CONTINUOUS DESCENT APPROACHES AGAINST MODIFIED TIMING REQUIREMENTS: A DESIGN STUDY

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Abstract

In order to meet the challenges of growing air traffic, many research activities have been initiated to come up with more efficient and safe flight operations including Trajectory Based Operations. One of the initiatives has been to control Time-of-Arrival during enroute descend phase of flight. The design studies presented in this paper investigate possibility of making minor adjustments using thrust control at near idle position to avoid final altitude errors. Nominal altitude time trajectories coupled with its boundaries using thrust control are adopted for the purpose. To synchronize with ground based Decision support Tools, message set requirements for Aircraft Intent, as proposed by Boeing, have been addressed. Simulation results on the flight path trajectories and typical case studies for changing the time of arrival are presented to validate the approach. Possible areas for further studies are highlighted.

Abbreviation

AI = Aircraft Intent
AIDL = Aircraft Intent Description Language
ATC = Air Traffic Control
ATD = Along Track Distance
CAS = Calibrated Air Speed
CDA = Continuous Descent Approach
DST = Decision Support Tools
EAS = Equivalent Air Speed
EPP = Extended Projected Profile
FMS = Flight Management System
HA = Hold Altitude
H_{CO} = Crossover Altitude
HPA = Hold Flight Path Angle
HS = Hold Speed
IAF = Initial Approach Fix
ISA = International Standard Atmosphere
M = Mach No
RTA = Required Time of Arrival
TBO = Trajectory Based Operations
TL = Throttle Law
TLP = Track Lateral Path
TLTHRO = Throttle Law-continuous Throttle Adjustment
TOD = Top of Descend
SL = Speed Law

Introduction

A three-fold or more increase in air traffic is expected by 2025, as predicted by Joint Planning and Development Office (JPDO) of which FAA is one member [1,2]. Single European Sky ATM Research (SESAR) launched by the European Community aims at implementing Trajectory Based Operations (TBO) to allow for desired flexibility, which rely on airborne system function as well as ground based Decision-Support Tools (DSTs) [3,4,5]. The DSTs are responsible for trajectory prediction and also for managing the trajectories between incoming aircraft and the ATC. Trajectory predicted by the ground-based DST must be consistent with the trajectory predicted by on-board Flight Management System (FMS) and hence a close coordination between the two becomes essential. Aircraft Intent Description Language (AIDL) [1 and 3] is a standard specification jointly evolved by FAA and the Boeing in this regard [1 and 3]. Generalized Profile Interface module, developed by NASA and abbreviated as GenProf [6] and Extended Projected Profile (EPP) formulated by RTCA [7] are some of the other studies in this

direction. Incoming aircraft are required to reach Initial Approach Fix (IAF) at Required Time of Arrival (RTA) specified by Air Traffic control (ATC). However, due to unforeseen circumstances, RTA needs to be changed even after or just before initiation of descent. There have been some studies on adjusting RTA for approach phase starting from IAF [8, 9 and 10]. A study conducted by Peter and team in association with Boeing [11] aims at adjusting RTA during enroute descent from Top of Descent (TOD) up to IAF using AIDL for synchronization. The method involves adjustment of Speed by controlling pitch attitude, keeping the thrust at idle position. The study shows encouraging results towards flying Continuous Descent Approach (CDA) but it results in large altitude errors at IAF.

The present thesis work aims at extending the work done by this team to avoid the altitude errors by using thrust control for adjusting speed and to evolve a simplified approach for possible implementation in FMS. Brief details of the proposed approach, simulations results and the associated elements of AIDL message structure are presented here, which are extracts of thesis report [12].

The Concept

Enroute flight descent is generally defined by a pair of flight parameters involving Mach Number (M) and Calibrated Air Speed (CAS) [10]. Initial descent is performed at constant M followed by flight at constant CAS up to IAF, with change over occurring at cross over altitude which is specific to the pair of M and CAS. It is therefore necessary to adopt the speed adjustments consistent with these two phases of flight for achieving desired RTA. The proposed approach envisages flight path at fixed gradient to avoid offset in final altitude and adjustment of speed using thrust control to achieve desired RTA. The concept involves determination of RTA boundaries for nominal speed schedule and two more boundaries for extreme conditions; one for early arrival and one for late arrival at desired flight path gradient as shown in Fig. 1. Boundary-1 is determined for speed lower than nominal speed allowing adequate margin such that the required thrust is above idle condition sufficient for speed control, considering the restrictions as per airplane performance manual. Boundary-2 is determined for speed higher than nominal speed, with increment chosen same as that for Boundary-1 to maintain uniformity. Final times $T_F$, $T_{F1}$ and $T_{F2}$ represent the time window available for modifying time of arrival ($\Delta$RTA) if the decision is made at Top of Descent (TOD). Similar altitude - time boundaries are required for the flight descent phase starting from crossover altitude $H_{CO}$ at time $T_{CO}$.

Changes to the time of arrival for incoming aircraft might be initiated by ATC at any point of time designated as lead time $t_L$ between $T_0$ and $T_F$ as shown in the figure. So, the speed increments must be determined for this time based on the boundary parameters. Considering the phases of flight during enroute descent, two types of speed schedules are required as follows:

- Revised Schedule involving change in M and CAS for $t_L < T_0$.
- Altered Schedule involving change in only CAS for $t_L \geq T_0$.

The goal is to arrive at speed increments in terms of $\Delta M$ and $\Delta CAS$ pair in order to achieve $\Delta$RTA using the Time Windows shown in the figure. In the present study, CAS is approximated by EAS, neglecting errors due to compressibility effects in measurements. External wind conditions are also not considered in this study.

Determination of Speed Increments

The process comprises of following two steps

- Step-1: Determination of nominal flight trajectory and the two boundaries as shown in Fig. 1 for both phases of flight.
- Step-2: Determination of speed increments and required speeds to achieve modified RTA at lead-time $t_L$.

Nominal flight profile and the two boundaries are to be determined through suitable simulations using aircraft characteristics and the governing equations of motion. For the present study, modelling and equations of motion are similar to the studies reported by Roshini and team [8] and for the sake of brevity are not reproduced here.

Step-2: Let M and EAS represent the speeds for nominal flight and let $\pm \Delta M_N$ and $\pm \Delta EAS_N$ represent the increments for the boundaries. At any time $t_L$, the time difference between the nominal trajectory and the boundaries can be determined.

\[
\Delta t = t_1 - t_L \quad \text{for late arrival} \quad (1)
\]

\[
\Delta t = t_2 - t_L \quad \text{for early arrival} \quad (2)
\]

Where
t₁ and t₂ are the time intervals of boundary-1 and Boundary-2 corresponding to same altitude of nominal trajectory at time tₐ as shown in Fig.1.

Since the required speed increments depend on this time difference, it is proposed to represent this parameter as function of tₐ as shown in Fig.2.

In the limiting case when tₐ is T₀ at TOD, ∆t can be expressed as follows:

\[ ∆t = T_F - T_{F1} = ∆T_1 \] for late arrival (3)
\[ ∆t = T_F - T_{F2} = ∆T_2 \] for early arrival (4)

Where

T_F is the time at which the aircraft reaches final altitude for nominal flight.

T_{F1} and T_{F2} are the time intervals for Boundary-1 and 2 to reach altitude at IAF.

\[ ∆T_1 \] and \[ ∆T_2 \] are the time windows representing maximum permissible variations at T_F.

Depending upon the present position of aircraft, there are two possibilities; Revised Schedule (RS) when aircraft is between TOD and above H_{CO} and Altered Schedule (AS) when the aircraft is below H_{CO}.

Revised Schedule

Both M and EAS are to be altered to M_desired and EAS_desired in order to achieve desired RTA. Let the aircraft be at position A at time tₐ, as shown in Fig.2 and let ∆RTA be the time required for adjustment. Step by step procedure is as follows:

1. Determine maximum ∆RTA possible at A, represented as ∆T₁max using speed increments of ∆M_N followed by ∆EAS_N followed for the boundaries as follows:

\[ ∆T₁_{max} = DT₁ (T_F - T_L) / T_F \] for late arrival (5)

\[ ∆T₁_{max} = DT₂ (T_F - T_L) / T_F \] for early arrival (6)

2. Compute speed increments for ∆RTA as:

\[ ∆M = ± (\frac{∆RTA}{∆T₁max}). M_N \] (7)
\[ ∆EAS = ± (\frac{∆RTA}{∆T₁max}). EAS_N \] (8)

3. Compute desired speeds as

\[ \text{Mach}_{\text{desired}} = M_N ± ∆M \] (9)
\[ \text{EAS}_{\text{desired}} = EAS_N ± ∆EAS \] (10)

Positive speed increment is used for early arrival and negative speed increment is used for late arrival.

Altered Schedule

EAS alone is to be altered to EAS_desired. Let the aircraft be at position B at time tₐ, as shown in the Fig.2. Determine maximum ∆RTA possible at B, using speed increment of ∆EAS_N followed for the boundaries as follows:

\[ ∆T₂_{max} = DT₃ (T_F - T_L) / (T_F - T_{CO}) \] for late arrival (11)

\[ ∆T₂_{max} = DT₄ (T_F - T_L) / (T_F - T_{CO}) \] for early arrival (12)

Computation of ∆EAS and EAS_desired is similar to the method outlined for step 2 and 3 in section - Revised schedule.

Simulation Studies

The studies were performed using set of aircraft characteristics representative of a typical, medium range, 150 seat, transport aircraft, which are available in open literature for the purpose of academic studies [13]. Numerical integrations of the aircraft energy balance equations have been carried out to determine various flight trajectory parameters as function of time using height step interval of 200 ft. Case studies were performed to evolve design framework for the required ∆RTA as well as to analyse the parameters required for defining message set using AIDL. The flight parameters chosen for the present study are as follows:

- Aircraft weight: 44678 Kg
- Max Mach No: 0.8; Max EAS: 280 knots
- Nominal enroute descend Mach / CAS pair: 0.65 / 260 knots
Top of Descent altitude: 35000 ft
Flight path Angle: 2 deg, chosen as constant
Final altitude: 5000 ft
Atmosphere: ISA
Speed increments: as per Table-1

Assumptions: External winds are not considered for the studies. Time taken for aircraft to reach the speed increments has been considered negligible and hence not considered. Lateral path is assumed to be flown manually by pilots based along the desired track for the purpose of computing Along Track Distance (ATD).

Simulation Results

Figure 3 shows nominal trajectory parameters as function of time. During the constant Mach flight, EAS increases from 208 knots at TOD to 260 at $H_{CO}$ after which it remains constant. During the constant Mach flight, TAS increases from 375 knots at TOD to 391 knots at $H_{CO}$ after which it falls to 280 knots at IAF, indicating significant variation of TAS. Nonlinear variation of ATD and height of the aircraft can also be seen form the time response.

Similar time responses are generated for the chosen extreme boundaries for both phases of flight. Using these results, $\Delta RTA$ variations with the lead time are obtained and shown in Fig.4. Maximum available $\Delta RTA$ for the RS and the AS are also shown in the figure.

Case Studies for Achieving $\Delta RTA$

Studies were conducted to observe the actual $\Delta RTA$ parameters and the associated thrust variations needed at various lead times. Summary is presented in Table-2.

$\Delta RTA$ obtained and the associated errors are also shown in the table, indicating that the deviations are small. Thrust required for adjustment of the speed for lead time of 300 sec is as shown in Fig.5, which shows the change in thrust.

Message Set for Representation in AIDL

Trajectory predictions made by ground based DSTs must be consistent with the predictions made by on-board FMS and hence requires some form of synchronization. The trajectory data is a function of basic commands, guidance modes and control strategies implemented with which are collectively referred to as aircraft intent [1, 7]. Aircraft Intent Description Language (AIDL) developed by Boeing Research and Technology Europe (BRTE) is one such standard used to model the aircraft intent. Aircraft Intent can be expressed by means of AIDL, with

<p>| Table-1 : Flight Parameters for Trajectory Predictions |
|-----------------------------------|-----------------|------------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Mach</th>
<th>EAS, Knots</th>
<th>Crossover Altitude in ft</th>
<th>Phase of Flight</th>
<th>Flight Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.65</td>
<td>260</td>
<td>25000</td>
<td>From TOD</td>
<td>Nominal</td>
</tr>
<tr>
<td>0.585</td>
<td>234</td>
<td>25000</td>
<td>From H_{CO}</td>
<td>Extreme Boundaries</td>
</tr>
<tr>
<td>0.715</td>
<td>286</td>
<td>25000</td>
<td>Extreme Boundaries</td>
<td></td>
</tr>
<tr>
<td>0.65</td>
<td>270</td>
<td>23500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.65</td>
<td>250</td>
<td>27000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<p>| Table-2 : Summary of $\Delta RTA$ for Various Lead Times |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Lead Time $t_l$, Sec</th>
<th>$\Delta RTA$ Required, Sec</th>
<th>$\Delta RTA$ Available, Sec</th>
<th>$\Delta M$</th>
<th>$\Delta EAS$, Knots</th>
<th>$\Delta RTA$ Obtained, Sec</th>
<th>Error, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>100</td>
<td>131.6</td>
<td>-0.049</td>
<td>-19.8</td>
<td>97.5</td>
<td>2.5</td>
</tr>
<tr>
<td>400</td>
<td>-45</td>
<td>-97.8</td>
<td>0.030</td>
<td>12.0</td>
<td>-44.5</td>
<td>1.2</td>
</tr>
<tr>
<td>500</td>
<td>20</td>
<td>41.6</td>
<td>0.000</td>
<td>-4.8</td>
<td>19.2</td>
<td>4.0</td>
</tr>
<tr>
<td>500</td>
<td>-20</td>
<td>-35.0</td>
<td>0.000</td>
<td>5.7</td>
<td>-20.4</td>
<td>2.0</td>
</tr>
</tbody>
</table>
instructions and specifiers. Trajectory parameters requiring modification for vertical path have been formulated from the results of the above studies as shown in Table-3.

TLTHRO represents throttle law for continuous adjustment of throttle either manually or using auto throttle function. Since the approach has been to maintain constant FPA, thrust setting would not be at idle rating, as could be seen from the Fig.5.

Conclusions

Possibility of adopting near idle thrust control for accommodating last-minute minor adjustments to RTA have been studied using fixed FPA approach. A two step approach involving trajectory determinations followed setting up of linearized ΔRTA boundaries for possible implementation in FMS has been proposed. Simulations studied on typical transport aircraft indicate small errors in the desired RTA. Trajectory parameters for AIDL instruction set have been identified and summarized for synchronization with DSTs. Since precise thrust control is required, incorporating Auto Throttle function is expected to improve ΔRTA performance. Further studies are needed to study the effect of external winds, particularly w.r.t the additional thrust needed to maintain FPA. The studies are needed for a set of flight path gradients to accommodate different descend paths.

Acknowledgements

The authors thank Dr. Shrikant Rao and Venkata Subbaiah, Honeywell Technology Solutions Lab, Bangalore and Dr. A A Pashilkar, National Aerospace Laboratories (NAL), Bangalore for their critical review and constructive suggestions.

Table-3 : AI Parameter for AIDL Message Set

<table>
<thead>
<tr>
<th>Time, Sec</th>
<th>Altitude</th>
<th>AIDL Instruction</th>
<th>Flight Mode</th>
<th>AIDL Law Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>From</td>
<td>To</td>
<td>From</td>
<td>To</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>300</td>
<td>35000</td>
<td>282 FL</td>
<td>Hold Speed, HS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>at ALT = 282 FL</td>
<td></td>
<td>Speed Law, SL</td>
</tr>
<tr>
<td>300</td>
<td>445</td>
<td>282 FL</td>
<td>252 FL</td>
<td>Hold Speed, HS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>at ALT = 282 FL</td>
<td></td>
<td>Speed Law, SL</td>
</tr>
<tr>
<td>445</td>
<td>1578</td>
<td>252 FL</td>
<td>50 FL</td>
<td>Hold Speed, HS</td>
</tr>
<tr>
<td>0</td>
<td>1578</td>
<td>0</td>
<td>50 FL</td>
<td>Hold FPA, HPA</td>
</tr>
</tbody>
</table>

References


Fig.1 Flight Time Schedule Boundaries for Enroute Descent Phase
Fig. 2 ΔRTA Variations with Lead Time

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Mach</th>
<th>EAS, Knots</th>
<th>Total Time in Sec</th>
<th>ΔRTA Available in Sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>0.65</td>
<td>260</td>
<td>1480</td>
<td>0.0</td>
</tr>
<tr>
<td>RS</td>
<td>0.585</td>
<td>234</td>
<td>1645</td>
<td>165.0</td>
</tr>
<tr>
<td></td>
<td>0.715</td>
<td>286</td>
<td>1346</td>
<td>-134.0</td>
</tr>
<tr>
<td>AS</td>
<td>0.65</td>
<td>250</td>
<td>1524</td>
<td>44.0</td>
</tr>
<tr>
<td></td>
<td>0.65</td>
<td>270</td>
<td>1443</td>
<td>-37.0</td>
</tr>
</tbody>
</table>

Fig. 4 Variations of ΔRTA for RS and AS

Fig. 3 Time Responses of Nominal Trajectory

Fig. 5 Variation of Thrust for ΔRTA at Lead Time of 300 Sec