Effects of speed reduction in climb, cruise and descent phases to generate linear holding at no extra fuel cost

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Outline

- Motivation & Background
- Methodology of Speed Reduction
- Simulation Setup
- Illustrative Examples
- Conclusions & Further Work
Motivation & Background

Linear holding concept

- Impact on fuel consumption
- Maximum holding time
- Flexibility to absorb delay
- Range for implementation
Motivation & Background

Potential applicability under TBO

Capacity reduction at destination airport \(\rightarrow\) Ground Delay Program

Cruise at the lowest speed where the specific range remains as initially planned

If regulations are cancelled prior

Accelerate to the initial planned speed and recover delay at no extra fuel lost


Motivation & Background

Potential applicability under TBO

Capacity reduces en route

- Take off earlier than CTD (EDCT) but fly slower than initially planned to absorb delay airborne
- Meet CTO while saving some fuel
- Make use of the saved fuel from flown trajectory, and accelerate along the rest trajectory
- Part of the delay will be recovered without extra fuel cost
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**Methodology of Speed Reduction**

**Direct operating cost**

Not only fuel consumption but also time-related costs are considered.

\[
\text{Cost} = \text{Fuel} + \text{CI} \cdot \text{Time}
\]

\[
\text{CI} = \frac{C_{\text{Time}}}{C_{\text{fuel}}} \quad [\text{kg/min}]
\]

The higher the CI is, the more importance will be given to the trip time and the faster the optimal aircraft speed will be.
Methodology of Speed Reduction

Speed and fuel consumption (Cruise phase)

Lower bound → “Green Dot” speed: Minimum speed in automatic managed mode

Equivalent speed: the minimum speed yielding the same specific range as flying at the nominal speed

Green Dot speed: below FL200 equals to $2 \times \text{weight (tons)} + 85 \text{ (kt)}$, and above FL200, adds 1 kt per 1000 ft.
Methodology of Speed Reduction

Speed and fuel consumption (Climb and Descent phases)

A320 - Climb

A320 - Descent
Methodology of Speed Reduction

Speed and fuel consumption (Climb and Descent phases)

Equivalent speed for climb and descent

With CI decreasing, the speeds of both climb and descent decrease, as well as the fuel consumption, and the climb profile becomes steeper, while conversely the descent profile turns shallower.

For all speeds between the equivalent speed and ECON, the fuel consumption will be the same or lower than the nominal while linear holding will be performed.
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- **Simulation Setup**
- Illustrative Examples
- Conclusions & Further Work
Simulation Setup

Optimal trajectory generation tool

Dalmau, Ramon, and Xavier Prats. "How much fuel and time can be saved in a perfect flight trajectory?." *International Conference on Research in Air Transportation (ICRAT).* 2014.

Simulation Setup

Flight phases and objective function

Nominal flights:
\[
\min \sum (F_i + CI \cdot T_i)
\]

Speed reduction cases:
\[
\max \left( \sum T_{i}^{clb} + \sum T_{j}^{crz} + \sum T_{k}^{dst} \right)
\]
\[
\sum F_{i}^{clb} + \sum F_{j}^{crz} + \sum F_{k}^{dst} \leq F_{nom}
\]
Simulation Setup

➢ **Case-0**: **Nominal** optimal trajectories
  - Optimal trajectories minimizing the cost function consisting of fuel and time with given CI values

➢ **Case-1**: LH in **cruise** maintaining the nominal flight level
  - LH only in cruise with climb and descent fixed as the nominal flights

➢ **Case-2**: LH in **climb, cruise and descent** maintaining the nominal flight level
  - TOC and TOD *altitudes fixed*, but not TOC and TOD *distances* and not distances for step climbs (if any).

➢ **Case-3**: LH in **climb, cruise and descent** and optimizing for **cruise flight level**
  - LH is implemented along the *whole flight* while allowing the solver to optimize for the best cruise flight level(s)
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Illustrative Examples

Simulation examples and some assumptions

Aircraft type:
• Airbus A320

Accurate performance data from Airbus Performance Engineering Programs (PEP)

Routes:
• FCO-CDG: 595 nm
• AMS-SVQ: 1000 nm
• STO-ATH: 1305 nm

Cost index (kg/min):
25, 60, 100, 150, 300, 500

Assumptions:
✓ Great circle distance is considered instead of air traffic services routes
✓ A passenger occupation (payload factor) of 81% is considered for all flights
✓ No wind conditions are considered
✓ Alternate and reserve fuel are not included
✓ Only even flight levels are used (FL260 as the lowest altitude)
✓ Cruise step climbs are allowed with 2000ft steps and 5 minutes as minimum time for each flight level
### Illustrative Examples

#### Validation of the nominal flights from Airbus PEP

<table>
<thead>
<tr>
<th>Routes</th>
<th>Nominal flight by PEP</th>
<th>Nominal flight by the in-house tool</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>CI (kg/min)</td>
<td>FL (100 ft)</td>
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<tr>
<td>FCO-CDG (595 Nm)</td>
<td>25</td>
<td>380</td>
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<td>100</td>
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<td></td>
<td>500</td>
<td>260</td>
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<tr>
<td>AMS-SVQ (1000 Nm)</td>
<td>25</td>
<td>380</td>
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<td>380</td>
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<tr>
<td></td>
<td>500</td>
<td>260</td>
</tr>
<tr>
<td>STO-ATH (1305 Nm)</td>
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<td>360</td>
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<td>260</td>
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</tbody>
</table>
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Illustrative Examples

Trajectory variations and TAS intervals

FCO-CDG

STO-ATH

AMS-SVQ
Illustrative Examples

Trajectory variations and TAS intervals

AMS-SVQ: 1000 NM

Effects of speed reduction in climb, cruise and descent phases to generate linear holding at no extra fuel cost.
Illustrative Examples

Detailed analysis for AMS-SVQ at CI=150 kg/min

<table>
<thead>
<tr>
<th>Cases</th>
<th>Climb</th>
<th>Descent</th>
<th>Cruise</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fuel (kg)</td>
<td>Time (min)</td>
<td>Dist (nm)</td>
<td>Avg. V (kt)</td>
</tr>
<tr>
<td>CI=150</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 0</td>
<td>1685.4</td>
<td>21.5</td>
<td>157.3</td>
<td>438.0</td>
</tr>
<tr>
<td>Case 1</td>
<td>1685.4</td>
<td>21.5</td>
<td>157.3</td>
<td>438.0</td>
</tr>
<tr>
<td>Case 2</td>
<td>1415.8</td>
<td>23.3</td>
<td>110.7</td>
<td>285.1</td>
</tr>
<tr>
<td>Case 3</td>
<td>1064.4</td>
<td>13.7</td>
<td>76.4</td>
<td>335.3</td>
</tr>
</tbody>
</table>

Case 2: fuel and time trade-off:
-270kg (16%) in climb
+193kg (5%) in cruise
+77kg (71%) in descent

-2mins (8%)
+59mins (60%)
+10mins (81%)

Linear holding:
- Case 1: 22 min
- Case 2: 71 min
- Case 3: 72 min
Effects of speed reduction in climb, cruise and descent phases to generate linear holding at no extra fuel cost

Illustrative Examples

Detailed analysis for AMS-SVQ at CI=150 kg/min

Climb speed

Fuel (kg)
1685
1415
1124
1064

FL 340
FL 320

Case 2
Case 3
CI=0
CI=150 Case 0
Case 1

Specific Range (Nm/kg)
0.188
0.185
0.179

Cruise speed

FL 340
FL 320

Descent speed
Illustrative Examples

Trade-off between fuel and time
Effects of speed reduction in climb, cruise and descent phases to generate linear holding at no extra fuel cost

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Conclusions

- **Previous research** on linear holding strategies in cruise phase to absorb part of ATFM delays are **extended** by allowing speed reduction on **climb and descent phases**

- **Three different cases** are analysed and compared. Maximum airborne delay trajectories are computed by means of numerical optimisation using an **in-house trajectory optimisation tool**

- **Significant increases in delay** obtained when climb and descent are taken into account for linear holding (with no extra fuel consumption).

- **Fuel and time trade-off among phases**: some fuel savings in climb are allocated later on in cruise to increase linear holding even more
Further work

- Use linear-holing in the context of **Trajectory Based Operations (TBO)** as additional strategy for demand and capacity balance
- Consider **multiple regulations** at the same time
- Simulate realistic **scenarios** (or historical cases)
- Include effects of **wind** and non-standard atmospheres
- Consider scenarios where **extra fuel** consumption is an option to increase delay recovery
The End

Thank you!

Questions?