Controlled time of arrival windows for already initiated energy-neutral continuous descent operations

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A B S T R A C T

Continuous descent operations with controlled times of arrival at one or several metering fixes could enable environmentally friendly procedures without compromising terminal airspace capacity. This paper focuses on controlled time of arrival updates once the descent has been already initiated, assessing the feasible time window (and associated fuel consumption) of continuous descent operations requiring neither thrust nor speed-brake usage along the whole descent (i.e. only elevator control is used to achieve different metering times). Based on previous works, an optimal control problem is formulated and numerically solved. The earliest and latest times of arrival at the initial approach fix have been computed for the descent of an Airbus A320 under different scenarios, considering the potential altitudes and distances to go when receiving the controlled time of arrival update. The effects of the aircraft mass, initial speed, longitudinal wind and position of the initial approach fix on the time window have been also investigated. Results show that time windows about three minutes could be achieved for certain conditions, and that there is a trade-off between robustness facing controlled time of arrival updates during the descent and fuel consumption. Interestingly, minimum fuel trajectories almost correspond to those of minimum time.

1. Introduction

With the awareness of global warming and the rising of fuel prices, reducing the environmental impact of aviation has become a significant concern of various aviation stakeholders. Accordingly, Continuous Descent Operations (CDO) have demonstrated to be successful in the reduction of emissions, fuel consumption and noise nuisance in Terminal Manoeuvring Area (TMA) (Clarke et al., 2004).

In order to obtain the maximum benefits of CDO, aircraft should descent with the engines at idle from the Top Of Descent (TOD) down to the stabilisation point, where the aircraft is configured and ready for landing, typically 1000 ft above aerodrome level. However, such operations suffer from a main known drawback: the loss of predictability of the trajectory from the Air Traffic Control (ATC) point of view, in terms of altitude uncertainties and overfly-times at certain fixes along the route. Consequently, existing CDO implementations require ATC to introduce additional sequencing buffers to ensure safe separation among aircraft, thus reducing capacity (Enea et al., 2017).

An approach to enable CDO without compromising capacity consists on merging and sequencing inbound traffic by assigning Controlled Times of Arrival (CTA) at a metering fix (Klooster et al., 2009). With this type of flight operations, each arriving aircraft

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should compute its earliest and latest times of arrival at the metering fix well before the TOD (i.e. determine the feasible time window), and subsequently donwlink this information to the ground systems (SESAR Joint Undertaking, 2015). Then, an advanced arrival manager will be in charge of assigning CTA fitting in the feasible time window of each aircraft in the landing sequence. Finally, the ATC will send the CTA via data-link, and the on-board flight management system will plan and execute a descent satisfying the time constraint.

Extensive research has been devoted in the recent decades on on-board trajectory planning and guidance algorithms capable to fulfil one or various CTA (Vilardaga and Prats, 2015; de Jong et al., 2017). Similar efforts have been devoted to improve ground-based CTA assignment algorithms, enabling time based sequencing and merging procedures and minimising path stretching instructions by ATC (Takeichi, 2017; Kim et al., 2014; Man, 2015).

Several studies have dealt with the assignment of CTA (and the quantification of the feasible time window) when the aircraft is still in cruise, well before the TOD. See for instance (Park and Clarke, 2015), which computed earliest and fuel-optimal trajectories by allowing the aircraft to adjust the duration of the cruise phase and the descent airspeed profile. With similar purposes, Ref. (Takeichi and Inami, 2010) quantified the feasible time window that could be achieved by either enabling the addition (resp. omission) of waypoints to stretch (resp. reduce) the flight path length, or adjusting the duration of the cruise phase.

In the future ATM paradigm, however, we could envisage ATC updating the CTA once the descent has been initiated. In such cases, and aiming at minimising the environmental footprint, aircraft should be able to adjusts the time of arrival without requiring neither additional thrust nor speed-brakes use, flying what is commonly called an energy-neutral trajectory. This could be achieved by taking advantage of time and energy management (de Jong et al., 2014, 2017).

The robustness of CDO trajectories facing late CTA updates during the descent was assessed in Lindsay et al. (2009). Aiming to minimise the environmental impact, only elevator control was permitted to adjust the time of arrival at the metering fix, assuming rather simple Mach/calibrated airspeed (CAS) profiles and allowing a single and instantaneous modification of the scheduled airspeed. Furthermore, this assessment was performed for few initial conditions and the employed method could not ensure the optimality of the resulting trajectories in the mathematical sense.

Another important limitation of previous works is that most of them did not explicitly take into account for the remaining descent between the metering fix and the runway threshold. Adjusting the airspeed profile to minimise or maximise flight time may result in changing the altitude at which the metering fix is overflown. If the energy of the aircraft at this fix were too low, additional thrust would be needed after overflying it (thus interrupting the CDO) (Bronsvoort et al., 2012). Similarly, if the energy were too high it would be required to use speed-brakes and/or to deploy high-lifting devices or the landing gear earlier than planned. Furthermore, all previous works used the Base of Aircraft Data (BADA) v3 performance model, which has been reported to show significant limitations for accurate trajectory prediction and optimisation in TMA (Senzig et al., 2009; Senzig and Fleming, 2009; Hoekstra, 2016). More sophisticated aerodynamics and engine models are needed in order to compute realistic descent profiles and to obtain accurate fuel consumption and flight time figures.

The main contributions of this paper are summarised as follows. Firstly, we assess complete energy-neutral descents down to the stabilisation point, assuming that the descent has been already initiated when the ATC updates the CTA. In contrast to Refs. (Takeichi and Inami, 2010; Park and Clarke, 2015), in this paper the aircraft has already passed the TOD when receiving the CTA update, and the remaining descent is restricted in such a way that neither throttle nor speed-brakes use is allowed. Accordingly, the whole trajectory planning, as a result of the CTA update, is subject to optimisation where only elevator control is permitted to modify the airspeed profile and to adjust the time of arrival at the metering fix.

Secondly, the earliest and latest energy-neutral trajectories at the metering fix are computed for a wide range of initial conditions, aiming at investigating how the feasible time window changes with the altitude and distance to go. Previous works assumed a unique initial condition in cruise (Takeichi and Inami, 2010; Park and Clarke, 2015).

Thirdly, the feasible time window sensitivity to different longitudinal winds, initial airspeeds, metering fix positions relative to the runway threshold and aircraft masses is also investigated. The effects of the wind on the earliest and fuel-optimal trajectories were previously investigated in Park and Clarke (2015), considering a unique initial condition in cruise. Therefore, it is still unknown how the longitudinal wind impacts the feasible time window for different altitudes and distances to go during the descent.

Finally, the BADA v4 aircraft performance model is used to represent drag, engine thrust and fuel flow functions, aiming to derive realistic fuel consumption and time figures.

2. Background

In the recent years, several research has focused on the use of energy principles to perform accurate, time-constrained, engine-idle Continuous Descent Operations (CDO) to reduce the environmental impact of aviation (de Jong et al., 2014, 2017). The idea behind time and energy management is to exchange altitude for airspeed and vice versa to gain or lose time and energy through elevator control. Following this process, deviations from the plan, including Controlled Time of Arrival (CTA) updates, are corrected without the need for additional thrust or speed-brakes use, leading to what is called an *energy-neutral* trajectory. The earliest and latest energy-neutral trajectories at a metering fix can be computed by solving a trajectory optimisation problem, where the time of arrival at the metering fix is minimised or maximised at the same time different operational constraints are satisfied (and namely the impossibility to use thrust or speed-brakes during the descent).

Trajectory optimisation requires the definition of a mathematical model describing the aircraft dynamics and performance along with a model for certain atmospheric variables. Section 2.1 shows these equations of motion, while Section 2.2 provides a detailed description of the time and energy management concept. Finally, in Section 2.3 the formulation of the optimisation problem for an