New altitude optimisation algorithm for the flight management system CMA-9000 improvement on the A310 and L-1011 aircraft

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ABSTRACT

The current flight management system (FMS), CMA-9000, from CMC Electronics-Esterline, only optimises the vertical flight profile in terms of the speed of the aircraft. This article defines a methodology that optimises the speeds and altitudes for the vertical profile, obtaining a trajectory that reduces the global flight cost.

The performance database (PDB) provided by CMC Electronics-Esterline is presently used on aircraft such as the Lockheed L-1011, the Airbus A310 and the Sukhoi Superjet 100 Russian regional jet. The PDB is used as the reference to design different trajectory optimisation algorithms to obtain the altitude where the aircraft fuel efficiency is the best. These algorithms are compared with the part-task trainer (PTT), simulator that represents the FMS CMA-9000, supplied by CMC Electronics-Esterline as well.

To validate the results, the FlightSIM® software is used, which considers a complete aircraft aerodynamic model for its simulations, giving accurate results and very close to reality.

Paper No. 3829. Manuscript received 18 March 2012, revised version received 28 November 2012, accepted 24 January 2013.

NOMENCLATURE

3D PAM	3D path arrival management
ATC	air traffic control
CDA	continuous descent approach
CI	cost index
FMS	flight management system
GA	genetic algorithm
IAS	indicated airspeed
ICAO	International Civil Aviation Organization
PDB	performance database
PTT	part-task trainer
TAS	true airspeed
TOC	top of climb
TOD	top of descent

1.0 INTRODUCTION

The reduction of fuel consumption on aircraft has taken different tendencies: the development of more efficient engines to decrease the production of pollutant emissions, improvements to the frame to make the aircraft more fuel efficient, or the optimisation of the flight trajectories. This article will focus on the FMS capability of creating optimal flight trajectories.

Since the first FMS was added as standard equipment to an aircraft in 1982[1], FMS have been continuously upgraded, and presently all aircraft are equipped with one. The primary functions of a FMS are to assist the pilot in several tasks, such as navigation, guidance, trajectory prediction and flight path planning.

Even if researchers have been working impetuously on improving the performance of FMS, recent studies demonstrate that improvement areas are still vast. Herndon, Cramer and Nicholson[2] found that different FMS act differently in terms of optimisation and trajectories generation. It is then important to mention that this article focuses on the improvement for the FMS CMA-9000 from CMC Electronics-Esterline.

The studies of optimal trajectories in aviation have incremented considerably over the last ten years. Many different tendencies have appeared to reduce the fuel burn. Studies to include aircraft traffic control as one of the FMS functions, without the assistance of the ATC (air traffic control), have been analysed[3]. The main purpose of the ATC is to keep aircraft separated by a safe distance. The ATC will decide if the trajectory proposed by the FMS can be followed by the aircraft.

Other studies have focused specifically in the descent phase, where the goal is to reduce pollution near to air terminals in terms of noise pollution and fuel burn emissions. Different descent techniques have been proposed. Clarke *et al*[4] introduced the continuous descent approach (CDA) method to reduce noise, which consisted in the deceleration and descent of the aircraft at its own vertical profile from the top of descent (TOD). This method, however, depends on the ATC to proceed, since it needs to have a clear path to the runway. Tong *et al*[5] explained that the CDA can only be used in low air traffic conditions, since 'ATC lacks the required ground automation to provide separation assurance services during CDA operations'. He then proposed a 3D Path Arrival Management (3D PAM) algorithm to predict 3D descent trajectories and be able to apply CDA in high traffic conditions. Reynolds, Ren and Clarke[6] concluded after different tests in the Nottingham East Midlands Airport that CDA effectively reduced fuel burn and noise near the terminals simply by keeping the aircraft at the higher altitude possible before creating the descent. Stell[7] used an efficient descent advisor, which is a method to predict the latest descent point (equivalent to the TOD) in order to apply the 3D PAM technique, but it still needs an improved ATC in order to operate at its maximal efficiency.

To obtain a more substantial impact on the environment, all the flight phases — climb, cruise and descent — have to be analysed.

The cruise is the most important phase of the flight in terms of fuel economisation. Lovegren[8] analysed how the fuel burn could be reduced during the cruise if the appropriate speed and altitude is selected, or if step climbs are performed on this phase. The selection of the optimal climb, cruise and descent on a FMS will definitely reduce fuel burn.

Campbell [9] studied the influence of weather imposed obstacles, such as thunderstorms and contrails, in the analysis of air pollution and fuel burn augmentation. He modeled these climatic conditions as obstacles, and created an algorithm capable of creating trajectories to avoid these obstacles with the minimal fuel consumption.

Ideally, to obtain the optimal flight trajectory that minimises the global flight cost, all the possible flight trajectories would have to be analysed. However, this would result in a high calculation time process. Instead of calculating all the possibilities, an optimisation method is applied. Different optimisation methods have been used on aviation systems, such as the Monte Carlo method used by Ref. 10 to avoid air traffic conflicts and increase air safety, or the Genetic Algorithm (GA) used by Ref. 11 to create flight trajectories based on aircraft modeled in six different dimensions. The GA allowed the author to impose several restrictions and still optimise the trajectories.

The trajectory optimisation new algorithm proposed in this article is developed using the aircraft PDB data collected by CMC Electronics – Esterline with the aim to be adapted on their FMS; nevertheless, speed and altitude restrictions can be imposed at each waypoint of the flight trajectory. The maximal optimised trajectory is obtained when all the speeds and altitudes are used; and even if the ATC sets certain restrictions, the algorithm will still find the optimal trajectory within these restrictions. In our algorithm, with respect to other algorithms, a complete flight analysis is performed, and all the phases of the flight can be adapted to ATC's requirements to obtain the maximal optimisation and emissions reduction.

During its first phase, only the vertical profile is optimised. Wind conditions are also considered in the calculation of the costs, and the methodology is explained in the following sections of this article. The next versions of the algorithm should include the analysis of the lateral profile, and the obtaining of the weather automatically.

All the available speeds and altitudes are calculated for the climb and cruise, but since the descent start point varies in terms of aircraft weight and remaining flying distance, it would be inefficient to calculate every descent. Optimisation methods such as Monte Carlo or GA are expensive in terms of calculation time and not effective when the search space is reduced. Therefore, an interval reducing method was selected. The golden section search is the best of the interval-reducing methods and it is useful on this project because of its simplicity for implementation[12]. This method will be later explained in this article.

Aircraft fuel burn is an important contributor for carbon dioxide (CO2) emissions to the atmosphere, the principal greenhouse gas. Total CO_2 emissions dues to aircraft traffic represent between 2·0% and 2·5% of all carbon dioxide emissions to the atmosphere[13]. Greenhouse gases contribute to the global warming effect, which is one of the most important environmental problems encountered nowadays. The creation of more efficient trajectories for aircraft would contribute in the reduction of fuel burn, therefore in the reduction of CO_2 emissions to the atmosphere.

```
MODE CRUISE_PROFILE_MACH
! * * * * * * * * * * * * * * * * *
! Last Update    : 2011/01/23 8h2
! Aircraft       : A310 304 Basic
! Reference CG   : 28
! * * * * * * * * * * * * * * * * *
   SPEED  0.8
      GROSS_WEIGHT  100000
         ISA_DEV  -10
            !Altitude  FuelFlow
              20000     0
              21000     0
              22000     0
              23000     0
              24000     0
              25000     5355
              26000     5146
              27000     4948
              28000     4756
              29000     4574
              30000     4402
              31000     4243
              32000     4091
              33000     3946
              34000     3809
              35000     3685
              36000     3574
              37000     3495
              38000     3441
              39000     3405
              40000     3378
              41000     3376
```

Figure 1. Example of information given on the PDB.

In Canada, the Green Aviation Research & Development Network (GARDN) was founded in 2009. The first project in this network was called Optimized Descents and Cruise. The new proposed optimisation algorithm is developed in this project, where the data needed for validation was provided by the well known avionics company CMC Electronics-Esterline.

2.0 GLOBAL COST

In aviation, not only the fuel burn is considered in order to plan a flight trajectory. Variables such as the flight time and operation costs must be taken into account. The cost index (CI) is the term used by the airlines to calculate the operation costs for each flight.

To calculate the global cost of the flight, the fuel cost should be obtained first:

$$\text{Fuel Cost} = \text{Fuel Price} * \sum \text{Fuel burned} \qquad \ldots (1)$$

Where the fuel cost is expressed in \$, the fuel price in \$/Kg and the fuel burned in kg.

$$\text{Operation Cost} = \text{Fuel Price} * \text{Cost Index} * \text{Flight Time} * 60 \qquad \ldots (2)$$

Where the operation cost is given in \$, the cost index in Kg/min and depends on each company. The flight time is expressed in hours (h), and the number 60 is a constant to convert minutes to

Table 1
Inputs and outputs for the PDB for the Airbus A310

Type of table	Inputs	Outputs
Climb	Centre of gravity Speed Gross weight ISA deviation Altitude	Fuel burn Horizontal distance
Climb acceleration	Gross weight Initial speed Initial altitude Delta speed	Fuel burn Horizontal distance Delta altitude
Cruise	Speed Gross weight ISA deviation Altitude	Fuel flow
Descent deceleration	Vertical speed Gross weight Initial speed Final altitude Delta speed	Fuel burn Horizontal distance Delta altitude
Descent	Speed Gross weight Standard deviation Altitude	Fuel burn Horizontal distance

hours. The global cost is the sum of the operation and fuel costs, then:

$$\text{Global cost} = \text{Fuel Cost} + \text{Operation Cost} \quad \ldots (3)$$

$$\text{Global Cost} = \text{Fuel Price} * [\sum \text{Fuel burned} + \text{Cost Index} * \text{Flight Time} * 60] \quad \ldots (4)$$

It turns to be illogical to consider the fuel price, since it changes every time, therefore, to simplify the equation the global cost will be given in kg of fuel, that would have to be multiplied by the fuel price at the moment of the utilisation of the algorithm in order to obtain a quantity in terms of money ($).

$$\text{Global Cost} = \sum \text{Fuel burned} + \text{Cost Index} * \text{Flight Time} * 60 \quad \ldots (5)$$

The goal of this algorithm is to reduce the global cost of the flight.

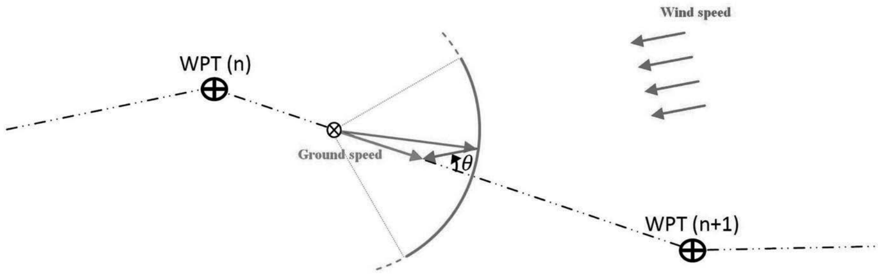

Figure 2. Wind factor calculation[14].

Table 2
Crossover altitude example for a 300/0·82 speed schedule

Altitude (ft)	TAS due to an IAS of 300 knots (knots)	TAS due to a Mach number of 0·82 (knots)
10,000	345·4	523·2
11,000	350·4	521·3
12,000	355·6	519·4
13,000	360·8	517·4
14,000	366·1	515·5
15,000	371·6	513·5
16,000	377·1	511·6
17,000	382·7	509·6
18,000	388·4	507·7
19,000	394·3	505·8
20,000	400·2	503·8
21,000	406·3	501·4
22,000	412·5	499·4
23,000	418·8	497·5
24,000	425·2	495·6
25,000	431·7	493·6
26,000	438·3	491·2
27,000	445·1	489·2
28,000	452·0	487·3
29,000	459·0	485·4
30,000	466·2	482·9
31,000	473·4	481·0
32,000	480·8	479·0
33,000	488·4	476·6
34,000	496·1	474·7
35,000	503·9	472·7
36,000	512·5	470·3
37,000	521·8	470·3
38,000	531·6	470·3
39,000	542·0	470·3

https://doi.org/10.1017/S0001924000008459 Published online by Cambridge University Press

Table 3
Crossover altitudes table (ft)

IAS/ Mach	250	260	270	280	290	300	310	320	330	340	350	360	365
0·78	38,000	36,000	35,000	33,000	31,000	30,000	28,000	27,000	25,000	24,000	22,000	21,000	20,000
0·785	38,000	36,000	35,000	33,000	32,000	30,000	29,000	27,000	26,000	24,000	23,000	21,000	21,000
0·79	39,000	37,000	35,000	34,000	32,000	30,000	29,000	27,000	26,000	24,000	23,000	22,000	21,000
0·795	39,000	37,000	35,000	34,000	32,000	31,000	29,000	28,000	26,000	25,000	23,000	22,000	21,000
0·8	39,000	37,000	36,000	34,000	33,000	31,000	30,000	28,000	27,000	25,000	24,000	22,000	22,000
0·805	39,000	38,000	36,000	34,000	33,000	31,000	30,000	28,000	27,000	25,000	24,000	23,000	22,000
0·81	39,000	38,000	36,000	35,000	33,000	32,000	30,000	29,000	27,000	26,000	24,000	23,000	22,000
0·815	40,000	38,000	37,000	35,000	34,000	32,000	30,000	29,000	28,000	26,000	25,000	23,000	23,000
0·82	40,000	39,000	37,000	35,000	34,000	32,000	31,000	29,000	28,000	26,000	25,000	24,000	23,000
0·825	40,000	39,000	37,000	36,000	34,000	33,000	31,000	30,000	28,000	27,000	25,000	24,000	23,000
0·83	40,000	39,000	38,000	36,000	34,000	33,000	31,000	30,000	29,000	27,000	26,000	24,000	24,000
0·835	41,000	39,000	38,000	36,000	35,000	33,000	32,000	30,000	29,000	27,000	26,000	25,000	24,000
0·84	41,000	39,000	38,000	36,000	35,000	33,000	32,000	31,000	29,000	28,000	26,000	25,000	24,000

3.0 METHODOLOGY

Currently, the FMS CMA-9000 provides a speed optimisation, which is calculated from the PDB. It also determines an optimal altitude for the initial values of the aircraft, which can be inaccurate because the fuel reduction is not updated during the flight, thus, the given altitudes and speeds are not truly optimal. The optimisation algorithm used by the FMS CMA-9000 is unknown for the realisation of this project.

In this paper, the new proposed algorithm will be explained in details. This algorithm improves considerably the FMS CMA-9000 trajectory planning by:

- A complete analysis of the variation of speeds and altitudes for the climb phase.
- The search of possible step climbs to be executed during the cruise phase to reduce the flight cost.
- The calculation of the optimal descent speed in terms of global cost reduction.

All flight phases are considered in order to obtain the best possible optimisation results. The new algorithm improves the path planning and reduces flight cost. Additional altitude, speed and time restrictions are also considered in the development of this optimisation algorithm.

The new algorithm was developed in Matlab® based on the PDB for the Airbus A310 and Lockheed L-1011 aircraft (same used on CMA-9000), and it is capable of reducing the fuel burn with an average of 2·57% (to the date).

Fundamental research data for this project is given by the PDB. The numerical model of the aircraft provides all the necessary information to create the algorithm. The PDB is a database of approximately 30,000 lines, which gives the information about real aircraft performances. It indicates the fuel consumption and the distance flown for a specific flight profile (climb, cruise or descent). For example, the fuel burn and distance for an aircraft cruising with a centre of gravity of 28% of the mean aerodynamic chord, flying at Mach 0·8 with a total gross weight of 100 tons, at an altitude of 30,000ft and a standard deviation temperature of –10ºC. Such an example is shown on Fig. 1(above).

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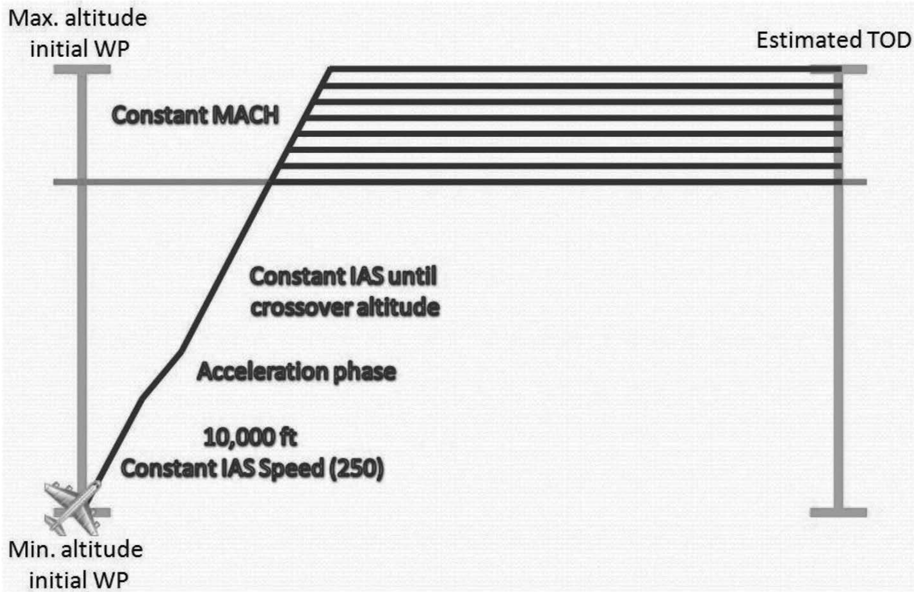

Figure 3 Climb phase.

The PDBs includes as inputs the aircraft weight, altitude, speed, centre of gravity and air temperature, and the outputs are the traveled distance and the fuel burn. The traveled time is calculated from the aircraft true air speed (TAS), while the wind influence is calculated with a wind triangle methodology, providing a travelled distance correction factor depending on the wind angle and speed. The wind speed and direction are entered manually into the algorithm, at four different altitudes, at each flight waypoint, in the same way as on the FMS CMA-9000.

The PDB contains very detailed aircraft information; however, there are five main tables that are used in this program. Inputs and outputs for different aircraft may differ. Airbus A310 tables can be observed in Table 1.

The wind influence on the trajectory will be calculated using the wind triangle method (Fig. 2). As the aircraft flights on a straight path, the wind affects the aircraft's speed. Depending on the direction and speed of the wind, the distance traveled by the aircraft will be either reduced or augmented in a time segment.

The wind factor can be calculated in the following way [14]:

$$Wind\_factor = \mathrm{Cos}\left[\mathrm{Arcsin}\left(\frac{\mathrm{Sin}(\theta) * \|\overrightarrow{Wind_{speed}}\|}{\|\overrightarrow{Air_{speed}}\|}\right)\right] - \frac{\|\overrightarrow{Wind_{speed}}\|}{\|\overrightarrow{Air_{speed}}\|} * \mathrm{Cos}(\theta) \qquad \ldots (6)$$

4.0 CLIMB

The PDB divides the TAS values in two different types of speeds: IAS (Indicated Air Speed) and Mach number. The TAS varies with the altitude. For the IAS case, the TAS increases with the altitude, while Mach decreases with the altitude. The altitude for which the TAS due to IAS

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is equal to the TAS due to Mach is called the crossover altitude. Table 2 represents an example for a 300/0·82 speed schedule (composed from an IAS/Mach pair), with an altitude step of 1,000ft.

The climb phase consists of four different phases:

- Initial climb. Aircraft is located initially at 2,000ft, and will climb up to 10,000ft at a constant predefined speed (normally 250 IAS).
- Acceleration phase. Aircraft will accelerate to the selected optimal IAS speed.
- IAS climb. Aircraft will climb at a constant IAS speed after the acceleration phase until the crossover altitude.
- Mach climb. Once the aircraft reaches the crossover altitude, it will climb at a constant Mach speed.

For the purpose of this project and in order to reduce processing time, the Mach speed selected during the cruise phase remains constant through the complete flight. Speed variation during the cruise phase will be considered for future work.

To select the optimal climb for the flight, all available speed schedules will be calculated. Each speed schedule expressed as IAS/Mach has its own crossover altitude that can be seen in Table 3. For each IAS/Mach couple, the crossover altitude is calculated using a 1,000ft altitude step.

The aircraft climbs at a constant 250 IAS from 2,000ft to 10,000ft. At 10,000ft, the acceleration tables are created for each IAS speed. At the final acceleration altitude, the climb for each available IAS is calculated up to the maximal climb altitude (normally, 40,000ft). The aircraft will only cruise at the Mach speed. After the IAS climb table is calculated, the Mach climb is calculated from the crossover altitude and up to the maximal altitude. From the crossover altitude and for each 1,000ft over the crossover altitude, the cruise cost is calculated for the entire length of the flight and is saved in the flight cost table. The flight cost table contains all the possible speed schedules and all the possible cruise altitudes. From the minimal cruise altitude (20,000ft) to the maximal altitude, only the lowest cost speed schedule for each altitude is selected. Fig. 3 represents the climb phase.

5.0 CRUISE

The cost optimisation algorithm calculates the optimal trajectory depending on the flight length. For short flights (under 500nm), where usually flight restrictions are not changed during the flight, the algorithm obtains the lowest cost altitude and speed schedule from the flight cost table. For short flights, the descent phase has high influence on the global cost of the flight. Since the descent is the lowest cost phase during a flight, it is possible that would be better if the aircraft would climb higher (higher cost) in order to have a longer descent and a shorter cruise. The cost optimisation algorithm uses the Golden Section search optimisation algorithm for the cruise. Calculating all the possible descents for the flight cost table would result in an excessive (and unnecessary) calculation time, therefore, the Golden Section method is applied. The Golden Section method is a non linear optimisation method that reduces the search interval by the same fraction, with each iteration, at a golden section ratio, which is commonly known in mathematics as the golden ratio[12]. The golden section search was selected over other interval reducing methods, such as the dichotomous search or the Fibonacci method, because its efficiency and ease of implementation. The dichotomous search calculates two new evaluations at each iteration, while the golden section search and the Fibonacci method only calculate one new evaluation at each new iteration. The Fibonacci method, however, reduces the size of the interval by the Fibonacci series, which changes the reduction size with each iteration. The golden section search uses a fixed interval reduction, making it simpler to implement.

Applied to the trajectory optimisation algorithm, the Golden Section search is the most adequate of the interval reducing methods. The fewest number of iterations are obtained, and its simplicity reduces the algorithm processing time.

The algorithm obtains the lowest cost speed schedule and altitude, which may not be the maximal altitude. Since it could be possible that climbing at a higher altitude (to have a longer descent phase) would result in a lowest global cost trajectory, the method should calculate the descent for all possible altitudes over the cost altitude selected from the flight cost table. Calculating all the possibilities, as it was mentioned before, would result in an excessive calculation time for the algorithm.

The Golden Section method selects a search range, which in this case is from the lowest cost altitude a to the maximal available cruise altitude b [a,b]. The algorithm divides the search range applying the gold ratio rule, creating two intersections within [a,b], that are named x_1 and x_2 and are calculated as follows:

$$x_1 = \gamma^*a + (1-\gamma)^*b \quad \ldots (7)$$

$$x_2 = (1-\gamma)^*a + \gamma^*b \quad \ldots (8)$$

Where γ is the golden ratio (0·618), and x_1 and x_2 are the altitudes within the search range, and are rounded to the nearest thousand (the algorithm calculates at each 1,000ft). The descent is calculated for altitudes x_1 and x_2, and both complete trajectories are compared to continue with the optimisation algorithm in the next way:

$$\begin{gathered}\text{If } f(x_1) < \mathrm{f}(x_2)\\ b = x_2\\ x_2 = x_1\\ x_1 = \gamma^*a + (1-\gamma)^*b\end{gathered} \quad \ldots (9)$$

$$\begin{gathered}\text{If } f(x_2) < f(x_1)\\ a = x_1\\ x_1 = x_2\\ x_2 = (1-\gamma)^*a + \gamma^*b\end{gathered} \quad \ldots (10)$$

Where $f(x_2)$ and $f(x_2)$ are the global cost for the trajectories at x_1 and x_2.

In case that because of the rounding of the altitudes, x_1 and x_2 are the same, the algorithm calculates the global cost values for a and b, and eliminates the trajectory with the highest cost. Variable a or b is replaced.

The Golden Section method stops at a desired tolerance. In this case, it will stop when the search interval is reduced to 2,000ft (the algorithm cannot calculate two intersections in this interval).

The algorithm gives the final trajectory, which is the lowest cost trajectory for the desired flight.

The Golden Section method, applied to the trajectory optimisation method, can be better explained by the flow chart in Fig. 4.

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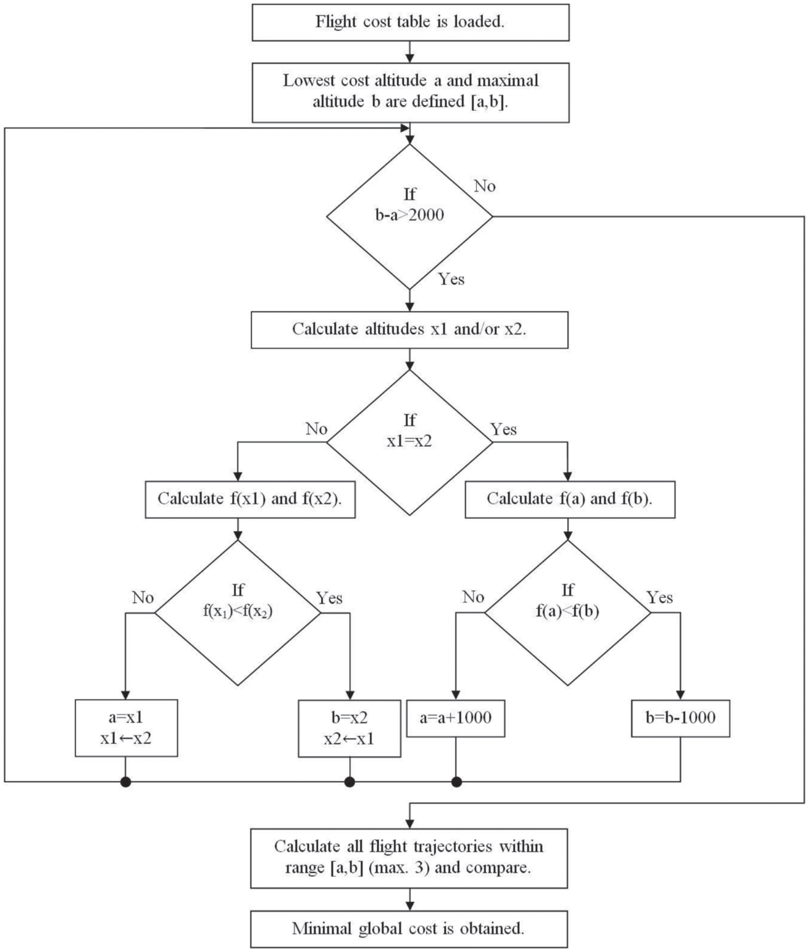

Figure 4. Golden section method flowchart.

With this methodology, not all possible descents are calculated, but only those for the lowest cost climb and cruise, reducing the number of iterations for the algorithm.

For long flights, the descent phase has a low influence on the global cost. The optimal trajectory is then selected using waypoints (Fig. 5). The trajectory is divided in a number n of waypoints, where the first waypoint is used for the climb, and the last one for the descent. In between, waypoints allow the imposition of constraints during the flight, such as altitude and speed restrictions, deviation angles, and even time restrictions. After the selection of the optimal climb (flight cost table), at each cruise waypoint, the possibility to climb at a higher altitude to reduce the flight cost is evaluated. The algorithm evaluates the cost of the climb and the cruise above current altitude, and determines if it is better to climb at a higher altitude to reduce the flight cost. At the last waypoint, the optimal descent is calculated.

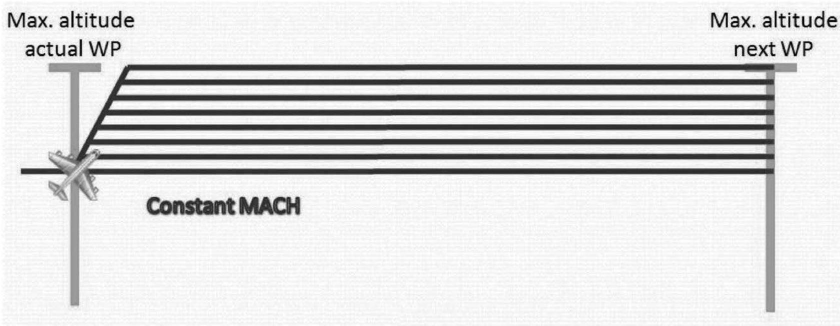

Figure 5. Cruise phase (flights over 500nm).

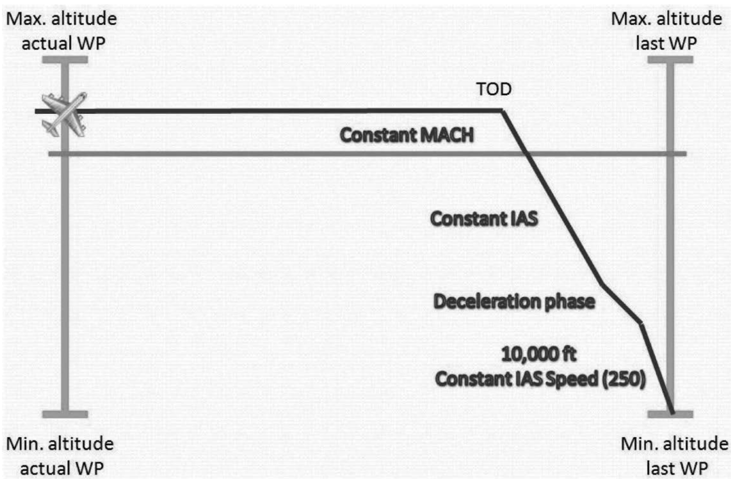

Figure 6. Descent.

6.0 DESCENT

To calculate the descent, the algorithm uses the Mach speed that the aircraft has at the TOD. The descent has the same phases as the climb, but calculated backwards. The descent is represented by Fig. 6.

In order to calculate correctly the descent, the horizontal distance has to be estimated.

- The descent from 10,000ft to 2,000ft is made at constant 250 IAS, and it is calculated first to estimate the horizontal distance traveled.
- The deceleration is calculated afterwards to obtain the altitude at which the deceleration process should start for each IAS speed.
- Since there is only one Mach speed available (current aircraft speed), the speed schedules will be those Mach/IAS pairs that have current Mach speed. The IAS descent from the crossover altitude and up to the deceleration altitude is calculated, followed by the Mach descent until the crossover altitude.

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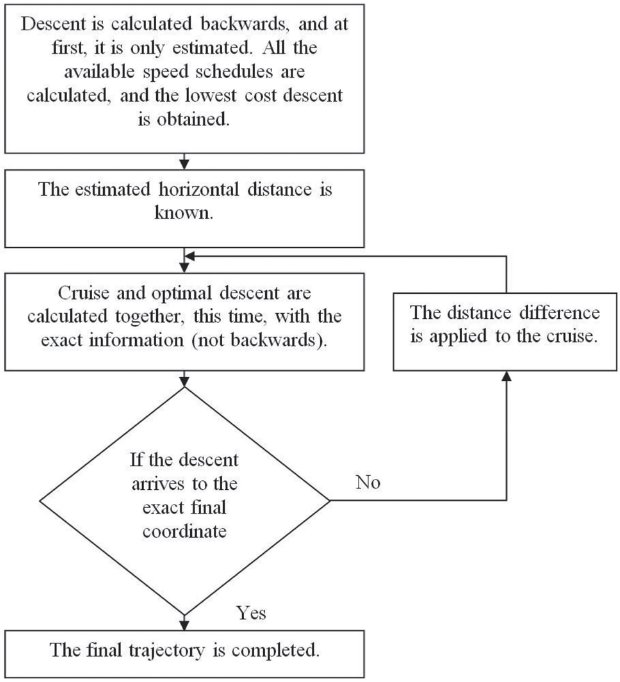

Figure 7. Descent flowchart.

- The approximated descent horizontal distance is now known for each Mach/IAS pair, and the descent that consists in the lowest fuel per nautical mile ratio is selected as the optimal descent. The cruise distance to arrive to the estimated TOD, is therefore, also known.
- Since the descent is estimated, the horizontal distance is not exact. If the aircraft does not arrive to the final co-ordinate, the distance difference is applied to the cruise distance, and the optimal descent is recalculated.

The descent methodology is explained by flowchart in Fig. 7.

7.0 RESULTS

The results are presented for two different analyses. Firstly, the tests to verify the algorithm precision and consistency were shown, where the algorithm was found to be more precise than the actual FMS. Secondly, a comparison between the algorithm and the FMS results was done to be able to quantify the advantages of the trajectory selected by the algorithm with respect to the trajectory of the FMS.

The results obtained have been validated with the flight simulator FlightSIM®, code developed by the Presagis Company. This software considers a complete aircraft aerodynamic model for its simulations, giving results in terms of fuel burn, flight time and traveled distance, which are accurate and very close to reality. For the purpose of this project, FlightSIM® represents the reference of reality. Only the Lockheed L-1011 aircraft flight dynamics are modeled in FlightSIM®.

Table 4
Fuel burn precision analysis with FlightSIM®

Flight	Altitude (ft)	Speed schedule IAS/Mach/IAS)	Depart airport code	Arrival airport code	FLSIM fuel (kg)	Algorithm fuel (kg)	PTT fuel (kg)	Algorithm error fuel (%)	PTT error fuel (%)
1	36,000	300/0·78/300	YUL	YYZ	4,518·1	4,559·8	4,554·74	0·92%	0·81%
2	32,000	300/0·78/320	YUL	YYZ	4,608·9	4,648·6	4,634·42	0·86%	0·55%
3	34,000	300/0·78/300	YUL	YYZ	4,544·5	4,590·5	4,688·97	1·01%	3·18%
4	38,000	300/0·78/300	YUL	YYZ	4,528·8	4,581·6	4,700·56	1·17%	3·79%
5	36,000	310/0·79/290	YUL	YYZ	4,528·8	4,574·4	4,657·1	1·01%	2·83%
6	40,000	340/0·82/260	YUL	YYZ	4,103·9	4,223·7	4,240·9	2·92%	2·19%
7	36,000/38,000 (step climb)	310/0·83/340	YUL	YVR	29,133·8	29677·5	29,770·9	1·87%	2·43%
8	38,000	310/0·82/340	YUL	YVR	29083	29693·1	29790·73	2·10%	3·82%
9	40,000	340/0·82/260	YUL	YWG	11939·7	12404·7	12396·36	3·89%	3·34%
			Average					**1·75%**	**2·55%**

Table 5
Flight time precision analysis with FlightSIM®.

Flight	Altitude (ft)	Speed schedule (IAS/Mach/IAS)	Depart airport code	Arrival airport code	FLSIM time (hr)	Algorithm time (hr)	PTT time (hr)	Algorithm error time (%)	PTT error time (%) (abs)
1	36,000	300/0·78/300	YUL	YYZ	0·69	0·69	0·7	0·48%	1·49%
2	32,000	300/0·78/320	YUL	YYZ	0·68	0·68	0·7	0·74%	3·13%
3	34,000	300/0·78/300	YUL	YYZ	0·69	0·69	0·69	0·43%	0·26%
4	38,000	300/0·78/300	YUL	YYZ	0·69	0·69	0·69	0·50%	0·50%
5	36,000	310/0·79/290	YUL	YYZ	0·69	0·69	0·69	0·51%	0·06%
6	40,000	340/0·82/260	YUL	YYZ	0·69	0·69	0·71	0·34%	1·94%
7	36,000/38,000 (step climb)	310/0·83/340	YUL	YVR	4·3	4·28	4·26	0·46%	0·93%
8	38,000	310/0·82/340	YUL	YVR	4·34	4·32	4·37	0·48%	0·76%
9	40,000	340/0·82/260	YUL	YWG	2·21	2·2	2·22	0·50%	0·17%
			Average					**0·49%**	**1·03%**

The PTT is the software that represents the FMS CMA-9000 from CMC Electronics – Esterline. In this section, PTT will be used for clarity of the results presentation. There is no difference between the PTT and the FMS CMA-9000.

The new optimisation algorithm is applied for two different aircraft: the L-1011 and the Airbus A310. Nine different trajectories for the Lockheed L-1011 were tested on FlightSIM®, using the same speeds, altitudes and distance. Both, the PTT and the proposed algorithm, were compared to FlightSIM® to determine which method has the more precise results. These results are shown on Table 4 and Table 5.

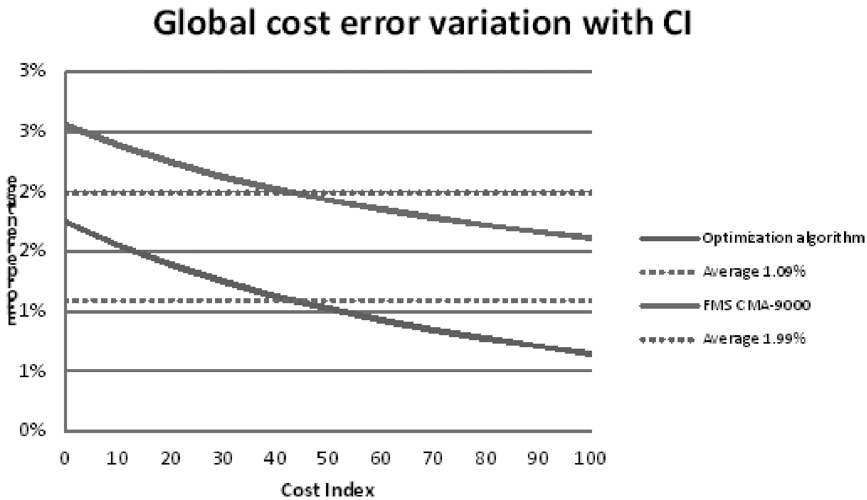

Figure 8. Global cost error variation with CI.

Table 4 shows the fuel burn analysis and Table 5 shows the flight time analysis. The first five columns represent the flight trajectory selected, with the speed, altitude and destination flown. It can be seen on both tables that the optimisation algorithm performs better than the PTT, with a 1·75% against a 2·55% error in terms of fuel burn, and 0·49% against 1·03% in terms of flight time. The algorithm gave more precise results.

Since on the global cost formula the time is important, and so is the CI, it should be considered in order to calculate an accurate optimisation percentage. For a CI of 0, the time has no influence on the global cost, opposite to a high CI of 100, when the time has a lot of influence in the total cost of the flight. Figure 8 displays the error variation depending on the CI.

Results from Fig. 8 indicate that the proposed algorithm results are closer to the results obtained with FlightSIM®, which as it was indicated before, is the reference used to validate the results. A 1·09% flight cost difference between the new algorithm and FlightSIM® was found, while a 1·99% flight cost error was obtained when compared with the PTT. Therefore, the proposed algorithm gave more precise results than the FMS CMA-9000.

Previous results show only the precision of the optimisation algorithm and the PTT compared to our reality reference, FlightSIM®. To verify that a fuel burn reduction can be obtained in respect to the PTT, a different set of test has been made.

To analyse the fuel burn, 56 tests for the A310 were performed, where:

- 20 tests where the same altitude and distance was imposed, looking to compare speed only optimisation.
- 36 tests where only the same distance was imposed, looking to compare speed and altitude optimisation.

https://doi.org/10.1017/S0001924000008459 Published online by Cambridge University Press

Table 6
Speed only optimisation comparison for the A310

Flight	CI	Altitude	Algorithm cost (kg)	PTT cost (kg)	Algorithm optimisation
1	0	32,000	9,532·4	9,603·1	0·74%
2	10	32,000	11,183·5	11,186·7	0·03%
3	20	32,000	12,800·9	12,808·9	0·06%
4	30	32,000	14,396·3	14,415·7	0·13%
5	40	32,000	15,932·7	15,933·4	0·00%
6	50	32,000	17,430·4	17,464·8	0·20%
7	60	32,000	18,893·0	19,020·6	0·68%
8	70	32,000	20,362·1	20,425·7	0·31%
9	80	32,000	21,830·6	21,889·8	0·27%
10	90	32,000	23,270·2	23,286·7	0·07%
11	0	36,000	9,147·5	9,147·0	0·00%
12	10	36,000	10,728·4	10,740·5	0·11%
13	20	36,000	12,280·0	12,263·9	–0·13%
14	30	36,000	13,804·7	13,789·0	–0·11%
15	40	36,000	15,296·3	15,356·9	0·40%
16	50	36,000	16,765·7	16,790·4	0·15%
17	60	36,000	18,225·7	18,245·0	0·11%
18	70	36,000	19,685·6	19,707·0	0·11%
19	80	36,000	21,145·5	21,138·5	–0·03%
20	90	36,000	22,605·4	22,585·4	–0·09%
		Average			**0·15%**

Table 6 shows the first 20 tests. In all cases, the same distance and altitude was traveled, and each method was allowed to select its own optimal speed. Results show that the speed selected by the optimisation algorithm produced trajectories with a lower cost than those selected by the PTT. In average, a 0·15% cost reduction was obtained. However, these tests only optimised the speed of the flight, since the altitude was imposed. In order to improve results, a speed and altitude optimisation is presented next.

Table 7 shows the results for the speed and altitude optimisation. It can be seen that the optimisation algorithm has better performance when it can select its own altitude along with the optimal speed.

Two different trajectories were traveled: from Montreal to Winnipeg and from Montreal to Vancouver. The CI was varied from 0 to 99, and three different aircraft weights were tested. In all of 36 cases, the optimisation algorithm gave a lower cost flight trajectory. An average of 2·57% cost reduction was obtained within these 36 tests.

Table 7
Speed and altitude optimisation comparison for the A310

Flight	Trajectory	CI	Aircraft fuel	algo	PTT	Difference
1	Montreal-	0	138	19,933·7	20,437·2	2·46%
2	Vancouver		141	20,378·6	20,894·6	2·47%
3			144	20,904·6	21,141·8	1·12%
4		20	138	25,412·1	26,452	3·93%
5			141	25,582·5	26,678·5	4·11%
6			144	26,091·8	26,861·9	2·87%
7		40	138	30,727·8	31,761·4	3·25%
8			141	31,156·6	32,430·6	3·93%
9			144	31,664	32,568·6	2·78%
10		60	138	36,028·1	37,545·1	4·04%
11			141	36,432·4	38,220·8	4·68%
12			144	36,917·6	38,292·7	3·59%
13		80	138	41,297·7	42,718	3·32%
14			141	41,703·7	42,718	2·37%
15			144	42,171·1	43,668·6	3·43%
16		99	138	46,303·9	48,208·6	3·95%
17			141	46,711·3	48,259·6	3·21%
18			144	47,162	48,785·8	3·33%
19	Montreal-	0	138	10,503·2	10,561·9	0·56%
20	Winnipeg		141	10,706·1	10,824·8	1·10%
21			144	10,877·9	10,940·9	0·58%
22		20	138	13,221·4	13,392·8	1·28%
23			141	13,456·5	13,687·2	1·69%
24			144	13,724·5	13,778·4	0·39%
25		40	138	15,921·5	16,237·7	1·95%
26			141	16,167·1	16,551·7	2·32%
27			144	16,415·9	16,621·5	1·24%
28		60	138	18,575·7	19,132·3	2·91%
29			141	18,821·7	19,444	3·20%
30			144	19,056·4	19,487·5	2·21%
31		80	138	21,229·9	21,731·1	2·31%
32			141	21,469·7	22,042·4	2·60%
33			144	21,695·4	22,170·9	2·14%
34		99	138	23,767·7	24,481·1	2·91%
35			141	24,001·3	24,533·1	2·17%
36			144	24,202·4	24,764·9	2·27%
			Average			**2·57%**

https://doi.org/10.1017/S0001924000008459 Published online by Cambridge University Press

8.0 CONCLUSIONS

'Cruise Control' has been an important aspect of civil jet operations since the introduction of the Comet 1 in 1952. The original Comet used some relatively simple calculations to ensure it always flew at the performance limits of the engine airframe. However it was the only aircraft of its type flying and was no subject to the increasing conflict of other airframes operating in a similar environment.

The very large increases in jet propelled aircraft has made it much more difficult to accommodate small adjustments in different airline operating techniques and, in fact, the more pressing demands for collision avoidance and air traffic control and similar events mean that ATC requirements are often dominant in cruise control areas.

Even when certain flight restrictions are imposed by the ATC, such as speed and altitude limits, these restrictions can be defined in the new algorithm and it will search the optimal trajectory within these restrictions, to reduce fuel burn and emissions to the atmosphere. However, the maximal optimisation is obtained when the trajectory is entirely defined by the algorithm.

Better results were obtained in terms of precision than current FMS CMA-9000 from CMC Electronics-Esterline, obtaining an error of 1·09% compared with FlightSIM®, while the FMS CMA-9000 had a 1·99% error.

When the comparison was made between the trajectories proposed by the algorithm, and those proposed by the FMS CMA-9000, the proposed algorithm from this paper improved the global flight cost on 2·57%.

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https://doi.org/10.1017/S0001924000008459 Published online by Cambridge University Press