HOW MUCH FUEL AND TIME CAN BE SAVED IN A PERFECT FLIGHT TRAJECTORY?

CONVENTIONAL VS CONTINUOUS OPERATIONS

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What can be considered a *perfect* flight trajectory?

- Reducing fuel consumption (and therefore emissions) is perhaps one of the main concerns of the different aviation stakeholders.
Continuous operations = *perfect* trajectories
Conventional operations = inefficient trajectories

- Constant cruise altitudes
- Interrupted climb
- Level off during descent
- Minimum rate of climb
- Speed limitations
- FMS segments at constant CAS or Mach

ROC ≥ 500 ft/min

FL100

CAS≤250 kt
How much fuel can be saved by flying such *perfect* trajectories?
Optimisation of an aircraft trajectory is a multi-phase constrained optimal control problem.

Solved using numerical methods.
Optimal control problem formulation

Direct collocation methods

Continuous problem

Discrete NLP
Optimal control problem formulation

\[
\begin{align*}
\frac{dv}{dt} &= \dot{v} = \frac{T - D}{m} - g \sin \gamma \\
\frac{ds}{dt} &= \dot{s} = v \cos \gamma \\
\frac{dh}{dt} &= \dot{h} = v \sin \gamma \\
\frac{dm}{dt} &= \dot{m} = -FF
\end{align*}
\]

- FL100
- \( \gamma_{min} \leq \gamma \leq \gamma_{max} \)
- \( 0 \leq \pi \leq 1 \)
- \( M \leq MMO \)
- \( \nu_{CAS} \leq VMO \)

- ROC \( \geq 500 \text{ ft min}^{-1} \)
- CAS \( \leq 250 \text{ kt} \)
- ROD \( \leq -500 \text{ ft min}^{-1} \)

- \( \dot{\nu}_{CAS} = 0 \)
- \( \dot{M} = 0 \)

- \( x = [v, s, h, m] \)
- \( u = [\pi, \gamma] \)

- \( J = \int_{t_0}^{t_f} FF(t) \, dt \)
Optimal control problem formulation

\[ \frac{dv}{dt} = \dot{v} = \frac{T - D}{m} - g \sin \gamma \]
\[ \frac{ds}{dt} = \dot{s} = v \cos \gamma \]
\[ \frac{dh}{dt} = \dot{h} = v \sin \gamma \]
\[ \frac{dm}{dt} = \dot{m} = -FF \]

\[ \gamma_{\min} \leq \gamma \leq \gamma_{\max} \]
\[ 0 \leq \pi \leq 1 \]

\[ M \leq \text{MMO} \]
\[ v_{\text{CAS}} \leq V_{\text{MO}} \]

\[ x = [v, s, h, m] \]
\[ u = [\pi, \gamma]. \]

\[ J = \int_{t_0}^{t_f} FF(t) \, dt. \]
Optimised trajectories

99% of maximum landing mass.
600 NM trip distance.

87% of maximum landing mass.
2400 NM trip distance.

CONTINUOUS OPERATIONS FOLLOW THE CRUISE CLimb
Cruise climb

- Aircraft burns fuel
- Aircraft mass decreases
- Lift needed is reduced
- Drag is reduced
- Thrust required is lower
The optimal procedure consists in maintaining the optimal throttle setting and the optimal cruise speed using the excess thrust to slowly climb the aircraft.

- 87% of maximum landing mass.
- 1600 NM trip distance.
Why conventional operations are flying below the *perfect* flight trajectories?

The minimum rate of climb mandated by ATC
Increasing altitude

Excess thrust decreases

Rate of climb performance decreases

Aircraft burns fuel

Excess thrust increases

Rate of climb performance increases

Step climb to the next flight level
As the minimum rate of climb is reduced conventional operations are able to fly at higher and more fuel-efficient altitudes.

- 87% of maximum landing mass.
- 1800 NM trip distance.
Experimental setup

\[ LM \in [0.71MLM, 0.99MLM] \]
\[ DIST \in [400NM, 2400NM] \]

Scenario \( i \)

- LM \( i \)
- DIST \( i \)

Airbus A320

Fuel and time comparison
Total trip fuel needed

Conventional operations

Continuous operations

From 71% to 99% of maximum landing mass. From 400 NM to 2400 NM.
Fuel savings of flying *perfect* flight trajectories

**Absolute fuel savings**

Up to 300 kg representing the 2% of the total trip fuel!
- 94% of maximum landing mass.
- 2000 NM trip distance.
Fuel savings are mainly achieved by the possibility to fly a continuous cruise climb.

In the simulations conventional operations are allowed to perform continuous climb and descent.
Time savings of flying *perfect* flight trajectories

Up to 16 min representing the 5% of the total trip time!
More fuel-efficient and faster operations

Minimum rate of climb + engine limitations

Flying at lower altitudes

Flying at lower optimal speeds

More time and fuel!
Conclusions.

Remarkable figures in terms of **fuel consumption**, mainly for longer routes.

Continuous operations **not only reduce fuel consumption**, but **also the trip time**.
Conclusions.

New avionic systems will be able to support trajectory-based operations in the forthcoming years.

Aircraft themselves will be responsible for keeping separation amongst each other

POSSIBILITY TO FLY CONTINUOUS OPERATIONS
Conclusions.

The cost of the time is also considered for flight planning.

Aircraft usually fly at higher speeds.

CDA are not usually performed.

Climbs are usually interrupted.

Fuel savings of continuous operations would be even larger.

This work quantified the minimum benefits that could be achieved by flying perfect flight trajectories.
Future works.

Study long-haul aircraft (A340)

Sensibility study on the influence of real weather scenarios (e.g. winds effects)
THANK YOU!

Any question?