Exploiting Wind to Optimize Flight Paths for Greener Commercial Flight Operations

M. Marino 1, A. Gardi 1, R. Sabatini 1, T. Kistan2

1 RMIT University, School of Aerospace, Mechanical and Manufacturing Engineering, Bundoora, Melbourne, VIC 3083, Australia
2 THALES Group Australia, Air Traffic Management, WTC Northbank Wharf, Melbourne, VIC 3000, Australia

Abstract

Trajectory Based Operations (TBO) has been identified by ICAO as a key aviation evolution with significant developments in Next Gen Flight Management Systems (FMS) to communicate with ground based 4DT Air Traffic Management (ATM) system of the future. The Next generation ATM and FMS systems will include the capability of generating 4D trajectories to increase aircraft efficiency and reduce emissions. Natural resources, such as the wind, can be exploited to reduce the aircraft’s fuel usage and travel time while improving its operational efficiency. These benefits are realized if trajectories are formulated to maximise the time in tailwind scenarios. The results presented here quantify the fuel and time savings of a typical Australasian route using a simulated wind field as an input to the optimization problem. Minimum fuel burn and emissions are achieved by minimising flight time at constant cruise speed. The attainable savings appeal to aircraft operators as they reduce operational cost. Optimization algorithms to formulate efficient flight trajectories are hence an essential tool in reducing aviation’s carbon footprint. Future research will focus on the implementation of 4DT operations and associated logistics. Simulations of common commercial and international flight routes from departure to destination using 4DT intent negotiation and validation routines will allow for an accurate evaluation of the potential savings in fuel and reduction in emissions.

Keywords: 4 dimensional trajectory optimization, trajectory based operations, flight path optimization, green operations, ICAO, TBO, 4DTO, emission reduction, efficient flight paths.

Introduction

Human travel operations are growing due to the exponential growth in population. As a consequence the growth in transportation systems is also growing in a manner where fossil fuel consumption is ultimately increasing the amount of emissions within the earth’s atmosphere [1]. Although air travel operations contribute approximately 2-3% toward the global warming conundrum, various organizations have set ambitious emission reduction targets to revert the trend and relieve aviation’s impact on global warming and climate change [2]. The most known emission target is a 50% reduction in emissions by 2050 set by the International Civil Aviation Organization (ICAO) [3]. Aviation specific emissions reductions have also been outlined by the Advisory Council for Aviation Research and innovation in Europe (ACARE) with the FlightPath 2050 campaign, a strategic research and innovation agenda for a more sustainable aviation future.

Table 1: ACARE Strategic Research and Innovation Agenda (SRIA)

<table>
<thead>
<tr>
<th>Variable</th>
<th>2050 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions per passenger</td>
<td>75% reduction</td>
</tr>
<tr>
<td>NOₓ emissions reduction per passenger</td>
<td>95% reduction</td>
</tr>
<tr>
<td>Perceived ground noise</td>
<td>65% reduction</td>
</tr>
<tr>
<td>Aircraft lifecycle</td>
<td>Recyclable aircraft materials</td>
</tr>
<tr>
<td>Fuels</td>
<td>Increasing use of alternative fuels</td>
</tr>
</tbody>
</table>

16th Australian Aerospace Congress, 23-24 February 2015, Melbourne
Stringent targets not only encourage research and development into new aircraft technology but also prompt changes in air travel operations where potential fuel savings (up to 24%) can occur [4]. The current air traffic control operations are still significantly based upon procedures which are decades old. They were developed at a time where aircraft emissions were not an economical or environmental concern to aircraft operators, and were based on the limited Communication, Navigation and Surveillance (CNS) technologies available at that time. As such the Air Traffic Management (ATM) operations are not optimized for minimal environmental impact. A common example of an inefficient ATM operation is one where aircraft are stacked in holding patterns due to airport congestion. Another procedural inefficiency is when the avoidance of weather cells and the sequencing of arrival traffic are manually performed by human ATM operators via tactical measures.

The current ATM operation can be improved to reduce inefficiencies however the main and overarching constraint will always be operational safety. As such a revolutionary change in the operational context would be unrealistic and disruptive in nature. ICAO has identified Trajectory Based Operations (TBO) as one of the key enablers for a more sustainable aviation future[3]. TBO’s depart from vector based operations and allow the introduction of a 4 Dimensional Trajectory (4DT) which can be mathematically optimized with respect to various economic and environmental criteria [5]. In some cases multiple objectives can be applied to the optimization routine [6]. This form of ATM operation allows for individual routes to be optimized based on various criteria while satisfying multiple constraints. The route can be optimized in sections by applying one set of constraints for the terminal area operation and a different one for the en-route phase. This allows for an a priori approach in applying appropriate criteria to the optimization problem [7]. As a significant portion of fuel is consumed in the cruise or en-route phase of flight, an optimized cruise trajectory minimizing fuel burn is highly favourable from an economical and environmental perspective. Although it is logical to assume that the great circle arc is geometrically the fastest and most efficient ground path between two points on the Earth’s surface, the atmospheric wind field can be included in the optimization problem to generate trajectories that maximise the exploitation of favourable tailwind scenarios. The resulting trajectory is no longer linear and would require assistance from airborne guidance systems to continuously meet scheduled waypoints along the route. This operational approach has the potential to significantly reduce fuel burn, travel time and environmental impact. It is also a solution that can be applied to most commercial aircraft in current air travel operations, given the maturity attained by innovative avionics systems.

**Problem Definition**

The optimization problem formulated here is one where flight time is minimized subjected to various constraints and boundary conditions. This allows a general optimized trajectory from point to point which can then be transferred into a fuel saving by using Thrust Specific Fuel Consumption (TSFC) for the aircraft flying that particular route. The atmospheric wind field is supplied to the optimizer which calculates the most optimum path between two points. From the mathematical perspective, trajectory optimisation problems can be numerically solved either via direct methods or indirect methods [8]. Direct methods attempt a direct solution of the physical problem, by introducing some sort of aircraft dynamics model and optimising the control variables’ profiles. Indirect methods are based on various possible surrogate models. For instance, in our optimization problem formulation, geometrical descriptors of the trajectory are the variables actively controlled by the optimiser to minimise the fuel consumption. As we are focussing on the en-route phase, our formulation assumes an aircraft in its cruise flight condition; therefore we can constrain the problem to a constant airspeed and neglect the aircraft dynamics.
The Trajectory Optimization Problem

The formation of the trajectory optimization problem begins with defining the time cost function. This requires the introduction of the scalar performance index \( J_i \) that quantifies the achievement of the corresponding objective \( i \in [1; n_i] \). The optimization problem can then be expressed mathematically and can either be minimized or maximized. In this case a minimised travel time is of interest. The performance index is determined by a cost function that can be expressed in the traditional Bolza form [9]. This cost function is formed by summing the Mayer term and the Lagrange term. The Mayer term is a function of initial and final trajectory states while the Lagrange term is an integral function of the state, control and parameters with respect to time. The complete performance index is hence calculated as in equation 1.

\[
J_i = \Phi[x(t_o), x(t_f), p] + \int_{t_o}^{t_f} L[x(t), u(t), p] dt
\]  

The performance index allows a quantitative assessment of the trajectory objective, in this case the minimum travel time between two points. In an iteration loop each calculated trajectory is assessed on its performance until the process converges onto a solution with the best performance index.

Path Constraints

Due to the nature of this optimization problem, constraints are not necessarily required unless a human imposed no fly zone, large weather cells or other identified obstacle needs to be avoided. Avoidances such as these can be represented by an inequality constraint (Eqn 2):

\[
g_i(x(t), u(t), t; p) \leq 0
\]  

Furthermore a constraint can be applied as an equality constraint (Eqn 3) and would be used to force the aircraft to pass by a specific point in space-time.

\[
h_i(x(t), u(t), t; p) = 0
\]

Boundary Conditions

Boundary conditions within this optimization problem can represent the boundaries of an individual sector or the external boundaries of multiple sectors along the route. For the purpose of this optimization problem the perimeter of a group of sectors that the aircraft is assumed to fly within will form the boundary condition of the optimization problem.

Boundary constraints are represented by in an inequality fashion by:

\[
\Phi_{\text{min}} \leq \Phi[x(t_o), x(t_f), u(t_o), u(t_f); p] \leq \Phi_{\text{max}}
\]  

where equality conditions are still encompassed by simply imposing \( \Phi_{\text{min}} \) = \( \Phi_{\text{max}} \).

Optimizing a Melbourne to Shanghai Trajectory

Introducing the case study

Unlike Flex Tracks, which are also generated using the forested wind field and only account for European bound traffic from Australia, a personalized flight trajectory using winds to
reduce fuel consumption can be formulated for a variety of flights in the off line planning stage of each aviation operation. A green trajectory would be formulated on a “first come first serve” basis. This is the simplest and most responsive scheme but it requires tight coupling between the advisory route generator and the ATC system due to the time lag between when the reroute is generated, when it is implemented or rejected by ATC and/or the Airline Operator and when the advisory route generator is informed of this status. Reroute requests from other Airline Operators can be received before the first Airline Operator has had a chance to implement a cleared reroute request that results in an update of the real-world flight plan database of the centralised advisory route generator. Consequently the advisory system can clear cumulative changes that end up being in conflict with each other or reject changes that are currently in conflict but which would be clear of conflicts with routes as subsequently amended. The optimized trajectory would need to be flown accurately throughout the cruise phase of flight for maximum benefit and would require a NextGen Flight Management System which has been proposed by ICAO and CleanSky. The proposed FML will be capable of flying 4D trajectories with various degrees of flight autonomy and is a primary focus of current research[10, 11]. This would also require the aircraft to take precedence in the sky with surrounding traffic to be routed around the aircraft flying the optimized trajectory. The case study presented here is summarized in table 2 and represents a frequent international travel operation.

<table>
<thead>
<tr>
<th>Assumptions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft Similarity</td>
<td>A330 – 200</td>
</tr>
<tr>
<td>L/D ratio</td>
<td>20</td>
</tr>
<tr>
<td>Passengers</td>
<td>241 pax</td>
</tr>
<tr>
<td>Weight per passenger (75kg Human + 20kg luggage + 10kg carry on)</td>
<td>115 kg</td>
</tr>
<tr>
<td>$W_{\text{empty}}$</td>
<td>119,600 kg</td>
</tr>
<tr>
<td>$W_{\text{full}}$ (+10% reserve fuel)</td>
<td>216,160 kg</td>
</tr>
<tr>
<td>$C_{\text{DD}}$</td>
<td>0.01895</td>
</tr>
<tr>
<td>Cruise Velocity</td>
<td>220 ms$^{-1}$</td>
</tr>
<tr>
<td>Gravity constant</td>
<td>9.2 Nm$^{-1}$kg$^{-1}$</td>
</tr>
<tr>
<td>Range (Melbourne to Shanghai)</td>
<td>8,050 km</td>
</tr>
</tbody>
</table>

Although maximum benefit would be achieved by performing a trajectory optimization using a 3D wind field to produce a 4D trajectory, the current ATM operations prescribe the adoption of stringent flight level rules to maintain aircraft separation for east and west bound traffic. A 4D trajectory would require an aircraft to continuously vary altitude and would increase the amount of ATC workload and violate standard procedures in the current operational paradigm however research is underway in these operational scenarios [12]. An alternative method of optimized trajectories for each flight level to evaluate which trajectory is the most efficient may be a viable alternative (Fig. 1). This would ultimately create a trajectory that would be constrained to a single flight level through the cruise phase of flight with an entry waypoint and exit waypoint. The human ATC operator would retain full understanding and management capabilities on the optimised aircraft trajectory defined by waypoints at a constant flight level. Although this method would produce a sub-optimal flight trajectory it allows for optimized trajectory to be readily applied and integrated into the current ATM operation.
The wind field used for this case study is simulated using a random number generator however an effort was made to match the wind field for a flight level of 30,000ft on a day specified in Fig. 2. A number of online resources, such as Sky Vector, display real time renderings of wind barbs at various flight levels. Real wind vector data can be obtained through meteorology departments and will be implemented in future studies.

Fig. 2: Melbourne to Shanghai wind barbs from Sky Vector at FL300 on the 15/10/2013

The optimized trajectory in this case uses a cost function related to the time between destinations. The cost function is a function which sums the aircraft velocity vector with the wind vector which will either increase or decrease the aircraft’s ground speed. The optimizer continuously iterates until the converging onto a trajectory solution of minimum time. For this example we use mathematical solver embedded in a MATLAB function called “fmincon” which is inbuilt into the software. This solver uses the subspace trust region method which is mainly based upon the interior-reflective Newton method [13].
In order to estimate the fuel consumption, for the purpose of the simulation the A330-220 Base of Aircraft Data (BADA) provided by Eurocontrol was used [14]. In normal circumstances the Breguet equation would be sufficient to calculate the amount of fuel used throughout the aircraft flight however it is reliant on the aircraft range and assumes no influences of wind. As such the briquette equation cannot be used. For this case study we calculate the DATA Trust Specific Fuel Consumption (TSFC) expressed in Eqn. 8 where a constant cruise velocity of 220ms$^{-1}$ is assumed.

$$TSFC = C_1 \times \left( \frac{V_{TAS}}{C_f} \right)$$  \hspace{1cm} (8)

The TSFC can then be multiplied by the time (in minutes) and the amount of thrust (in kN) to achieve the amount of fuel for both routes. Thrust can be calculated by assuming a cruise flight phase which allows Thrust (T) to be approximately equal to Drag (D). Drag was calculated using the standard drag equation with all coefficients taken from BADA.

$$D = C_D + kC_L^2$$  \hspace{1cm} (9)

### Table 3: Optimized trajectory results summary

<table>
<thead>
<tr>
<th>Variable</th>
<th>Straight Line Path</th>
<th>Optimized Trajectory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Travelled</td>
<td>9hrs 47.8 min</td>
<td>9hrs 38.2min</td>
</tr>
<tr>
<td>Distance Travelled</td>
<td>8050km</td>
<td>8207km</td>
</tr>
<tr>
<td>TSFC @ $V_{cruise/TAS}$</td>
<td>0.8254 Kg/(min*kN)</td>
<td></td>
</tr>
<tr>
<td>Fuel Used (mass)</td>
<td>62.06 tons</td>
<td>61.05tons</td>
</tr>
<tr>
<td>Fuel Used (volume)</td>
<td>49.89 x 10$^3$ Lts</td>
<td>48.90 x 10$^3$ Lts</td>
</tr>
<tr>
<td>Fuel Saving</td>
<td>990 Lts (217.77 Gallons)</td>
<td></td>
</tr>
<tr>
<td>Cost Saving</td>
<td>~ A$1,584 (@ $1.6 per litre)</td>
<td></td>
</tr>
<tr>
<td>CO$_2$ Emissions (3156g/Kg)</td>
<td>195,861 Kg</td>
<td>192,674Kg</td>
</tr>
<tr>
<td>CO$_2$ Emission Reduction</td>
<td>~1.6%</td>
<td></td>
</tr>
</tbody>
</table>

### Discussion

The Melbourne to Shanghai case study allows for a direct comparison between a straight line path and an optimized path using atmospheric winds (Table 3). One noticeable result is the
increase in distance travelled to direct the aircraft into favourable winds to increase its overall ground speed. Although the cruise velocity remains constant throughout the flight, tailwinds allow for a faster groundspeed without any drag penalty of or development of transonic flow phenomena since the flow velocity around the aircraft remains constant at all times. This also assumes that the autopilot is programmed to maintain a constant flight velocity using the local pitot static tube to measure TAS. The flight time is reduced approximately 9.6 minutes and translates into fuel saving of 990Lts. From an airline perspective the fuel saving appeals to the cost of the operation as the amount of fuel used is significantly reduced with savings of approximately A$1,584 in fuel purchase costs. This would also reduce the cost of carbon emissions when applied to either a carbon trading or a carbon tax scheme. As the optimized trajectory is formulated offline, presumably a day before the operation, the difference between the predicted and actual wind conditions may differ and add error when fuel burn is calculated. Error could be reduced by a validated trajectory hours before the operation however this would depend on the supplier load and the operational cost of a pre-flight trajectory validation. We must also note that the atmosphere is a constantly changing environment and as such the wind vector field will change with respect to time. The wind field used here is of a static nature and can be taken at a time where the aircraft is predicted to be mid-way on its journey. Due to this approach we can consider an addition of error due to this computational constraint. Using a dynamically changing wind model would increase the accuracy of the trajectory however wind models are often computationally intensive and require significant resources to run themselves. A predicted wind field at a predicted mid-journey flight time from weather organisations, such as the Bureau of Meteorology (BoM), would allow trajectories to be formulated in minutes without the need of extraordinary computational facilities.

Conclusion

Using optimized trajectories for commercial operation offers real cost and emission savings from an operational perspective. Although trajectory based operations would require an autopilot to track the optimized trajectory, current civil aircraft could be able to correctly track the optimal route in a coarse and linear fashion by flying to each waypoint along the trajectory. This would produce a sub-optimum result and lead to lesser fuel savings however this is operationally viable without any additional flight systems. This is currently being done Flex Tracks which are formulated daily and utilize the energy in the wind to reduce fuel burn for long international routes. Although the emission targets are significantly larger than CO2 reductions found here, optimized trajectories provide a cost effective approach in reducing fossil fuel usage and carbon emissions which can be readily applied to current ATM operations and future 4DT based operations.

References


16th Australian Aerospace Congress, 23-24 February 2015, Melbourne


