Economic Analysis of Continuous Climb Operation

Donglei Xu, Gang Xiao, and Dongjin Ding

Abstract Due to the limitations of ground facilities and ATC technology, the existing departure and arrival procedures usually adopt the procedures of step climbing and descent. The level flight process increases the operational cost for the aircraft, especially during the climbing phase where a maximum thrust is needed. Trajectory-based operation (TBO) provides a solution to improve the efficiency of flight procedures. The addition of four-dimensional trajectory with time dimension improves the predictability of aircraft operation. Before it is widely used, it is of great significance to evaluate economic benefits. In this research, a method of economic evaluation of continuous climb program (CCO) is proposed. The CCO model is built by using aircraft performance data, and then the fuel cost and time cost are calculated and analyzed based on the cost index (CI). Through the simulation analysis of specific paths, the result shows that CCO procedure has a significant improvement in economy compared with the traditional climb, which is helpful for the future implementation of new air traffic control service.

Keywords Flight procedure · Continuous climb operation · Economic analysis · Cost index · Fuel consumption

1 Introduction

Economic characteristics describes the flight procedure in terms of operating cost effectiveness, especially in terms of reducing fuel consumption and shortening flight time and distance. This leads to the two main economic measurement for flight procedure: fuel cost and time cost. Previous research mainly focuses on the calculation and trade-off between fuel–time costs. Fuel consumption is closely related to the thrust

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provided by the aircraft, as well as flight velocity and height. For the climb stage, the value of thrust affects the climb speed and altitude, and in turn affects the amount of time to enter the optimal cruise level. A coupling relationship exists between the fuel cost and time cost of the climb procedure, therefore, an integration of the two factors is needed while considering the economic characteristics.

This paper uses the BADA model to calculate fuel consumption of the CCO procedure and uses cost index to construct the economic evaluation model. Then a case study using the model is carried out based on the actual flight from Shanghai to Paris. The second section describes previous researches related to CCO and economic evaluation of flight procedure. The third section introduces the model construction methods, consisting of continuous climb model, fuel consumption model, and cost calculation model. In the fourth section, the method is used for designing and evaluation of CCO procedure of MU553 flight. The simulation results show that CCO has huge benefits in saving fuel and time. The fifth section summarizes the research content and points out the shortcomings and future research directions.

2 Related Research

For aircraft operational cost, calculation elements include fuel cost, trip cost, crew cost, aircraft and ATC costs, maintenance cost, and so on. Factors related to these cost elements are flight hours, aircraft weight, and size, as well as systems and components prices. When it comes to evaluation of the economic characteristics of an operational procedure, the fuel and time cost becomes a crucial point.

For airlines, the concept of Cost Index (CI) [1] which is proposed to calculated the time cost verses fuel cost has been adopted as a way to adjust the navigation strategy to save cost by altering the value of CI, and this method has been widely applied to the Flight Management Computer (FMC) [2].

However, from the operation perspective, the optimal climb efficiency cannot be achieved merely by adjusting CI. Due to limitations of airspace conditions and safety requirements from air traffic control, in most cases step climb is still the major way for aircrafts to departure. After reaching the specified altitude and speed, the aircraft needs to execute level flight until receiving instructions from the air traffic controller, which leads to an increase in operational costs. Therefore, as one of the air traffic stakeholders, ATC needs to make innovations in flight procedures to reduce the level flight during departure and design new instrument flight procedures (IFR) to improve climb efficiency, that in turn contributes to economic aircraft operation.

Continuous climb operation (CCO) is a type of operation for departure achieved through proper airspace design, procedure design, and appropriate ATC clearance. During the operation, the departing aircraft uses optimal engine thrust setting without ATC interference until it climbs to the initial cruise altitude [3]. Over the past two decades, empirical data regarding CCO performance has been collected and analyzed in previous researches. In the United States, Melby et al. [4] analyzed the operating radar data of 34 OEP (Operational Evolution Partnership) airports established by FAA for approximately 45,000 takeoff and landing routes in one day. It is concluded that the implementation of vertical continuous operation in the critical climb and descent phase saves fuel and flight time. For all OEP airports, an annual economic benefit of 380 million U.S. dollars can be estimated. In Europe, the 2018 EUROCONTROL study revealed that fuel saving from CCO/CDO were up to 340,000 tonnes per year for the airliners, or around €150 million fuel costs [5]. For non-CCO profiles below FL100, a typical level flight of 168 s can consume 15 kg more fuel than CCO profiles.

Models and simulations on CCO have also been developed for academic research. Javier et al. [6] proposed six CCO operation concepts, and implemented CCO simulation analysis at Palma Airport for fuel consumption, climb time, and horizontal flight distance analysis. Comparisons were made among different concepts regarding reducing fuel consumption and time [7]. In terms of the calculation method for fuel consumption and time, Runping G. used the original performance data to obtain the calculation formula of climb fuel consumption by a linear regression fitting equation [8], Ramon and Xavier [9], Judith [10] calculated the fuel consumption savings of CCO optimized trajectory through the correlation coefficient from BADA (Base of Aircraft) model. In addition, there are literatures using QAR data to perform aerodynamic and wind corrections on fuel consumption models, which improves the accuracy of the model [11]. In China, the Civil Aviation Administration of China attaches great importance to energy conservation, emission reduction, and efficiency improvement. The implementation of continuous operation procedures in CDO/CCO is in a stage of combining theoretical exploration and experimentation together, and large-scale trial flights have not yet begun [12].

3 Methodology

3.1 CCO Model

Continuous climb operation (Continuous Climb Operations, CCO) refers to obtaining the initial cruise altitude as soon as possible by setting the optimal speed and thrust by means of continuous climbing [3]. The CCO trajectory is defined as the trajectory executed by the aircraft from the takeoff end point to the initial cruise altitude, including horizontal vertical profile. The horizontal profile follows the existing standard instrument procedures for departure, and climbs and turns through waypoint/navigation stations according to the designated runway and departure route. The vertical profile is a continuous and uninterrupted climb, without ATC control constraints. The profile is affected by the performance of the aircraft, as well as intended flight tasks.

The premise of the basic CCO departure procedure design is that all aircraft climb rates are not restricted. This requires a certain amount of vertical airspace to ensure continuous climb without interference, and the design climb gradient is 60–3000 m/nm. ICAO stipulates the maximum climb rate and minimum climb rate of the standard departure procedures, and has set up routes that match the climb performance of different aircraft [3], so as to shorten the climb time and improve the efficiency of departure. In this research, the designing of airspace will not be further looked into, and it is assumed that the airspace can support the execution of CCO.

3.2 Aircraft Performance Model

In this section, a fuel consumption model for jet aircraft during continuous climb operation is constructed. BADA (Base of Aircraft Data) is a database consisting of performance data for aircraft developed and maintained by EUROCONTROL. It is based on a kinetic approach to aircraft performance modeling, which models aircraft forces, and is intended for trajectory simulation and prediction in Air Traffic Management research [13].

The parameters used in the model are:

Thr Thrust, N;
D Drag, N;
V_{TAS} True airspeed, m/s;
V_{CAS} Calibrated airspeed, m/s;
m Mass, kg;
h Height, m;
$\dot{h}$ Vertical speed, m/s;
γ Aircraft path angle, rad;
g Gravitational acceleration, 9.80665 m/s^2;
ρ Air density, kg/m^3;
ρ_0 MSL air density, 1.225 kg/m^3;
P Air pressure, Pa;
P_0 MSL air pressure, 101,325 Pa;
T Air temperature, °C;
T_0 MSL air temperature, 15 °C;
κ Adiabatic index of air, 1.4;
R Real gas constant for air, 287.05287 $m^2/K s^2$
S Wing area, m^2;
C_L Lift coefficient;
C_D Drag coefficient;
η Thrust specific fuel consumption, kg/(min × kN);
C_{f1} 1st thrust specific fuel consumption coefficient, kg/(min · kN);
C_{f2} 2nd thrust specific fuel consumption coefficient, knots;

Total energy model

Following the law of conservation of energy, regarding the aircraft as a mass point, the work done by the external force acting on the aircraft is converted into kinetic energy and potential energy. The energy model of the aircraft during the climb phase is

$$(Thr - D)V_{TAS} = mg\dot{h} + mV_{TAS}\dot{V_{TAS}} \tag{1}$$

Generally speaking, the fuel consumption of an aircraft equipped with a turbine engine depends on the amount of thrust. The fuel consumption per unit time and unit thrust η [kg/min•kN] during the climb phase is (the unit of V_{TAS} is knots):

$$\eta = C_{f1}(1 + \frac{V_{TAS}}{C_{f2}}) \tag{2}$$

Combining the thrust of the aircraft in the climb phase in the flight profile, we can get the fuel consumption per minute f_{climb} [kg/min] (the unit of Thr is kN):

$$f_{climb} = \eta Thr = C_{f1}\left(1 + \frac{V_{TAS}}{C_{f2}}\right)Thr \tag{3}$$

Kinematics model

During the climb of an aircraft, the lift, gravity, thrust, and drag acting on the aircraft will affect the speed and climb rate of the aircraft. From the perspective of fuel consumption, full thrust setting can make the aircraft enter the cruise altitude as soon as possible, providing the optimal fuel economy. The maximum climb thrust of the aircraft can be calculated according to the coefficient of the flight stage of the aircraft, which is given based on different type of aircraft in BADA 3:

$$Thr_{max} = C_{T_{C,1}}\left(1 - \frac{h}{C_{T_{C,2}}} + C_{T_{C,3}} \cdot h^2\right) \tag{4}$$

The aircraft lift and drag are calculated using lift and drag coefficients as follows:

$$\begin{cases} L = C_L \rho {V_{TAS}}^2 S/2 \\ D = C_D \rho {V_{TAS}}^2 S/2 \end{cases} \tag{5}$$

Considering the airplane is in a horizontal position, therefore lift also equals to mg, so from Eq. (5) we can get the lift coefficient as

$$C_L = 2mg/\rho {V_{TAS}}^2 S \tag{6}$$

The drag coefficient C_D is related to aircraft configuration, including lift-induced drag and zero-lift drag [14]. BADA 3 specifies the clean configuration during the climb stage, and the drag calculation coefficients of different aircraft types are given in the OPF file. In the nominal case, the formula for calculation of the drag coefficient C_D is as follows:

$$C_D = C_{D_0} + C_{D_2} \times {C_L}^2 \quad (7)$$

For simpler calculation of the trajectory, the vertical speed $\dot{h}$ can be represented as

$$\dot{h} = \left(\frac{Thr - D}{mg}\right) V_{TAS} \cdot ESF \quad (8)$$

Among which ESF is the energy distribution coefficient, which describes the available power allocated to the climb relative to the acceleration during the climb. According to the selected speed profile, ESF is given as

$$ESF = \left(1 + \frac{V_{TAS}}{g}\frac{dV_{TAS}}{dh}\right)^{-1} \quad (9)$$

In order to simplify the calculation, BADA has defined the ESF value for aircraft not climbing according to the constant CAS or constant M number. For example, when $ESF = 0.3$, 70% of the thrust is used for acceleration, and 30% of the thrust is used for climbing. It is necessary to adjust the value of the ESF to achieve a reasonable climb trajectory.

Considering speed changing during climb, a time period $dt = 1$s is introduced to calculate the trajectory through the differential formula (10) and (11), and the vertical profile and speed profile can be generated:

$$h(t_{i+1}) = h(t_i) + dh \quad (10)$$

$$V_{TAS}(t_{i+1}) = V_{TAS}(t_i) + dV_{TAS} \quad (11)$$

dV_{TAS} can be represented using ESF:

$$dV_{TAS} = \left(\frac{1}{ESF} - 1\right)\frac{g}{V_{TAS}} \cdot dh \quad (12)$$

Atmospheric model

The atmospheric condition changes as the aircraft climbs to higher altitude. The formula for calculating air pressure, air temperature and air density at the altitude H of the aircraft is

$$\begin{cases} P = P_0(1 - 0.00003387H)^{3.5009} \\ T = T_0 - 0.0065 \times H \\ \rho = 0.0035P/T + 273.15 \end{cases} \quad (13)$$

The takeoff environmental condition varies from airports to airports. BADA provides International Standard Atmosphere (ISA) data and four types of non-ISA data models. Considering the change in pressure caused by the altitude change, the conversion formula between the true airspeed V_{TAS} and the Mach number M is

$$M = V_{TAS}/\sqrt{\kappa \cdot R \cdot T'} \tag{14}$$

T' represents the air temperature T in K.

3.3 Operational Cost Model

The operational cost model considers fuel cost and time cost as inputs. The fuel cost is calculated by the amount of fuel used multiplied by fuel price. The time cost coefficient is however not easy to obtain, so we use Cost Index (CI) to calculate the time cost. CI is the ratio of aircraft operating time cost to fuel cost. The formula for CI is

$$CI = C_t/100C_f \tag{15}$$

where C_t represents the hourly time cost in \$/h, and C_f represents the fuel cost per pound in cents/lbs. The determination of CI is generally allocated according to the airline's task requirements. For example, when the fuel price is high, CI is set to 0, it is the most economical situation for this scenario. When CI is set to 999 or MAX (depending on aircraft type), it is the Minimum Time Mode for Maximum Speed. In this research the Operating Cost (OC) is proposed to calculate the combined fuel and time navigation cost.

Operating Cost (OC) is the cost of operation within the limitation of aircraft performance, ATC procedures, and airspace conditions during the operation of an aircraft. In a single climb phase of a single flight, the formula for defining limited operating cost OC_{climb} is

$$OC_{climb} = C_t t_{climb} + C_f W_f = C_f \left(CI \times t_{climb} + W_f \right) \tag{16}$$

where t_{climb} [h] is the time of flight to complete the climb, W_f [lbs] is the total fuel consumption, $C_t t$ is the time cost, and $C_f W_f$ is the fuel cost.

The objective function is constructed as follows: take time as the numerical integration unit, f_{climb} is expressed as the function of time $f_{climb}(t)$, then the fuel consumption and the total time cost for the objective function J can be expressed as

$$J = C_f \int_{t_0}^{t_1} (f_{climb}(t) + CI)dt \tag{17}$$

Constraints should be determined according to specific aircraft type and flight conditions. The goal is to obtain the minimum operational cost. Note that the selection of CI depends on fuel price and hourly time cost. Once it's set, the climb-related data such as velocity is determined.

4 Case Study

4.1 Simulation Object

In this section, the route from Shanghai Pudong Airport to Paris Charles de Gaulle Airport (PVG-CDG) is selected as the simulation object. The selected departure route is PIK-81D, and the en route waypoints are PD301-PD302-PD303-SS303-SS304-SS305-EKIMU-POMOK-SS320-PIKAS [15]. The horizontal profile is determined by the SID procedure. The information of each waypoint is shown in Table 1.

4.2 Numerical Modeling

This section the climb phase of Boeing 777-300ER is modeled. The B77W is a dual-engine wide-body passenger aircraft. The climb performance data of B77W is shown in Table 2 [16].

The next step is to set initial values to parameters in the model. Constraints are divided into two categories: initial conditions and performance constraints. The initial condition is when the aircraft completes the takeoff process, reaches the V_2 speed and the safe above-ground height h_{TO}. The end point of the climb procedure is to reach the Top of Climb (ToC) point and goes into initial cruise phase, the altitude of which is h_{TOC}. In terms of performance constraints, the maximum speed during

Table 1 Waypoint information of SID

Way point	Category	Latitude	Longitude
PD301	RNAV way point	N305944	E1215036
PD302	RNAV way point	N305741	E1214309
PD303	RNAV way point	N310024	E1212825
SS303	RNAV way point	N310413	E1210733
SS304	RNAV way point	N310924	E1210716

the climbing phase shall not exceed TAS $V_m = 490$kts (CAS 310kts) for h_{TOC}, and the minimum speed shall not be lower than $V_{stall} = 133$kts. The initial conditions as well as final states are shown in Table 3.

We use various ESF s for each time step to generate different trajectories as a way to simulate real aircraft operation controlled by pilot. The goal is to find the optimal solution for operational cost, which refers to a minimum result of J. Trajectory simulation results are shown below (see Fig. 1), where 200 iterations are generated

Table 2 B77W performance table for climb

Identification		Configuration			Climb		
ICAO	Engine Type	MTOW [t]	Wing span [m]	Aircraft length [m]	Vlow [kts]	Vhigh [kts]	Mach
B77W	JET	351,534	64.80	73.86	310	310	0.84

Table 3 Initial conditions and final states for different parameters

Variables	Initial value	Final state
t, s	1	Not constrained
V_{TAS}, knots	$V_2 = 168$knots	V_f
h, ft	$h_{TO} = 35ft$	$h_f = h_{TOC}$
m, kg	217,700 kg	Not constrained

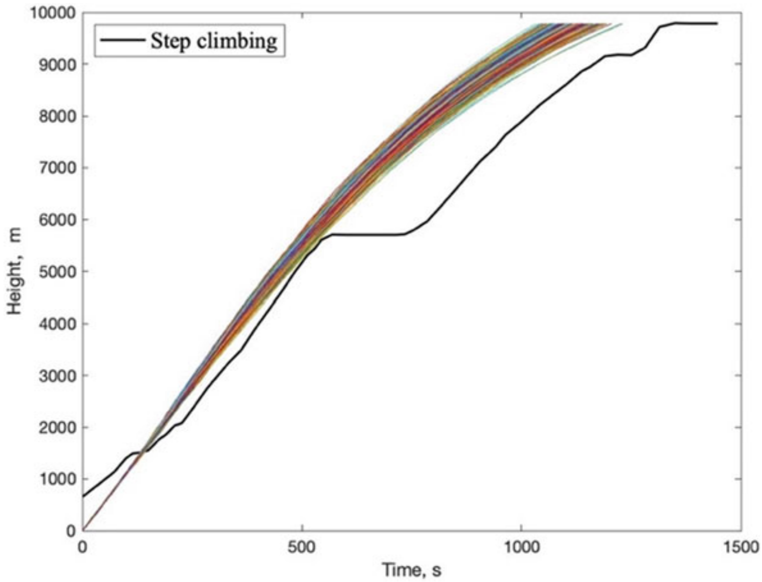

Fig. 1 Tradition step climb and CCO trajectories

with ESF ranges from 0.6 to 1.2. The step climbing data is taken from real open-source flight data by ADS-B surveillance. CCO shows improvement in climb time, compared with over 20 min of climb in traditional ways. Without ATC restrictions, such as speed limitation of 250 kts below FL100 and traffic-induced maintaining flight level. However, the separation should be given by ATC previous to takeoff and climb in order to avoid collision between aircrafts, especially those with different climb performance.

The total fuel flow consumption during climb for each iteration is given below (see Fig. 2). The data is sorted out from minimum to maximum. We can see that with shorter climbing time, fewer fuel will be used. This is because using maximum thrust for climb, which is represented as a function of height, and so is the time specific fuel flow.

The fuel flow rate in kg/s for the most time efficient flight trajectory is shown below (see Fig. 3). The result shows that the fuel flow rate decreases as the aircraft climbs up till ToC. This is consistent with the fuel estimation in the flight manual for pilots and calculation tables for FMC. As a result, a level flight in step climb profile of 3 min in Fig. 2 from $t = 500s$ to $t = 680s$ can add up to 42.51 kg more fuel consumed than CCO procedure. The distance traveled at cruise altitude for CCO that covers the level flight range at lower altitude for step climb is proved more fuel efficient, which is a critical economic performance improvement of this operational concept.

After obtaining the total fuel consumption and climb time, the operation cost can be determined. The fuel price is chosen as ¢23.58/lbs [17]. Four different CI

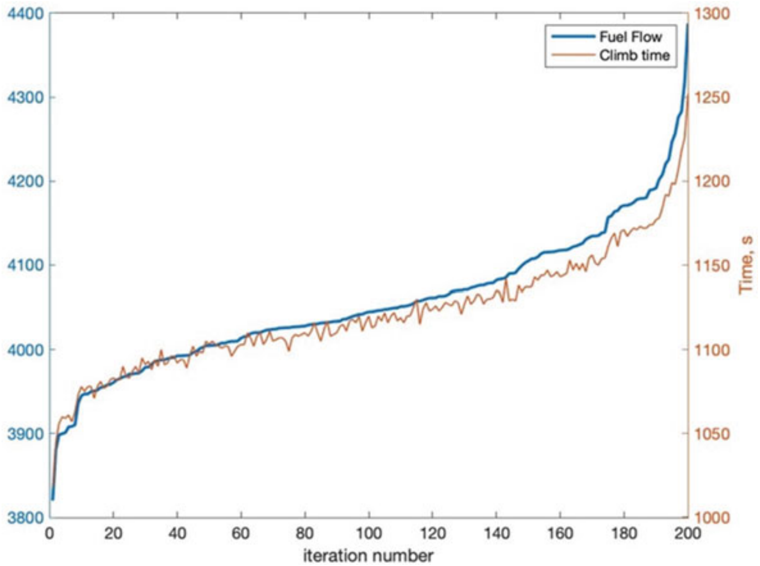

Fig. 2 Total fuel flow of each iteration and corresponding climb time

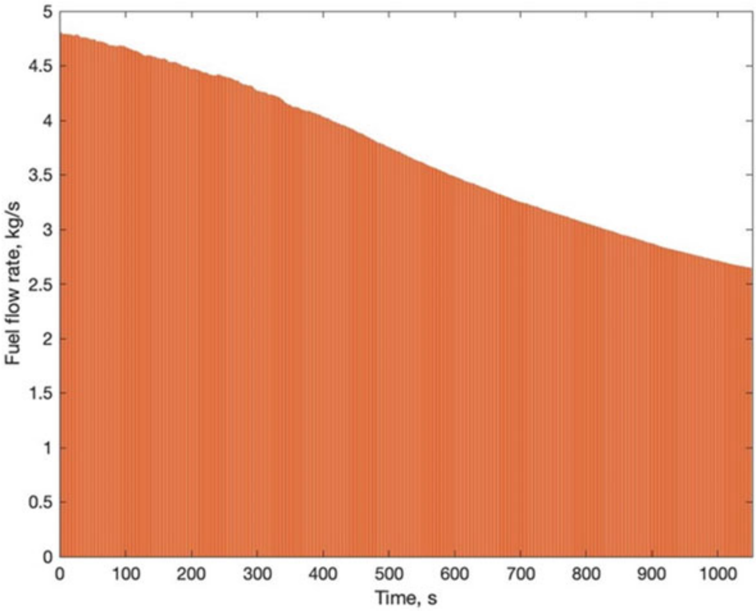

Fig. 3 Fuel flow rate with the change of climbing time

(100, 50, 20, 0) is selected to simulate different navigation strategies for airlines. The economic analysis results are shown in Table 4.

Table 4 CCO economic analysis

Fuel flow [kg]	Time [s]	OC [$]			
		CI = 100	CI = 50	CI = 20	CI = 0
4109.54	1149	2884.46	2508.16	2282.38	2131.86
4014.56	1105	2806.37	2444.48	2227.35	2082.59
4011.20	1099	2800.69	2440.77	2224.82	2080.85
4136.44	1153	2901.03	2523.43	2296.86	2145.82
3996.19	1093	2788.98	2431.02	2216.25	2073.06
3935.11	1071	2742.88	2392.13	2181.68	2041.38
4111.76	1145	2882.99	2508.00	2283.01	2133.02
4037.16	1112	2822.67	2458.49	2239.99	2094.31
4063.45	1120	2841.56	2474.76	2254.68	2107.96
4064.42	1131	2849.26	2478.86	2256.62	2108.46

5 Conclusion

In this research, a method of economic evaluation of continuous climb operation is constructed, focusing mainly on fuel cost and time cost. BADA 3 is adopted to construct the CCO trajectory as well as fuel consumption model, and is used to calculate total operational cost. The results show that with the maximum thrust setting for climb, the aircraft can reach the initial cruise altitude in shorter time and save a good amount of fuel compared with step climb. For airlines to use in real operation scheduling, this method can be used to implement economic analysis of climb trajectory, in order to reach an optimal cost efficiency.

For different airspace design and operational goals, the CCO procedure can be executed in various manners. In future research, the different operational concepts will be studied, along with multiple aircrafts for CCO integration. In this case, airspace demand and capacity will also be considered in economic analysis of CCO.

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