Optimal civil aircraft missions exploiting free routing possibilities

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Abstract. A method is presented for optimizing burnt fuel and flight time of civil aircraft missions, under the scope of a full-scale free route airspace implementation as well as usage of actual environmental data, focusing on ambient temperature and pressure. A computational analysis model, using online available aircraft data is considered, for flight envelopes defined by the user, is used as the base tool. The model is validated over real flight data, before it is used as the main tool for optimization of flight missions. Flight paths are analyzed by considering both their vertical and horizontal aspect. Optimal paths are derived, for each chosen mission, through an optimization process that takes advantage of the flexibilities that become available by implementation of Free Route Airspace. Vertical flight path is shown to play very important role in achieving optimal flights, while horizontal paths also offer optimality possibilities, with a strong dependence on weather conditions.

1 Introduction

As a direct response to the dramatic rise in air traffic, EUROCONTROL [1] brought forth the Single European Sky act in order to tackle this century's air transportation obstacles. Dividing Europe's airspace into Functional Airspace Blocks (FABs) and later into Flight Information Regions (FIRs) regardless of national borders was the first step into a much-needed new direction. This action became the foundation on which Free Route Airspace (FRA) was born, coming to substitute the old-fashioned fixed route system, which up to that point created unnecessarily elongated missions which ultimately deviated greatly from the optimal flight path.

The FRA concept has been gradually applied to FIRs across European airspace proving its many benefits daily. It is the aim of EUROCONTROL [1] that this way of mission planning be spread to all FABs by 2023, aiding in the process the bloom of the modern aviation industry. Naturally, since its appearance in 2008, the free route airspace project has occupied researchers around the world, who have offered great insight in the advantages of this new tool in the hands of aerial transport.

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The effectiveness and potential benefits from this new concept have been examined by a number of researchers. For example, Krzyzanowski [2] underlined the effectiveness of this new implementation in diminishing air conflicts. The same number of flights passing through different airways, results in fewer overlapping trajectories and significantly raising the airspace capacity. Pereira, [3], in turn, examined the inefficiency of applying free routing to two separate Portuguese FIRs, instead of a proposed united one. Benefit of this endeavor alongside its environmental impact were examined by Lennert and Hoffmann [4], who estimated the potential economy in operating costs through applying the FRA. Later on in 2016, Aneeka and Zhong [5] highlighted the need for reduction of Green House gases in the ASEAN region by enforcing free routing, as well as discussing how free routing can be implemented using existing ATM technologies of the area. Jensen et al. [6] presented a simple route optimization solution for application in real world FRA scenarios, while in the same year a similar project was put into motion by Nakamura et al. [7] investigating optimal flight paths in Japanese airspace considering FRA alongside wind measurements.

The issue is of current interest, with related studies continuing to appear to date (e.g. [8], [9], [10]). A systematic framework towards the adoption of optimal flight path definition is under development by NASA [11].

In the present paper an approach for exploiting the capabilities offered by FRA is proposed. The approach is a numerical one, allowing thus the minimization of simplifying assumptions, taking advantage of current day computing abilities, as well as information availability on weather conditions. The description is generic, with particular application cases, focusing on the possibilities unveiled rather than on particular features that may vary depending on the different applications.

The approach proposed uses computational modelling of flight missions, for evaluating the detailed mission characteristics for transport aircraft flights between two destinations. Missions are represented in a way that allows modification of their trajectories and speeds, suitable for implementation in optimization algorithms. The well-known influence of weather conditions, namely ambient temperature, pressure and winds is taken into account by information retrieval from appropriate data bases. Numerical optimization schemes are employed to determine trajectories that fulfill optimality requirements, emphasis being given to minimum fuel consumption. The constituents of the approach, the procedure followed, and indicative results of application to real flight cases, are described in the following.

2 Mission Analysis

Mission Modeling requires the consideration of aircraft aerodynamics alongside engine performance, within an environment that accurately reflects ambient conditions in the form of temperature, pressure and wind. Therefore, a computational tool is needed, that appropriately represents the aircraft's mission, both functioning as a baseline formulation as well as for obtaining optimized trajectories.

In order to achieve a full 3D representation of flight trajectories, two views are employed, Fig. 1:

(a) the X-Y view, consisting of the projections of the flight path on the earth surface, which will be termed "the horizontal flight path".

(b) the L-Z view, consisting of the loci of vertical positions along the horizontal flight path, which will be termed the "vertical flight path" respectively.

Examination of the horizontal flight path allows for minimization of the horizontal distance travelled. The notion of the Great Circle Distance (GCD) is useful in this respect, being the shortest distance between two points on the earth's surface. The choice of X-Y paths is influenced by the prevailing atmospheric condition, the most obvious one being wind.

Examination of the vertical flight path provides the possibility to alter the vertical mission characteristics, e.g. flight altitudes for different segments, rates of climb/ descent etc.

Both paths are offered for alteration within the FRA concept. While a combined modification of both is ultimately sought, it is useful to formulate the optimization problem in terms of parameters describing each path, while having the possibility to separately optimize each one.

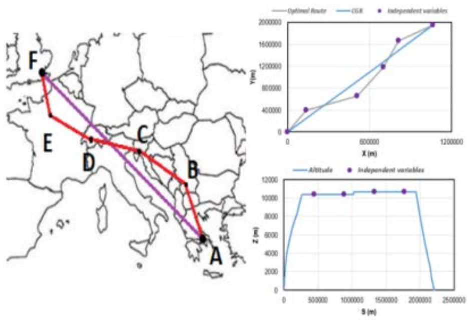

Fig. 1. Visualization of horizontal and vertical flight paths.

2.1 The Mission Computation Model: CAMACM

The computational model (CAMACM – Commercial- Aircraft Mission Analysis Computational Model) used here was originally developed in 2006 [12] in the Laboratory of Thermal Turbomachines of the NTUA. The version of the code employed in the present work is written in PROOSIS [13], allowing for the creation of a component responsible for calculating aircraft performance.

The simulated aircraft is considered a point mass, while the atmospheric model is based upon the International Standard Atmosphere (ISO 2533:1975), with the assumption of a still, undisturbed, homogenous perfect gas liquid, with zero moisture. Aircraft performance data are introduced through an aircraft data file, including performance and operations data provided by BADA [14]. Lastly, on account of the engine, we presume that the vectors of thrust and speed are parallel to one another and that transitions to engine settings are instant and without side-effects.

Ambient conditions for the calculations in CAMACM are introduced by obtaining ground temperature, pressure and wind speed from online meteorological data providers. In order to perform the calculations along a flight path, the distribution of temperature, pressure and wind speed is retrieved from a grid covering the area of interest. The values of these quantities at any point along the calculation path is then evaluated using

The values at the current flight altitude are then evaluated by using the thermodynamic deviations (ΔT, Δp) from the ISA model (T0=288,15 [K], p0=101325 [Pa]), calculating temperature and pressure alike. For the calculation of wind data at different altitudes two expressions are implemented. The first was suggested by Banuelos-Ruedas et al. [15] and is used in the lowest atmospheric layers, for altitudes up to one kilometer. At greater altitudes, wind is considered approximately geostrophic and is calculated as proposed by J. Vilà-Guerau De Arellano et al. [16].

Burnt fuel is calculated for a specific point of flight from the Thrust Specific Fuel Consumption of the engines at their corresponding operating condition and Thrust [17].

Thrust is evaluated from the aircraft dynamics at each point, determined from its aerodynamic performance and kinematic condition.

2.2 Mission Model Validation

Before the calculation model is employed for optimization purposes, it is necessary that it is validated over known missions, for which data are available, for the aircraft of interest. The known data are compared with the model calculations and, where necessary, key parameters are adjusted for accurate mission reconstruction. Data from different sources have been used. Initial testing with the Piano-X [18] program for mid-to-long range missions for four different types of aircraft including the A346, A388, B763, F70 showed an agreement between the two calculation tools. A comparison between calculations by CAMACM and data obtained from FlightRadar [19], has been used to check how actual flight data can be predicted, for several test cases of flights, demonstrating sufficiently accurate mission calculation by our tool. A final validation was performed using detailed mission data obtained from a commercial airline. A calibration is realized for the particular airplane, so that fuel consumption for the given mission is calculated with satisfactory accuracy.

Once the mission model is validated, it can be used for optimizing flight missions.

3 Optimization Procedure

Free routing allows users of airspace to define the trajectory of an aircraft's mission in order to best suit the outcome of the journey executed, defined between a fixed entry and exit, without guidance from local ATS services. Essentially, the FRA project offers the possibility of redesigning the flight envelope of every mission, to accustom its optimal performance under the current flight conditions. Such flexibility could reprogram a civil aircraft's mission to elect the Great Circle Distance (GCD) route, reducing considerably time of flight and cost of operations through minimizing fuel burn. It will be shown below that GCD is not necessarily the optimal path, if weather conditions are taken into account. Similarly, a different flight path can be chosen, in order to avoid harsh weather patterns, of thunderstorms or severe turbulence, or restricted flight areas.

Optimization is attempted by first considering only the L-Z plane, namely the vertical flight path characteristics, without altering the horizontal path. It is investigated whether the FRA could offer a margin of improvement in redesigning the flight envelope, without altering the path of the mission in the horizontal plane. This examination demands the application of an optimizer set to diminish fuel costs, while retaining the mission's overall length, expressed through an objective function to be minimized.

The optimization process is based on a number of design variables that determine the mission and can be altered in order to achieve the optimization objectives. By electing a small number, we maintain a low processing time of convergence and avoid overcomplicating the problem by choosing the most suited factors that better express the flight envelope. Amongst them the most representative are final segment altitudes, cruise length, Mach number and calibrated air speed of climb and descent.

The horizontal plane optimization is based on altering a flight path through modification of its X-Y trajectory. The way this approach is enabled is by using “control points” along the horizontal flight path, which can be shifted to modify the route taken, as shown in Fig. 1. The coordinates of theses control points are used as design variables during the optimization. Apart from defining the design variables, several constraints are introduced, in order to make sure that physical and regulatory limits are respected [17]. The optimization procedure is structured as shown in Fig. 2.

4 Sample Results of Mission Optimization

The optimization procedure has been applied to several cases of flights. Flights originating from the home city of the authors (Athens) have been chosen, due to their local application relevance. Optimizations in L-Z and X-Y planes alone will first be presented, concluding with a case where all possible design variables have been considered, optimizing the three-dimensional flight path.

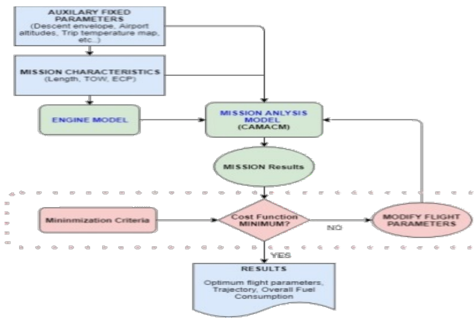

Fig. 2. Flow chart of optimization procedure.

4.1 Vertical Path and Mission Features

The test case of a flight between Athens and Moscow is used to demonstrate the effectiveness of vertical path optimization. It is assumed that the horizontal path follows the Great Circle Distance route and vertical trajectory is altered considering the ambient conditions on a given day. While the horizontal path is kept the same, 14 flight components defining the vertical path are considered as design variables, including altitudes, calculated airspeed and flight Mach numbers [17].

Applying the optimization procedure defines a new vertical flight path and flight parameters, that result to a reduction of about 4.5% fuel consumed (the absolute figure is 362 kg of fuel, corresponding to 1150 kg of CO2 emissions). Flight altitude pre and post optimization is shown in Fig. 3. It is observed that optimization would require a slightly shorter cruise length and a higher cruise altitude. The corresponding Mach numbers are shown in Fig. 4, thus proving that optimal flights would require higher aircraft speeds for the cruise segment.

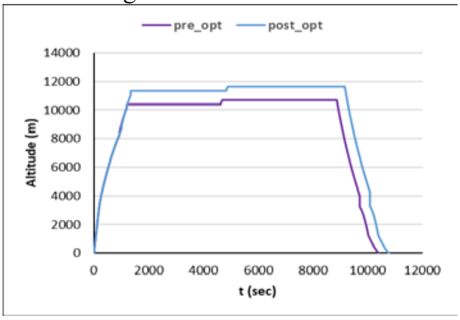

Fig. 3. Comparison between pre and post-optimization missions of the aircraft's Altitude with time (ATH-MOW).

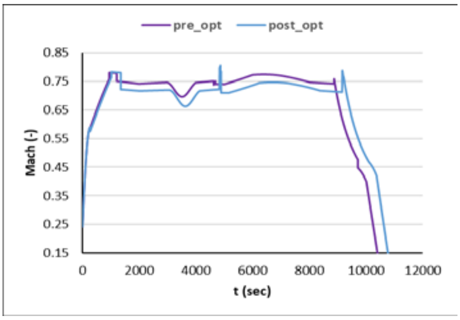

Fig. 4. Comparison between pre and post-optimization missions of the aircraft's Mach number in relation to time (ATH-MOW).

It should be mentioned here that the importance of optimization of vertical path and missions speeds has been discussed in recent publications [8, 20]

4.2 Horizontal Flight Path

Horizontal path modifications may offer possibilities for more efficient flights if environmental influences are taken into account.

Weather conditions have always played a crucial role in the execution of a mission, leading to its cancellation when extreme weather patterns are present such as thunderstorms, intense wind phenomena, snowstorms etc. However, environmental conditions also play a role in the execution of regular flight missions.

Temperature and pressure have a strong effect on jet engine performance, while wind influences the airplane’s bearing, thus altering the geometric paths that allow for more efficient mission execution. Before presenting sample optimization results, those effects are discussed, in order to facilitate understanding of the underlying reasons leading to different optimum flight.

4.2.1 Ambient Conditions Effect

Temperature is a crucial factor influencing jet-engine performance. Increasing temperature reduces the density of the air flown into the engine, while reducing the temperature ratio available in terms of thermodynamic cycle, since the maximum allowed cycle temperature cannot be exceeded. Pressure does not have the same magnitude of effect. It influences the air density (increasing pressure, increases density), but does not influence the cycle. Additionally, the variability of pressure is not expected to be significant (a yearly variability much lower than the corresponding one for absolute temperature).

Wind influences the mission directly, since the plane flies relative to the atmospheric air, which is constantly moving. Tail wind, namely in the direction of flight, has an obvious beneficial effect, since the aircraft speed with relation to the ground is the sum of the relative speed (CAS) and the wind speed. The opposite is true for head wind, namely wind aligned to be against the flight speed.

4.2.2 Horizontal Plane FRA Implementation

Free routing allows the airspace user to design a direct mission towards the target destination, an option not available with the current fixed route system. Ideally, the great circle distance (GCD) route would be elected, providing the least traveled distance. The distance is the primary factor determining burnt fuel; thus, the minimum distance is in principle linked to the minimum fuel consumption. Favorable weather conditions can lead to deviation from the shortest distance, in order to take advantage of more favorable flight conditions, as explained above.

When a horizontal flight path is to be optimized, the coordinates of control points are the design variables, as explained in section 3. Example results from such an optimization are shown in the next section, where it is shown that the GCD path, which seemingly would give the least fuel consumption for a mission between two destinations, is not the optimal one, for the given environmental conditions.

4.3 3D Flight Path Optimization

If the full potential of free routing is to be exploited, both L-Z and X-Y paths can be altered, to define a fully three-dimensional optimized mission. The optimization problem is then defined by simultaneously using as design variables all those previously considered, for both planes.

An example result of such an application is shown in Fig. 5. The combined optimization leads to a fuel reduction of 5.8% (the absolute figure is 467 kg of fuel), while there is an insignificant increase, below 1% (equal to 1 minute), in flight time. The overall fuel saving is roughly equal to the sum of the individual L-Z and X-Y optimizations shown above (L-Z gave a 4.5% reduction, X-Y gave a 2% reduction).

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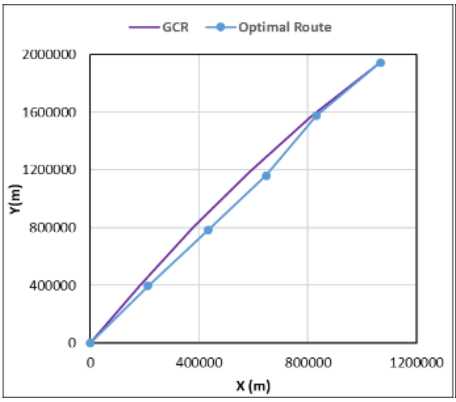

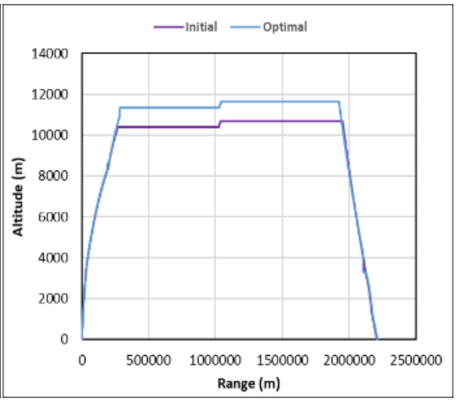

Fig. 5. Optimal flight path for an optimized mission Athens-Moscow.

The amount of fuel saving could be considered as very high, since achieving equivalent improvement by advancing aircraft or engine technology, would require a significant leap. Alternatively, this saving can be achieved by using the same aircraft and engines more efficiently and by planning optimal routes accounting for weather conditions!

5 Conclusions

An examination of free routing benefits in the European airspace has been presented, providing beneficiary margins in operation costs (burnt fuel) both in the vertical plane regarding flight envelope redesign and the horizontal one proposing trajectory rerouting due to weather conditions contribution.

A Mission Analysis Model has been used to demonstrate optimization capabilities in several test cases. Vertical flight profile alterations provide more potential for optimizing missions.

Optimal flights can be planned, when weather conditions are taken into account. Different routes give optimal results at different weather conditions. Although flight distance is a significant factor to fuel consumption, weather conditions are also an important factor.

Introducing Free Route Airspace allows exploitation of such benefits, with significant fuel and emissions savings.

References

1 EUROCONTROL, "Free Route Airspace, EUROCONTROL," 2018. Online. Available: http://www.eurocontrol.int/articles/free-route-airspace.

2 M. Krzyzanowski, "Conflict Free and Efficient Flight Routes Planning in Free Route Airspace," 2013.

3 J. Pereira, "Free Route Airspace for Route Optimization," Master Thesis, Instituto

Superior Tecnico. University of Lisbon. Delft University of Technology, Delft, 2015.

4 L. Bentrup and M. Hoffmann, "Free Routing Airspace in Europe," 2016.

5 S. Aneeka and Z. Zhong, "NOx and CO2 emmisions from current air traffic on ASEAN region and benefits of free route airspace implementation," School of Mechanical and Aerospace Engineering, Nayang Technological University, Singapore, 2016.

6 C. K. Jensen, M. Chiarandini and K. S. Larsen, "Flight Planning in Free Route Airspaces," University of Southern Denmark, Odense, 2017.

7 K. K. M. Y. M. H. Nakamura Y., "A Study on Free Routing Considering Interference of Air Traffic Flow," AIAA, Texas, 2017.

8 B. Dancila and R. Botez, "Vertical flight path segments sets for aircraft flight plan prediction and optimisation," *The Aeronautical Journal,* vol. 122(1255), pp. 1371-1424, 2018.

9 C. Nava–Gaxiola, C. Barrado and P. P. Royo, "Study of a Full Implementation of Free Route in the European Airspace.," in *2018 IEEE/AIAA 37th Digital Avionics Systems Conference (DASC) (pp. 1-6). IEEE*, 2018.

10 J. Rosenow, D. Strunck and H. Fricke, "Trajectory optimization in daily operations.," in *International Conference On Research In Air Transportation (ICRAT).*, 2018.

11 "Traffic Aware Strategic Aircrew Requests (TASAR)," Online. Available: https://technology.nasa.gov/patent/LAR-TOPS-148.

12 M. Kelaidis, N. Aretakis, A. Tsalavoutas and K. Mathioudakis., "Optimal mission analysis accounting for engine aging and emissions," *Journal of Engineering for Gas Turbines and Power,* vol. 131, no. 1, 2009.

13 PROOSIS, "Optimization Library 2.1.5," PROOSIS, 2015.

14 EUROCONTROL, "User Manual for the Base of Aircraft Data (BADA), Revision 3.9," EUROCONTROL, EUROCONTROL Experimental Center, 2011.

15 F. Bañuelos-Ruedas, C. Á. Camacho and S. Rios-Marcuello, "Methodologies Used in the Extrapolation of Wind Speed Data at Different Heights and Its Impact in the Wind Energy Resource Assessment in a Region," Instituto de Ingeniería de la UNAM, Escuela de Ingeniería de la Pontificia Universidad Católica de Chile, Mexico, Chile, 2011.

16 J. V.-G. D. Arellano, C. v. Heerwaarden, B. v. Stratum and C. v. d. Dries, "Governing equations for momentum," in *Atmospheric Boundary Layer: Integrating Air Chemistry and Land Interactions*, New York, Cambridge University Press, 2015, p. 71.

17 D. Katsikogiannis, "Optimal Civil Aircraft Missions Exploiting Free Routing Possibilities (in Greek)," ΕΜΠ, Athens, 2018.

18 "Piano-X," Lissys Ltd, Online. Available: http://www.piano.aero/.

19 FlightRadar, "FlightRadar, Live Air Traffic," 2018. Online. Available: https://www.flightradar24.com.

20 L. Jensen, R. Hansman, J. Venuti and T. Reynolds, " Commercial airline altitude optimization strategies for reduced cruise fuel consumption.," in *In 14th AIAA Aviation Technology, Integration, and Operations Conference (p. 3006).*, 2014.