Fuel Consumption Analysis of Gradual Climb Procedure with Varied Climb Angle and Airspeed

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Nomenclature

CD0	Zero lift drag coefficient
CD2	Induced drag factor
Cf1	1st thrust specific fuel consumption coefficient
Cf2	2nd thrust specific fuel consumption coefficient
Fnom	Nominal fuel flow [kg/min]
g	Gravitational acceleration [m/s^2]
m	Aircraft mass [kg]
THR	Thrust [N]
VTAS	True airspeed [m/s] or [knots]
γ	Angle of climb [rad] or [deg]
η	Thrust specific fuel flow [kg/(min·kN)]
ρ	Air density [kg/m^3]

1 Introduction

Climate change becomes a very serious issue today as it has vast and strong impact on humanity securities. One of the major causes of this problem is CO_2emission which largely produced from global aviation industry. To contribute on this concern, IATA issued a guidance material and best practices for fuel and environmental management (IATA, 2008) and issued a guidance material for sustainable aviation fuel management (IATA, 2015). A variety flight operation techniques for emission

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reduction were suggested such as engine out taxi, reduced takeoff flaps, reduced landing flaps, reduced acceleration altitude, optimum CG position, and continuous climb and continuous descent operation known as CCO and CDO.

For the past decades, there have been many researchers working and focusing on emission reduction during climbing and descending phases. Panklam and Kowanichkul (2011) performed flight simulation with RAMS PLUS software for A320 and B737 descending flights. It was found that with continuous descent operations, fuel consumption could be reduced 15.8% for A320 and 14.8% for B737 when descending from FL350. Ming et al. (2019) studied on fuel consumption of climbing phase of A320 aircraft based on flight data analysis. The continuous climb operation was simulated to climb from sea level to FL240 at standard temperature and with constant angle of climb. The results were compared with the flight of conventional climb procedure and show obviously that continuous climb operations provide fuel consumption reduction by 12.3%. Mori (2020) proposed a new fuel-saving climb procedure by reducing thrust near top of climb. 20–50 lbs of fuel could be saved for a large jet airliner.

2 Fuel Consumption Model

2.1 BADA Model

The calculation of fuel consumption and flight trajectory prediction in this study is based on the BADA aircraft performance model revision 3.8 (EUROCONTROL, 2010). The aircraft aerodynamics and fuel consumption model in the climbing phase are expressed as follows:

Total energy model

$$(T_{\mathrm{HR}} - D)V_{\mathrm{TAS}} = mg\frac{dh}{dt} + mV_{\mathrm{TAS}}\frac{dV_{\mathrm{TAS}}}{dt} \quad (1)$$

Rate of climb

$$\mathrm{ROC} = \frac{dh}{dt} = V_{\mathrm{TAS}} \cdot \sin(\gamma) \quad (2)$$

Angle of climb

$$\mathrm{AOC} = \gamma = \sin^{-1}\left(\frac{T_{\mathrm{HR}} - D - mV_{\mathrm{TAS}}\frac{dV_{\mathrm{TAS}}}{dt}}{mg}\right) \quad (3)$$

Lift coefficient

$$C_{\mathrm{L}} = \frac{2mg}{\rho V_{\mathrm{TAS}}^2 S \cdot \cos(\gamma)} \tag{4}$$

Drag coefficient

$$C_{\mathrm{D}} = C_{\mathrm{D0}} + C_{\mathrm{D2}} \times (C_{\mathrm{L}})^2 \tag{5}$$

True airspeed (m/s)

$$V_{\mathrm{TAS}} = \sqrt{\frac{2mg}{C_{\mathrm{L}} \rho S \cdot \cos(\gamma)}} \tag{6}$$

Thrust specific fuel flow (kg/(min·kN)

$$\eta = C_{\mathrm{f1}} \times \left(1 + \frac{V_{\mathrm{TAS}}}{C_{\mathrm{f2}}}\right) \tag{7}$$

Nominal fuel flow (kg/min)

$$f_{\mathrm{nom}} = \eta \times T_{\mathrm{HR}} \tag{8}$$

Cruise fuel flow (kg/min)

$$f_{\mathrm{cr}} = \eta \times T_{\mathrm{HR}} \times C_{\mathrm{fcr}} \tag{9}$$

2.2 Optimization and Numerical Models

The optimal true airspeed for gradual climb flight that varied with altitudes can be calculated from the lift coefficient which is determined from the optimization models (Anderson, 2014). The models are expressed as follows:

Lift coefficient for minimum thrust required

$$\mathrm{CL}_{\mathrm{TR,\,min}} = \sqrt{\frac{C_{\mathrm{D0}}}{C_{\mathrm{D2}}}} \tag{10}$$

Lift coefficient for best range (jet propelled airplane)

$$\mathrm{CL}_{\mathrm{R,\,max}} = \sqrt{\frac{C_{\mathrm{D0}}}{3C_{\mathrm{D2}}}} \tag{11}$$

The numerical model is formed for estimation of the acceleration of the aircraft and is given as follow:

$$\frac{dV_{\mathrm{TAS}}}{dt} \approx \mathrm{ROC} \times \frac{\Delta V_{\mathrm{TAS}}}{\Delta h} \tag{12}$$

2.3 Flight Simulation

In this study, climbing flights of three different cases were generated. These are continuous climb with constant angle of climb (CCO), gradual climb with minimum thrust required airspeed (GCO1), and gradual climb with best range airspeed (GCO2). All flights were simulated for A320 aircraft climbing from sea level to 24,000 ft. under the international standard atmosphere condition and at MTOW of 77,000 kg and then cruising to reach the distance of 120 km.

In gradual climb simulation, two different optimal airspeeds were examined, which are minimum thrust required airspeed and best range airspeed using Eqs. 10 and 11, respectively. The acceleration is then determined using Eq. 12 for altitude step of 1000 ft. Reduced thrust is applied with gradually reduced rate of 2% per 1000 ft. At every step of altitude, the aircraft mass is recalculated for the reduction due to fuel consumption. The flight trajectories of the studied cases were predicted and as shown in Fig. 1.

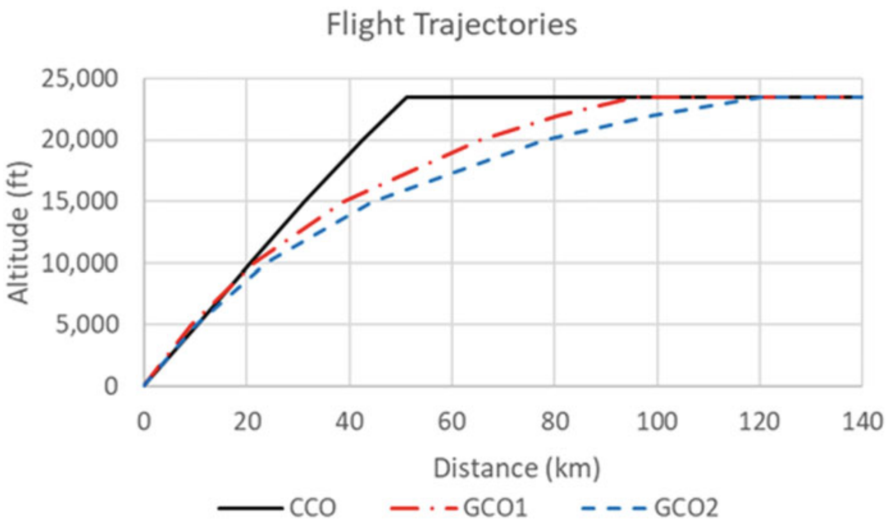

Fig. 1 Predicted flight trajectories of the tested cases, CCO, GCO1, and GCO2

Table 1 Validation of the calculation model used in this study

Model	Climb distance (km)	Cruise distance (km)	Total fuel consumption (kg)
Present calculation model	53.2	66.8	1084.9
Ming et al. (2019)	51.0	69.0	1116.0

Table 2 Fuel consumption of climbing phases, continuous climb (CCO), gradual climb with minimum thrust required airspeed (GCO1), and gradual climb with best range airspeed (GCO2)

Trajectories	Climb distance (km)	Fuel during climb (kg)	Cruise distance (km)	Fuel during cruise (kg)	Total fuel consumption (kg)
CCO	53.2	740.5	66.8	344.4	1084.9
GCO1	95.4	695.5	24.6	332.7	1028.2
GCO2	120.2	993.4	–	–	993.4

The fuel consumption model was validated with the calculation and the data analysis of Ming et al. (2019) for the case of continuous climb with constant angle of climb of 8 deg. The comparisons are shown in Table 1. The results of the present calculation model agree well with the reference model which has accuracy falling into 97.2%.

3 Results and Discussion

The calculation model for the flight trajectories of CCO, GCO1, and GCO2 was simulated and executed with a PC to give the climb distance, cruise distance, fuel flows during climb and cruise, and the total fuel consumption. The results are presented in Table 2.

The results in Table 2 show obviously that with gradual climb procedure, the fuel consumption is reduced when compared to the continuous climb procedure. The reduction of fuel consumption of GCO1 flight trajectory is 56.9 kg or 5.24%, while GCO2 flight trajectory provides even more fuel reduction of 91.5 kg or 8.43%. This agrees well with the works of Mori (2020).

4 Conclusion

The study of fuel consumption of aircraft flight with gradual climb procedure showed that the gradual climb procedure can improve fuel consumption up to 8.43%. To maximize fuel-saving, climbing with best range true airspeed is suggested. However, this suggestion should be further studied deeply to confirm the solutions. Actually, the optimization of the fuel consumption with gradual climb procedure is challenging as the fuel consumption of the climbing flight still has various variables to play with such as true airspeed, acceleration, angle of climb, and thrust of the aircraft, which can be written as in Eq. 13.

$$f_{\text{nom}} = f\left(T_{\text{HR}}, \gamma, V_{\text{TAS}}, \frac{dV_{\text{TAS}}}{dt}\right) \quad (13)$$

There are still a lot of works that can be done further on the development on the optimization with these variables.

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