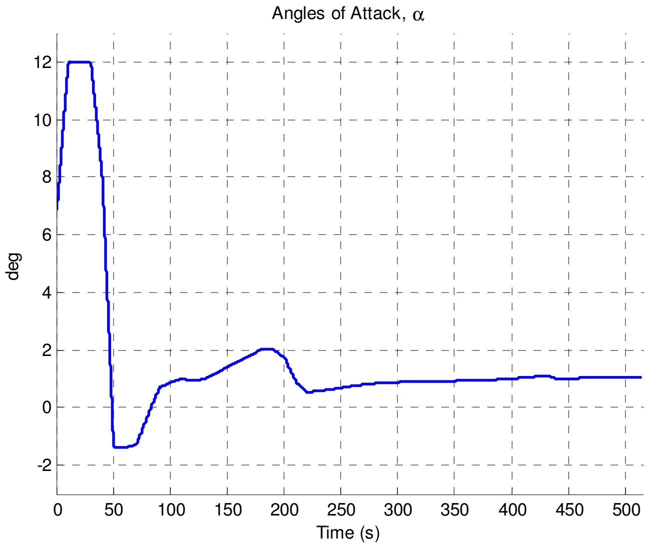

**Fig. 6** Reference AoA signal

The related trim deflection is shown in **Fig. 7**.

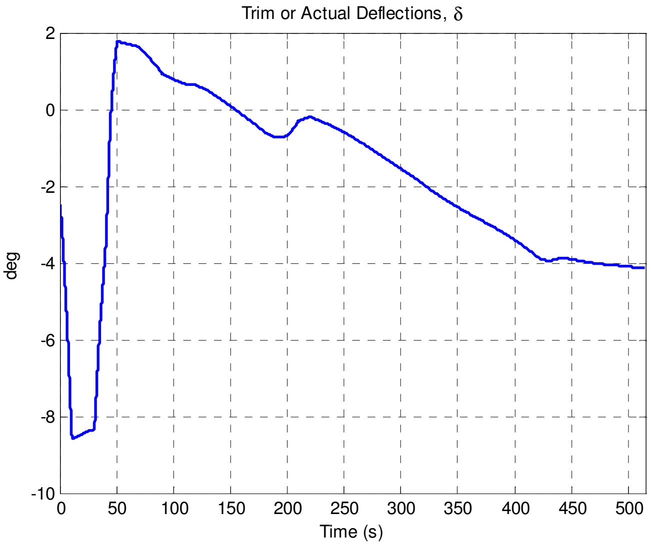

**Fig. 7** Reference trim deflection angle

The nominal HM time history is reported in Fig. 8 and its huge peak does not depend on the dynamic pressure, but mainly on the relationship between hinge moment coefficient and trim deflection (Fig. 9).

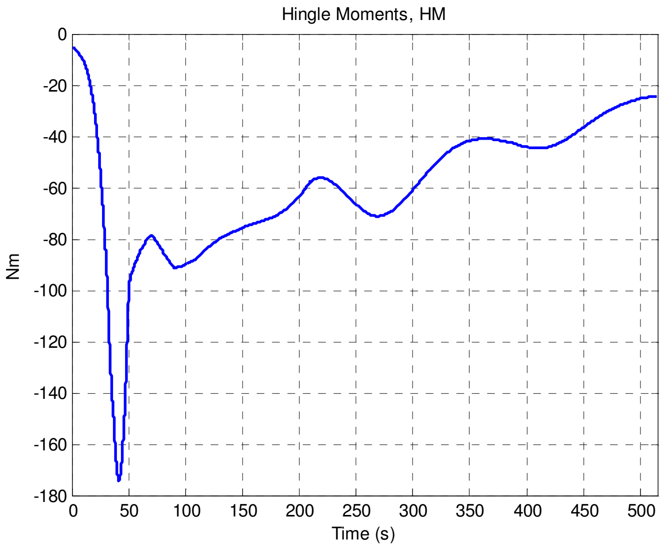

**Fig. 8** Reference Hinge Moment

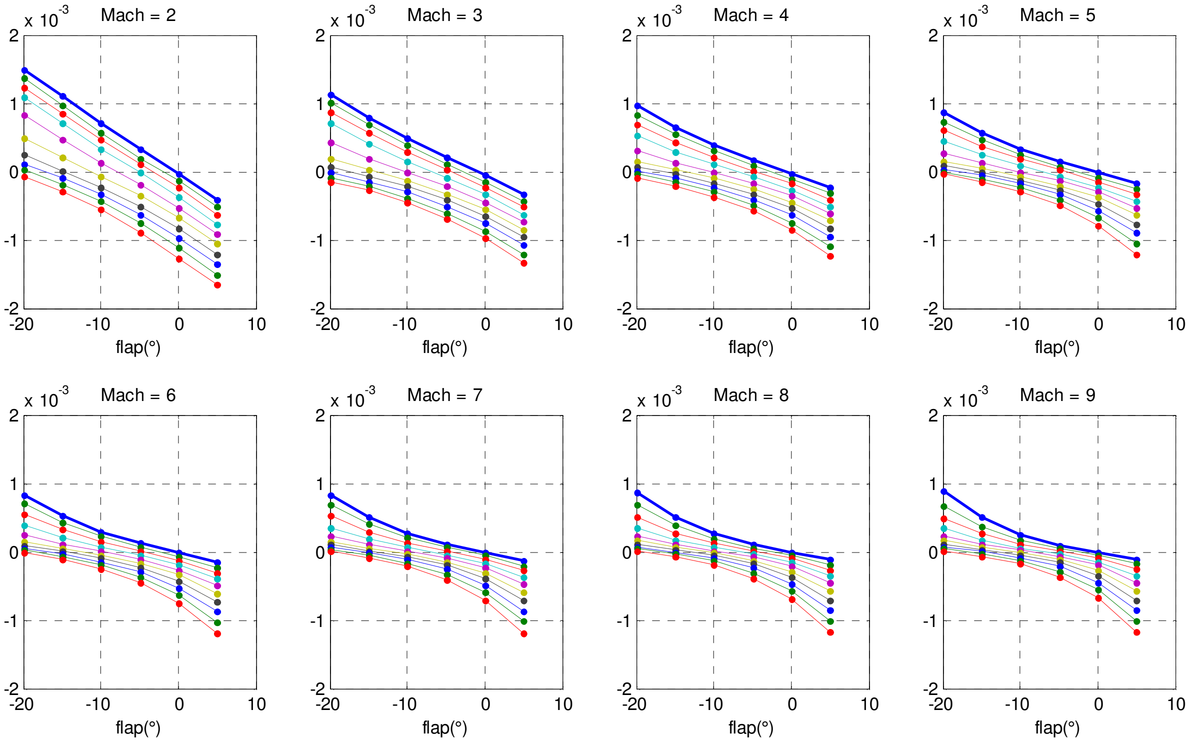

**Fig. 9** Hinge Moment coefficient behaviour with the flap deflection

In **Fig. 10** and **Fig. 11** the quantities related to the structural constraints are shown, i.e. heat flux, dynamic pressure, normal load factor. Also the L/D ratio is reported, greater than 2.5 ad peaking beyond 4 in the experimental window, as desired (Table 1).

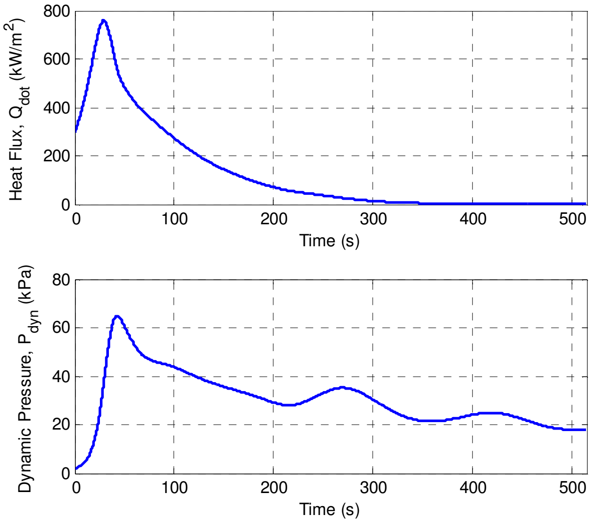

**Fig. 10** Reference heat flux and dynamic pressure

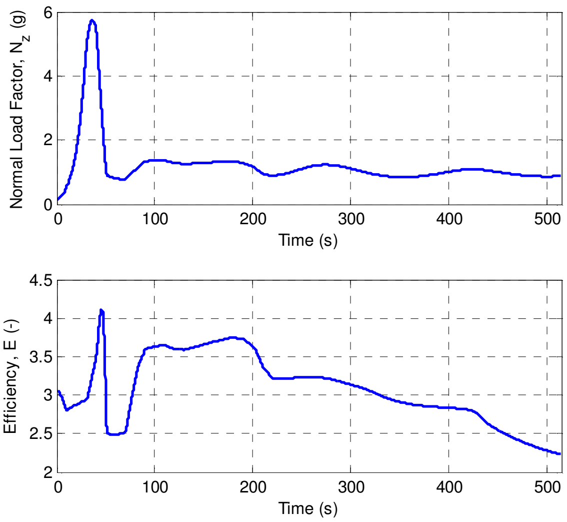

**Fig. 11** Reference load factor and efficiency

Finally, in **Fig. 12** the altitude time history – starting from 55km – is reported. As it can be seen from the figures, altitude range requirements (27-33 km) are satisfied.

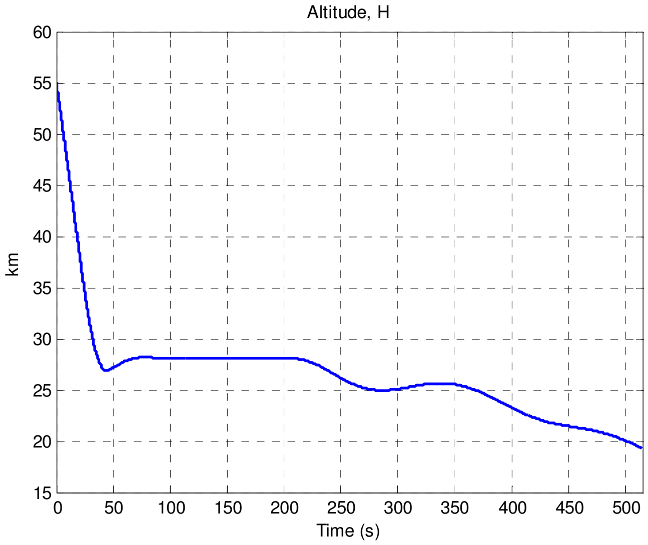

**Fig. 12** Reference altitude

In the experimental window the altitude is almost constant (≈28km) being the FPA almost zero.

### 6.3. Horizontal trajectory

For what concerns the horizontal trajectory, a bank angle reference profile must be defined. The bank angle must take into account the horizontal constraints from Table 1. Therefore, the lateral manoeuvre should start as soon as possible, before the vehicle is too far from Fortaleza and end when the desired heading angle (the Brazilian coast heading) is reached.

However, it is not recommended to start the bank manoeuvre in the Phase 0, during the steep descent into the atmosphere; as a matter of fact, a bank angle different from zero would lead to an even steeper descent and consequently to higher critical peaks.

The horizontal optimization provides the reference bank signal (Fig. 13).

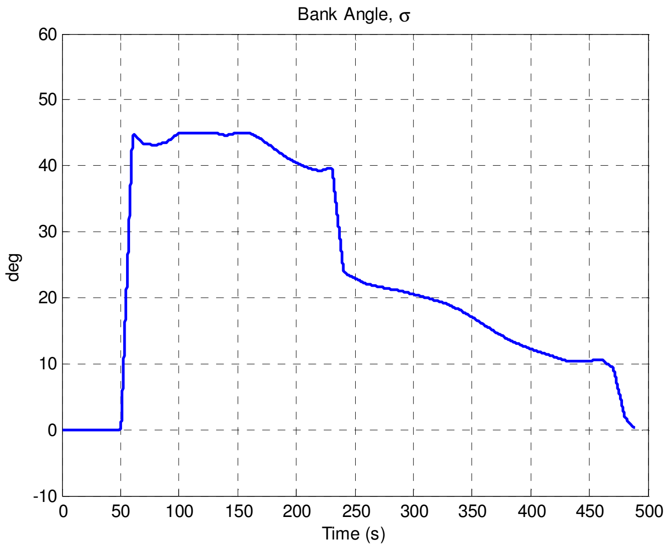

**Fig. 13** Reference Bank angle

This bank signal satisfies the horizontal constraints. It is worth noting that, the AoA and bank commands will not be given to the control laws as a function of time; indeed, they will be given as a function of specific energy and the downrange, respectively, in order to increase the robustness with respect to the flight time, which is highly affected by uncertainties.

The bank manoeuvre starts at 50 seconds and the constraint on the maximum distance from Fortaleza (600 km) is satisfied (Fig. 14).

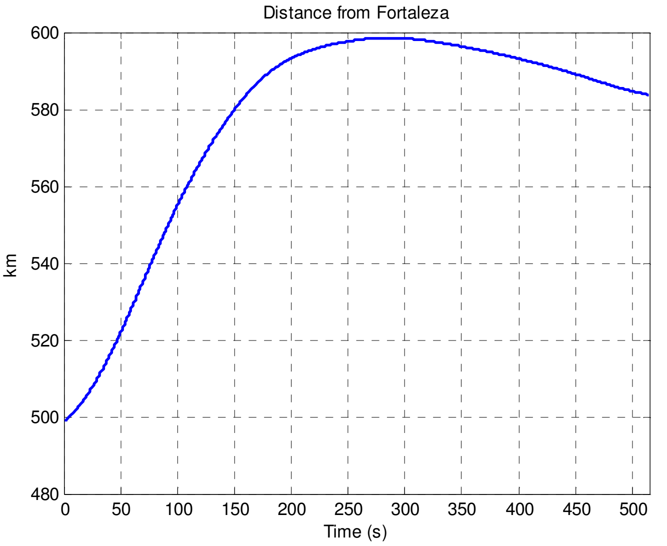

**Fig. 14** Distance from Fortaleza

At the end of the bank manouvre, the EFTV is almost parallel to the brazilian coart ($\chi \approx -48$ deg) with negligible time derivative of the track angle ($\chi_{dot}$), as shown in Fig. 15.

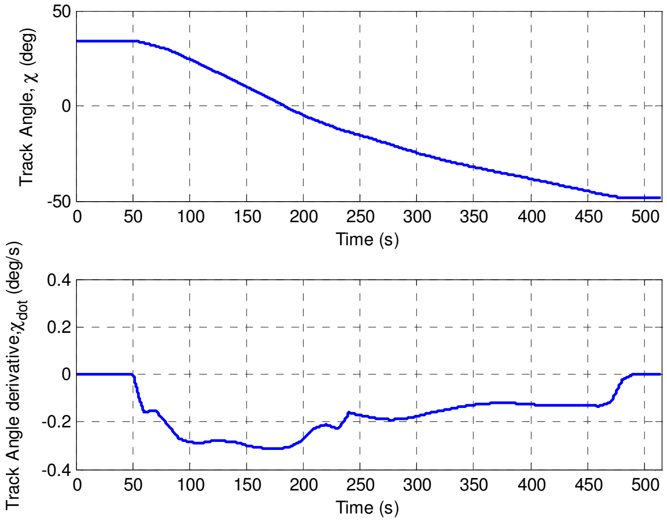

**Fig. 15** Track angle and its time derivative

In **Fig. 16** the EFTV horizontal trajectory is reported; as mentioned earlier, the vehicle remains in the circle centred on Fortaleza and having the radius of 600 km.

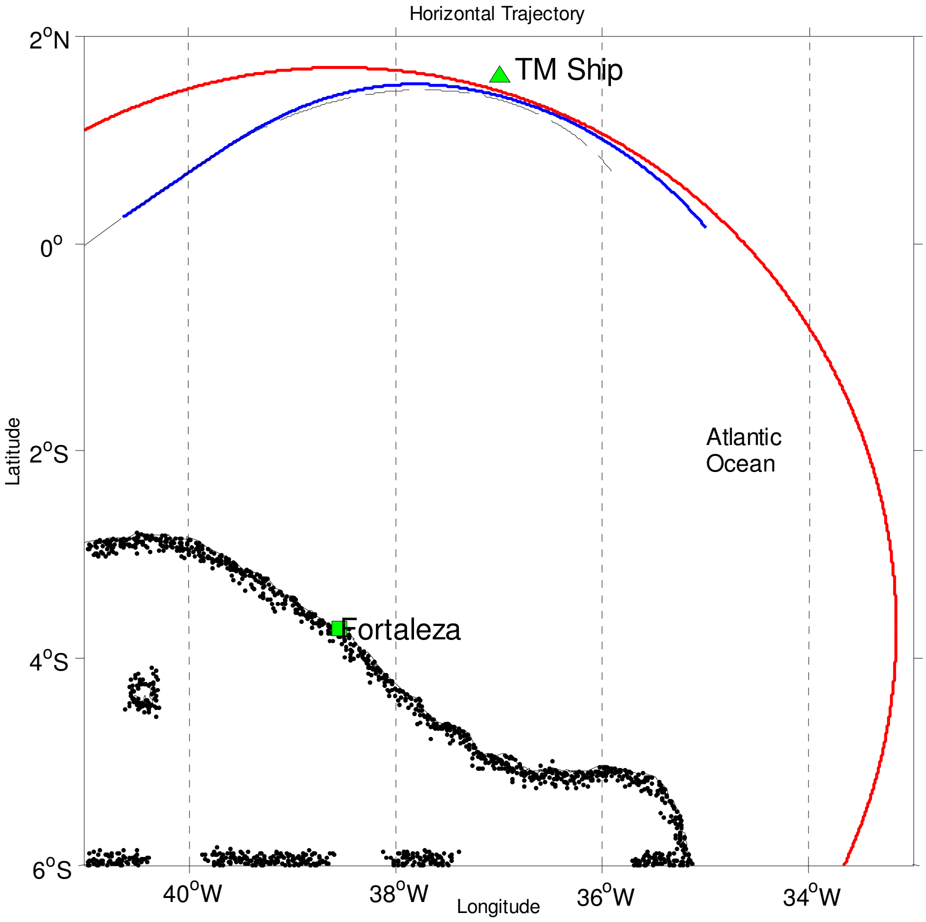

**Fig. 16** Nominal EFTV horizontal trajectory

**Table 2** collects the most important features of the optimized EFTV trajectory.

**Table 2.** Main trajectory parameters.

| Trajectory variable | Value | Req. compliance |
|---|---|---|
| Max Mach number [-] | 7.46 | N/A |
| Max dynamic pressure [kPa] | 64.9 | Yes |
| Max heat flux [kW/m$^2$] | 758.8 | Yes |
| Max vertical load factor [-] | 5.74 | Yes |
| Max L/D | 4.1 | Yes |
| Final Downrange [km] | 709.6 | N/A |
| Turn starting time [s] | 50 | N/A |
| Final track angle [deg] | -48.2 | Yes |

Finally note that the static margin is always positive along the trajectory (C$m\alpha$<0), ensuring that a positive AoA perturbation generates a pitching moment that tends to reduce the effect of the perturbation (**Fig. 17**).

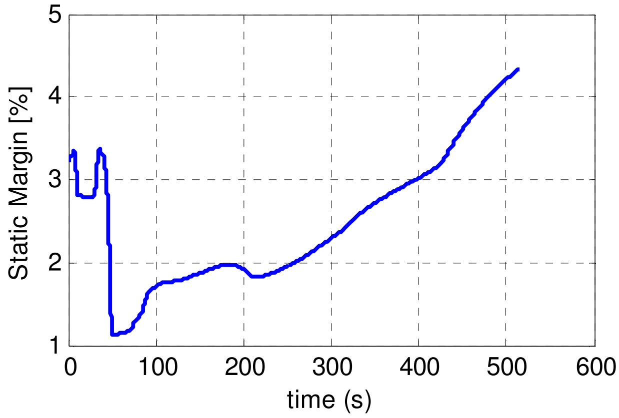

**Fig. 17** Static Margin in percentile along the trajectory

In **Fig. 18** only two marginal regions can be detected in which the Static Margin would be negative but they are not encountered by the EFTV trajectory (black line).

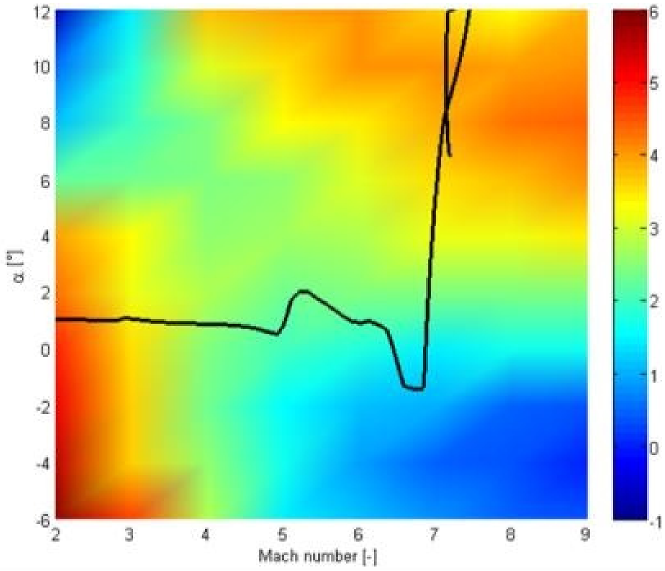

**Fig. 18** Heatmap of the Static Margin in percentile

## 7. Dispersed trajectories

A Monte Carlo simulation campaign (1000 runs) has been carried out by using the 3dof simulation model described in §2.

### 7.1. Sources of uncertainty

The following sources of uncertainty have been considered:

- EFTV mass and AEDB uncertainties [3];
- Position and Velocity Measurement errors.
- Tracking errors of AoA and bank angle, due to non-ideal control laws.

They are briefly described hereafter.

**Model uncertainties**:

- $\Delta$CL ±10%;
- $\Delta$CD ±20%;
- $\Delta$mass ±10% $\Rightarrow$ Mass$\in$[415.5, 507.9]kg.

**Position and Velocity measurement errors** come from a free integration starting from the last GPS fix at ESM/EFTV separation:

$$\Delta V \approx \Delta V_{GPS} + 1.5 * bacc * t$$

$$\Delta P \approx \Delta P_{GPS} + 1.5 * bacc * t^2/2$$

where:

- bacc is the accelerometer bias (300µg);
- The GPS errors are assumed as $\Delta$PGPS ±10m and $\Delta$VGPS ±0.1m/s
- t is the mission time since separation
- 1.5 is a safety factor.

In Fig. 19 and Fig. 20 the above measurement errors are reported for 1000 runs. The altitude error is approximately parabolic while the velocity ones are almost linear (in local levelled reference frame, not in the polar one).

As matter of fact, no complex navigation algorithms are foreseen in the HEXAFLY project. Because of the short mission time (several minutes), a free-inertial estimation can already achieve accuracies satisfying the Guidance and Control needs.

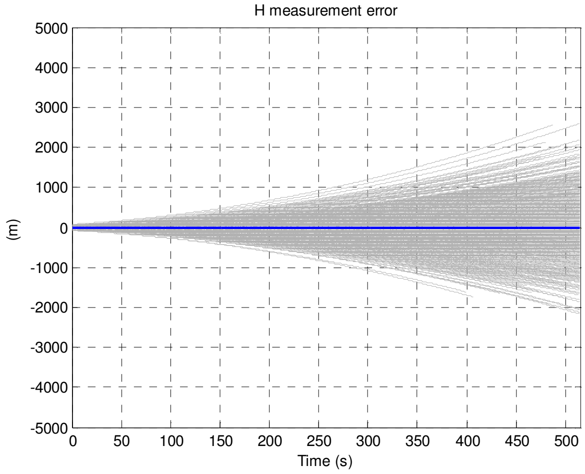

**Fig. 19** Altitude measurement error

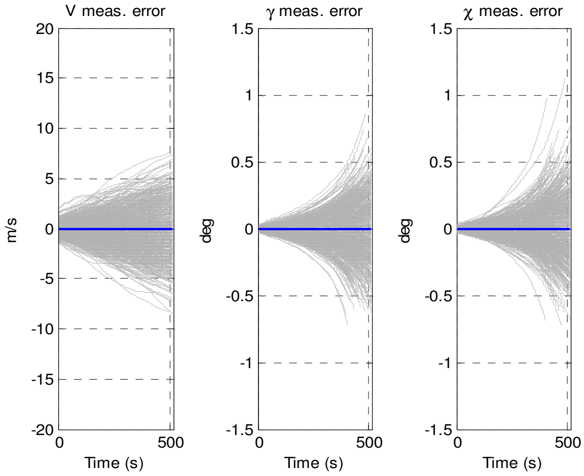

**Fig. 20** Polar velocity measurement error

Finally, **AoA and bank tracking errors** are assumed within ±2deg.

### 7.2. Results

In the figures below the error-free (nominal) time-histories are reported in blue while the off-nominal trajectories are in gray.

In Fig. 21 and Fig. 22 are reported the references to the control laws.

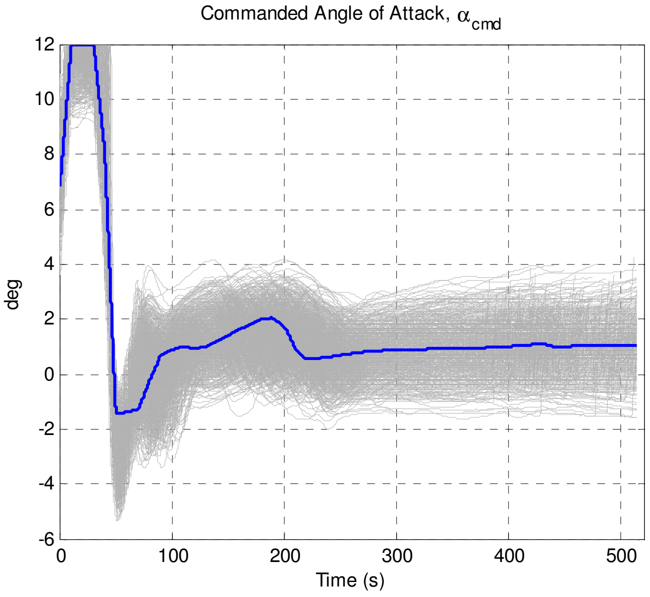

**Fig. 21** Off-nominal AoA commands

Regarding the Fig. 22, for the downrange smaller than the nominal one (evaluated at 50s) the lateral guidance is disabled.

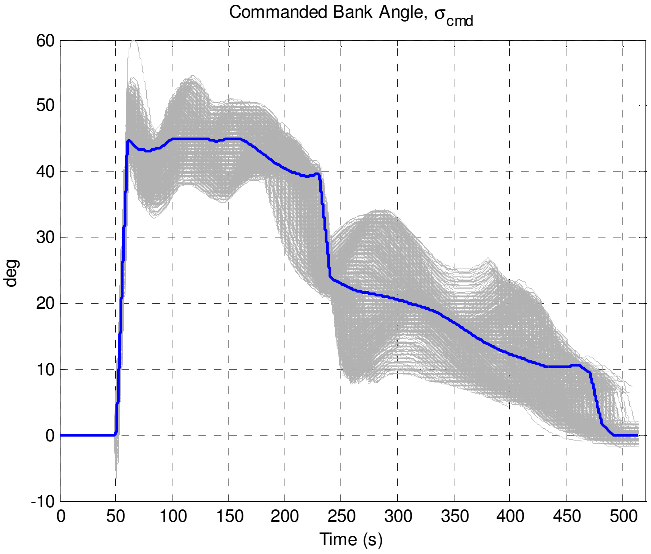

**Fig. 22** Off-nominal Bank commands

The first mission objective, i.e. the altitude almost constant (Table 1), is reached in the experimental window (defined from 50s to Mach 5).

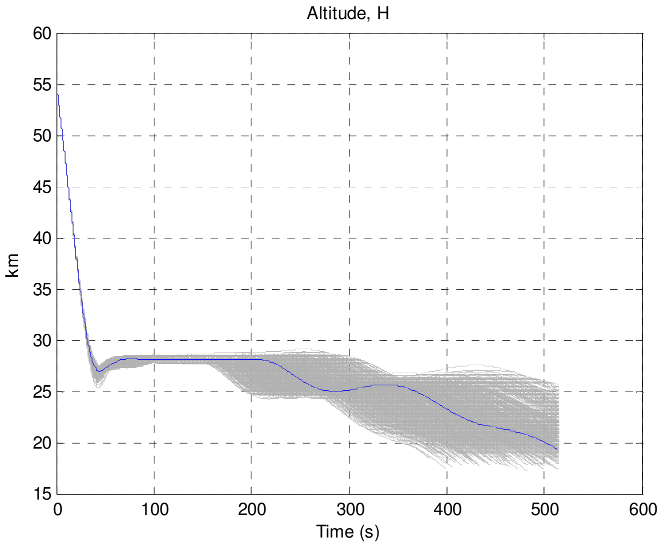

**Fig. 23** Off-nominal altitudes

About the efficiency, it becomes also negative around 50s because of negative lift coefficient, due to negative value of AoA. However, the requirement (E>2.5) is accomplished since about 70s.

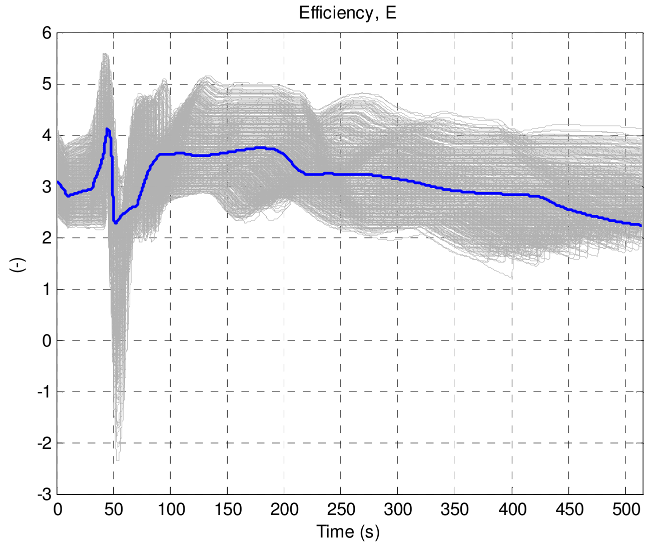

**Fig. 24** Off-nominal efficiency time histories

The control deflections are always kept away from their limits, ensuring large maneuverability margins in any case (Fig. 25). Furthermore, the vehicle is always statically stable (static margin, not reported here, is always greater than 1.7).

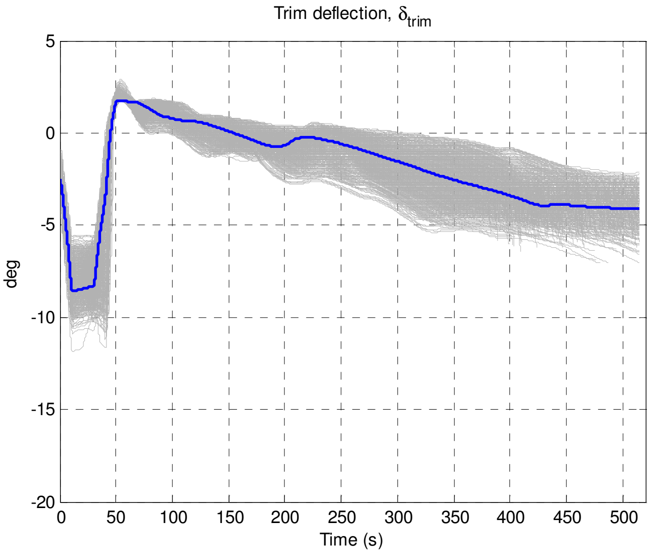

**Fig. 25** Off-nominal trim deflections

Regarding the critical constraints, the peaks on dynamic pressure and the heat flux could be reduced extending the AEDB for AoA greater than 12deg.

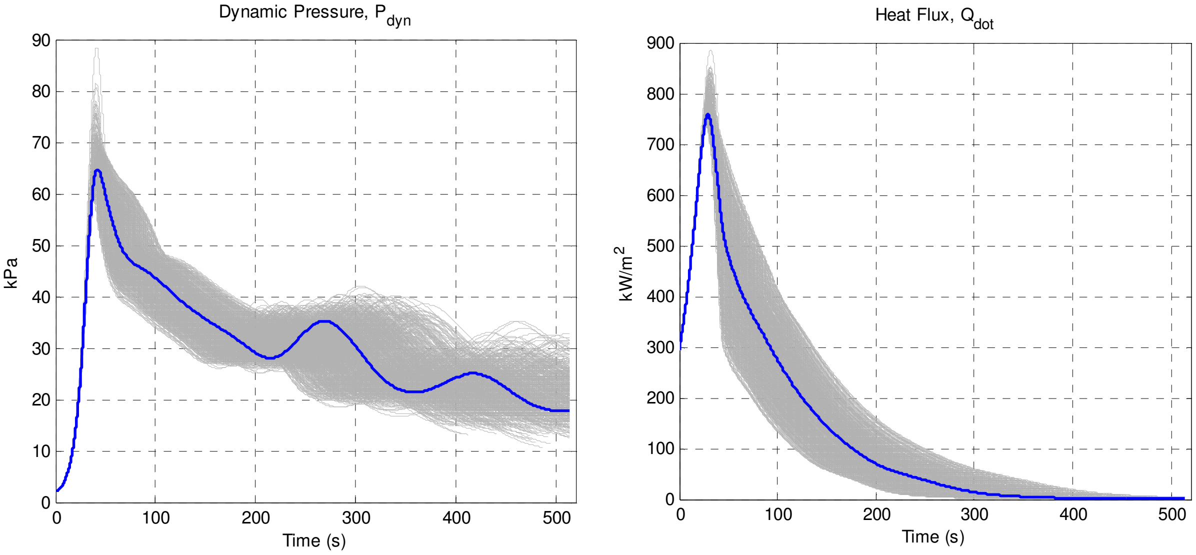

**Fig. 26** Off-nominal dynamic pressures

**Fig. 27** Off-nominal heat fluxes

The off-nominal vertical load factors are reported in Fig. 28, compliance to the given requirement (Nz<8).

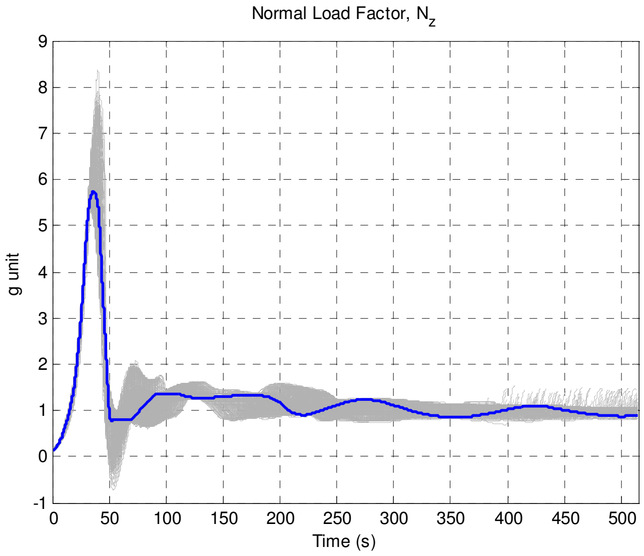

**Fig. 28** Off-nominal normal load factors

The distance of Fortaleza is greater than 600km in some cases but worst-case value is about 605 km (Fig. 29). In Fig. 30 the final track angles values are reported, showing that the EFTV is parallel to the Brazilian coast, at the end of flight.

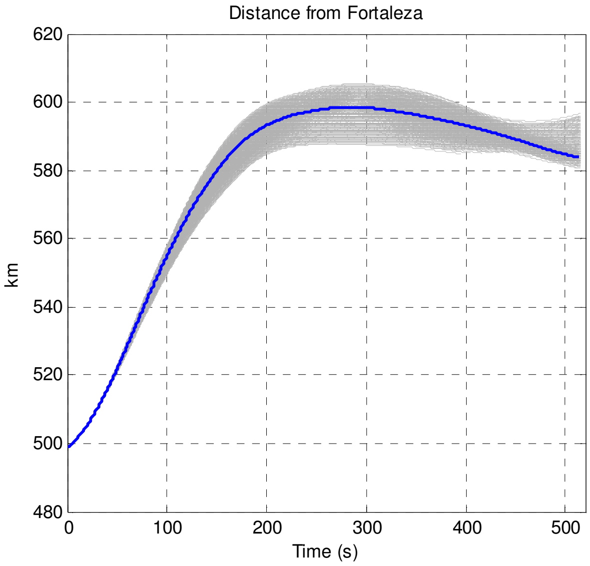

**Fig. 29** Off-nominal distance from Fortaleza

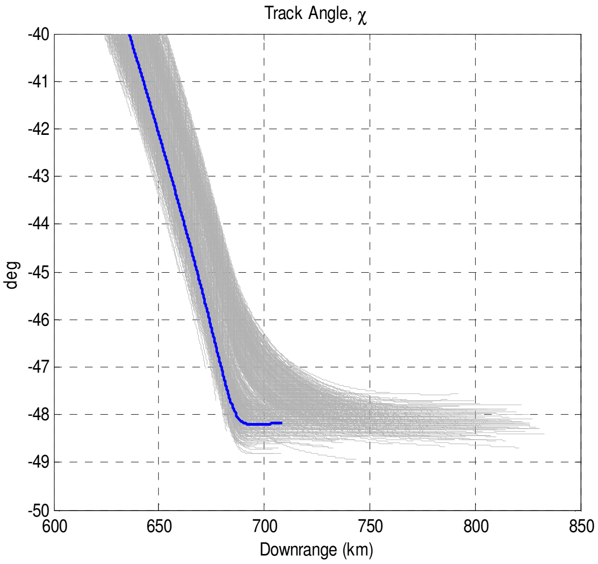

**Fig. 30** Off-nominal track angles

## 8. Conclusions

In this article, both the methodology and the results of the reference trajectory generation for EFTV, an experimental vehicle designed and developed within the *High-Speed Experimental Fly Vehicles – International* (HEXAFLY-INT), has been described.

Starting from the given mission objectives and constraints, a procedure has been built, based on the solution of a constrained optimization problem.

After the determination of the EFTV reference trajectory, a dispersion analysis has been carried out in order to evaluate whether the mission requirements are fulfilled also in presence of uncertainties. To this end, a Monte Carlo simulation campaign, with 1000 runs, has been carried out by using 3DoF simulation model taking into account all the available uncertainties about vehicle mass, aerodynamics, measurement errors, etc.

The results have shown that the trajectory requirements are fulfilled in the nominal case but not in dispersed conditions (i.e. with uncertain parameters). This means that EFTV vehicle and/or mission configurations could be modified or some trajectory objectives/requirements could be relaxed. After that, the EFTV trajectory shall be updated and its compliance with mission requirements shall be assessed.

Once that reference trajectory has been frozen, the next activities will concern the development of guidance and control laws for EFTV flight and subsequent performance evaluation. This will be done by using a 6Dof model including flight dynamics (both translational and rotational), guidance and control laws, external environment, actuators and sensors models.

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