Abstract: Development of a Model to Calculate and Optimize Hypersonic Aircraft Trajectories with Respect to Engine Gaseous Emissions

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A methodology is presented to simulate and optimize 4D trajectories for hypersonic airliners. The software tool is embedded in MATLAB and represents a further development of the Trajectory Calculation Module (TCM) which was developed by the DLR Institute of Air Transportation Systems. This simulation model is divided into a performance module which deals with the prediction of the aircraft's vertical flight path as a function of given airspeeds, altitudes and the selected thrust settings (VNAV) as well as a lateral navigation module to determine the aircraft's lateral flight path by detecting route waypoints and, if necessary, initiating curve flights (LNAV). The scientific contribution of this study is to point out trade-offs between gaseous emissions and flight altitude so that the VNAV will be - based on the minimization of a weighted cost function J - optimized iteratively with respect to ecological (e.g. emission-optimized) or economic (e.g. fuel-optimized) objectives. This work was done in the context of the European Union project STRATOFLY.

I. Introduction

STRATOFLY investigates the feasibility of high-speed passenger stratospheric flights with respect to key technological, societal, and economical aspects. The goal of STRATOFLY is to refine the design of a hypersonic vehicle up to 300 seats being able to fly at a cruise speed of 8500 km/h (Mach 8) above 30 km of altitude. The project will focus on the integration of innovative propulsion systems, unconventional structural configurations and systems for the thermal and energy management of the vehicle. Taking into account sustainability, the project will investigate strategies to reduce gaseous and noise emissions, while at the same time ensuring the required safety levels for passengers.

Figure 1: LAPCAT-MR2, the aircraft design basis for STRATOFLY-MR3

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II. State of the Art

The Trajectory Calculation Module (TCM) is a MATLAB-based simulation tool where the vehicle dynamics are embedded using a 3-degree-of-freedom point mass model. The rigid-body equations of motion are propagated using the so-called Total Energy Model [1] where geodetic longitude, latitude and height do form the aircraft's position state as well as the true airspeed, course and climb angle compose the aircraft's translation state. Since simplified performance data of the BADA database is used to generate engine and aerodynamic lookup tables, it is possible to calculate flight movements of a variety of conventional aircraft types.

The program flow of the TCM is divided into four functional main blocks as shown in Fig. 2. In the first block, a vertical target flight profile for conventional aircraft is generated and the aircraft model state variables are initialized to the corresponding start values. This is followed by the execution of the primary simulation loop which comprises the main blocks II to IV. In terms of the lateral navigation (LNAV), a reaching of waypoints is detected and; if necessary, curve flights are initiated and terminated based on the current position of the aircraft. During the vertical navigation (VNAV) which corresponds to the third main block, the simulation module checks whether flight conditions have been reached that terminate the current flight phase. If this is the case, the program routine switches to the subsequent flight phase. In the last block, flight performance calculations are performed, aerodynamic and engine models are evaluated and the desired aircraft movement is achieved by calculating a virtual control effort $\dot{h}$ and $\dot{V}$ (due to compatibility with the Total-Energy Model). The latter is based on a simple PI-controller. The new aircraft states are determined by integrating the current state variables over time numerically using *Euler's method*. This forms the starting point for the next run of the primary simulation loop, which is executed until the complete target flight profile has been flown. Finally, the results of the TCM simulation are stored.

As part of the DLR's internal project *Climate-compatible Air Transportation System* (CATS), the TCM was already used to examine the climate impact of fleet emissions as a function of changing flight altitude and airspeed ([2]). It has also been used for studies on the economic assessment of aircraft technologies based on natural laminar attitude ([3],[4]), and to investigate the efficiency potential of formation flying for commercial aircraft ([5]).

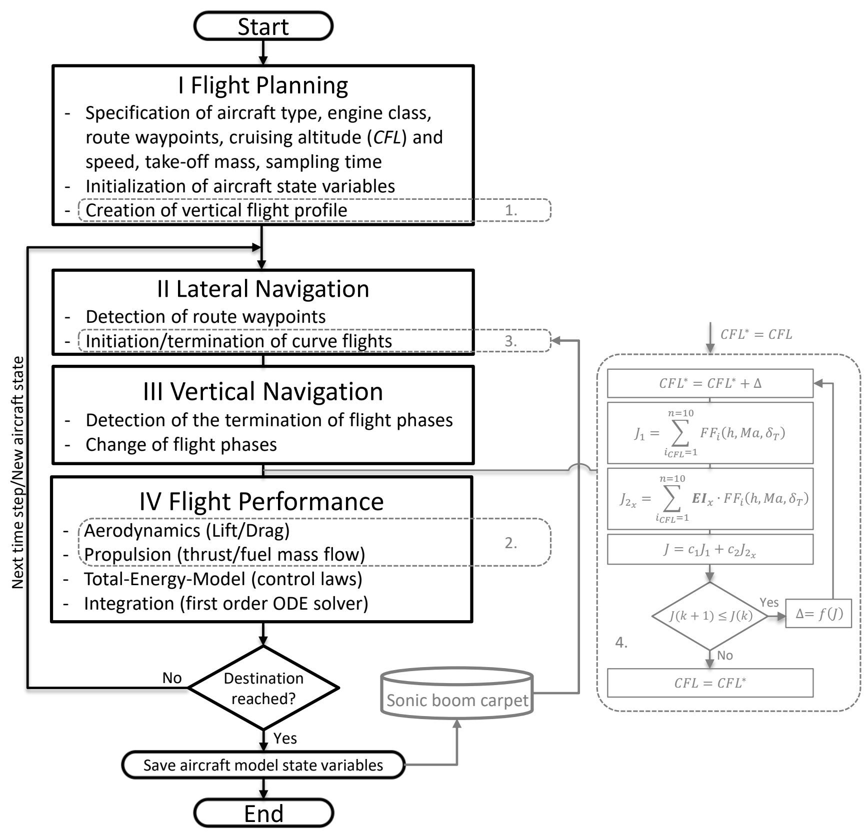

Figure 2: Program flow of Trajectory Calculation Module (based on [7])

III. Work description

As emissions have a different climate impact depending on the altitude and location at which they are released, climate-optimized mission profiles are highly dependent on emission-optimized mission profiles and might be lower (or higher) than fuel-optimized mission profiles ([6]). In order to investigate these trade-offs we extent the TCM by minimizing a weighted cost function J to either achieve a significant reduction in gaseous emissions or to find a minimum for the aircraft's fuel consumption during cruise within the upper stratosphere. Another restriction of the flight envelope is the sonic boom carpet which is not allowed to hit inhabited area around the globe (see Fig.4).

Based on a database of global airline ticket sales so-called Stratoports were already identified in a previous work package to encounter the demand for hypersonic flight routes. Overwater waypoints between these Stratoports must be rescaled as a function of the sonic boom carpet computations as well as the allowable vertical forces for the passengers during curve flights. In consequence, we will do the following work steps for the final paper which are also marked in Fig. 2:

1. **Design of realistic flight phase table for hypersonic airliners**
   → Waypoint detection for overwater flight envelope to activate hypersonic flight phases (in order to prevent the sonic boom carpet from making landfall)

2. **Adaption of coordinated turn flight mode**
   → Adaptive curve radius with regard to passenger comfort (n_z) while flying at Mach 8

3. **Embedding of aircraft performance data**
   → Implementation of aerodynamic module to obtain aerodynamic lift and drag coefficients as a function of the aircraft control surfaces: Canards, elevons, bodyflaps and rudders
   → Implementation of engine module to obtain aircraft thrust force and fuel flow based on Air-Turbo-Rocket (ATR; below Mach 4.5) as well as scramjet combustor (DMR; Mach 4.5 to 8) database
   → Implementation of emission module to obtain the aircraft gaseous emissions consisting of nitrogen oxides (NO_x), water vapour (H_2O) and unburnt hydrogen (H_2) by using engine-based emission indices EI_{NOx}, EI_{H2O} and EI_{H2}

4. **Implementation of a weighted cost function minimization to optimize flight trajectory:**
   → Program flow of the optimization routine is divided into several steps as shown in Fig. 2
   → Routine starts for $i = 1$ when the aircraft model reaches its Cruise Flight Level (CFL)
   → New Cruise Flight Level (CFL*) is initialized by the user input of the TCM
   → Two cost functions J_1 and J_{2_x} are calculated for $n = 10$ time steps
   → First cost function represents the amount of burned fuel which is a function of the geodetic height h, the Mach number Ma and the thrust lever position δ_T
   → Second cost function represents the amount of gaseous emissions for species x where $\boldsymbol{EI_x}$ denotes a vector of the mass ratios between the amount of released emissions of species x per kg burned fuel
   → Global cost function J is defined where J_1 and J_{2_x} are weighted through the gains $c_1 \in [0,1]$ and $c_2 \in [0,1]$
   → Gains are defined by the user input with regard to ecological (e.g. emission-optimized) or economic (e.g. fuel-optimized) objectives:
   - If subsequent cost function $J(k+1)$ is not smaller than the current cost function $J(k)$, an optimum is found and CFL* is saved to simulate the entire trajectory
   - If subsequent cost function $J(k+1)$ is smaller than the current cost function $J(k)$, the optimization routine starts from the beginning whereby the new Cruise Flight Level is a function of the preliminary CFL* and an adaptive increment depending on the amount of J

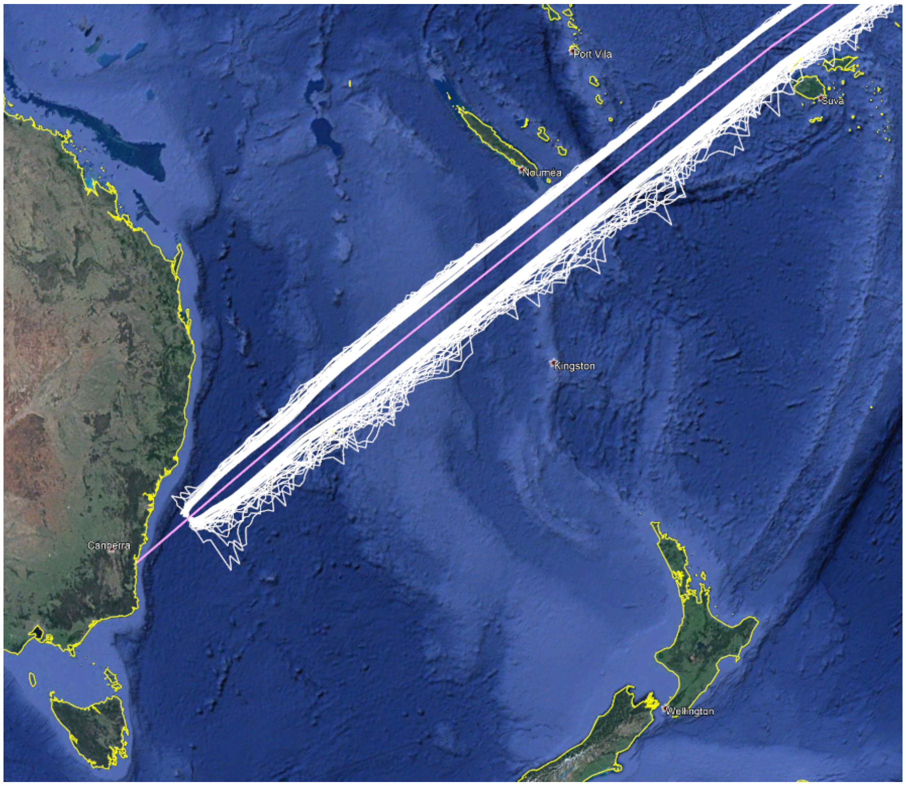

Figure 3: Sonic boom carpets for flight from Eastern Australia to U.S. West Coast

IV. Previous studies

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