CONTINUOUS DESCENT APPROACHES FOR MAXIMUM PREDICTABILITY

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Abstract

The current paper presents an innovative vertical guidance law suited to fly R-NAV Continuous Descent Approaches (CDAs) with ground speed histories that are very stable to wind uncertainties. The guidance law ensures arrival times and ground velocity histories that are far more predictable than when flown with other vertical guidance laws. This, together with the use of ground automation, could potentially help introduce CDAs in high density traffic airspaces and thus benefit from their huge environmental and economical advantages.

The mentioned guidance law was derived using linear aircraft dynamics theory, and the results were validated through simulations using a point-mass aircraft model based on Boeing performance data. The simulations also reveal that the proposed law does not compromise noise impact, fuel consumption or flight time with respect to other idle descents based on existing vertical guidance laws.

Introduction

CDAs have great environmental and economical advantages mainly in noise, time and fuel savings as have been extensively reported in [1, 2, 3] among others. Despite these advantages, CDAs are implemented only in a few airports for night operations or during low traffic density hours. The important capacity penalties associated with CDAs explain their limited use and this, with no question, should be resolved if a more extended use of CDAs is desired.

Although all aircraft operations are subjected to unpredictability due to variable winds and other uncertainties, large numbers of conventional flights can still operate safely confined in a relatively small air space since air traffic control can correct a potential loss of separation issuing heading, speed or altitude instructions to the pilots. These tactical corrections, however, typically result in unnecessary thrust use that conflicts with the concept of CDA where idle thrust needs to be ensured all throughout the descent. Hence, R-NAV CDA flights cannot be subjected to tactical corrections like in the case of conventional procedures, and that forces controllers to allow for plenty of separation between flights in CDA environments. This translates directly into low airport capacities, making R-NAV CDAs unacceptable, in many cases, for airport authorities. Improved ground speed predictability for CDA operations would allow reducing the separation between airplanes in CDA scenarios, and would mean a large step forward towards introducing CDAs in high density traffic without compromising airport capacity.

The problem of capacity and predictability in CDAs has been approached in the literature through innovative operational concepts as in [4, 5, 6]. However, it has less often been treated at the guidance law level. Wind uncertainty has been reported as the main cause of unpredictability in CDAs [1], and as airplanes are affected differently by wind depending on the flight conditions and the airplane guidance laws, airplanes following different vertical guidance laws should also be affected differently by varying winds. This paper aims at finding the vertical guidance law for which the influence of the uncertain winds in R-NAV CDA descents is minimized.

The theoretical optimum was found through mathematical analysis and then, simulations were used to validate the analysis and also to estimate the actual performance of these descents in varying wind environments. Additionally, a comparative quantitative assessment of this guidance law with respect to other descent laws is shown in terms of noise impact, fuel savings, flight time and predictability.

Current R-NAV Idle Descents

Typical R-NAV vertical guidance in descent presets a given vertical altitude profile to be followed at idle thrust, or else executes non-idle descents at constant calibrated air speed (CAS) [7]. In the first case, the vertical path is built by segments of constant inertial (geometric) flight path angle selected to best meet airline preferences or procedure restrictions.

The operator typically sets preferences by choosing between fuel or time savings (cost index) or to achieve low noise levels, so in order to range through all these possibilities, physical reasoning was used to build three idle descents at constant geometric flight path angle for respectively reduced noise impact, time and fuel consumption for a B737-300. These profiles will be used later in this paper to quantitatively assess the differences between current practices and the proposed guidance law.

The idle descent for reduced noise (CDA-RN) follows the highest altitudes and lowest possible speeds in two segments starting at 10,000 ft. The descent angle is selected such that for zero wind conditions, the airplane velocity is kept constant just above the slowest recommended speed in clean configuration. The airplane slows down during the second segment and deploys flaps at the nominal flap change speeds where the inertial angle is kept constant and equal to -2.9 to intercept the glide slope from below, as recommended, and at 2,000 ft and 180 KCAS.

The idle descent for reduced time (CDA-RT) consists of a descent from 10,000 ft down to 2,000 ft at 250 KCAS (the fastest allowed speed at those altitudes), followed by a short level idle segment where the airplane deploys flaps and slows down until 180 KCAS. In this case, the flaps are deployed at the earliest possible speeds to shorten this segment and reduce even more the total flight time.

Finally, the idle descent for reduced fuel consumption (CDA-RF) is executed at the geometric flight path angle which keeps the lift coefficient approximately equal to that of maximum efficiency between 10,000 and 2,000 ft. In this case there is also a short level idle segment after the descent where the airplane slows down until 180 KCAS.

Definitions and Theoretical Analysis

Let predictability be defined as the ability to accurately predict an aircraft trajectory in the presence of uncertainty. Time predictability, altitude predictability, thrust predictability, velocity predictability or acceleration predictability (calibrated, true or ground) are also useful concepts if specific aspects of the trajectory are of greatest interest. Furthermore, the different sources of uncertainty, like unknown winds or inaccuracies in the airplane systems, lead to a complimentary set of definitions like predictability to wind uncertainties or predictability to inaccuracies in the airplane systems.

Provided that the lateral profile of the trajectory is given (L-NAV mode engaged), and thus lateral profile predictability is ensured, ground speed predictability is of the greatest operational interest in CDAs since it could allow introducing CDAs in high traffic density scenarios maintaining reasonable levels of airport capacity, maybe through the use of ground automation. In addition, wind has been reported as the most important source of uncertainty in CDAs [4] and thus, ground speed predictability to wind uncertainty will be the focus of this paper.

It should be noted that ground position, ground speed and ground acceleration predictability are equivalent terms, provided that the starting ground position and speed are certain. The term predictability will be used in the following to refer to any of them.

Due to simple energy balance considerations, all aspects of the trajectory cannot be accurately imposed simultaneously in the presence of uncertainty, and in fact it is the role of the airplane guidance to determine which aspects of the trajectory will be actually predictable and which not. Figure 1 illustrates the balance of mechanical energy of the airplane during a descent when using current vertical guidance laws, where the contribution of the idle thrust to the energy balance has been neglected. The total mechanical energy of the airplane, that needs to be dissipated during the descent, is in the form of potential (altitude) plus kinetic (ground speed) energy, which are exchangeable forms of energy. Once the Flight Management Computer (FMC) for an R-NAV descent builds the guidance reference, the profile of altitudes is given [7] and thus, the potential energy of the aircraft is also known at each point. This ensures high predictability levels in altitude versus ground track distance. Provided that the total amount of mechanical energy of the airplane is influenced by unknown winds, it is clear from Figure 1 that current practices lead to very low ground speed predictability levels, since the unknown wind energy translates entirely into unknown kinetic energy.

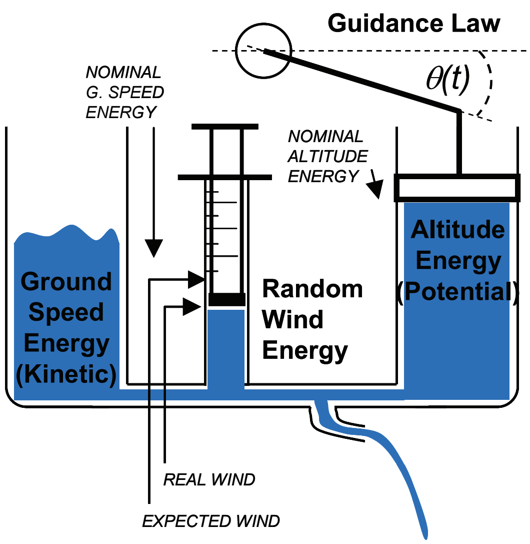

Figure 1. Mechanical Energy Balance in a Geometric Flight Path Angle Descent

This simple energy balance explains the fundamental reasons behind the unpredictability associated with current R-NAV CDAs.

To ensure more predictable ground speed histories in CDAs, an innovative guidance law is being proposed. Following the same energy conservation considerations and provided that wind is always uncertain up to some extent, the improved ground speed predictability can only be achieved at the expense of losing some altitude predictability as sketched in Figure 2.

Two additional notes should be considered at this point: first the proposed law, as it will be seen, is not based on direct control of the ground speed and secondly, the proposed concept would be of practical use as long as the required altitude uncertainties ensure obstacle clearance and safe altitude separation with other routes. With these two ideas in mind, a discussion on the proposed guidance law is given below.

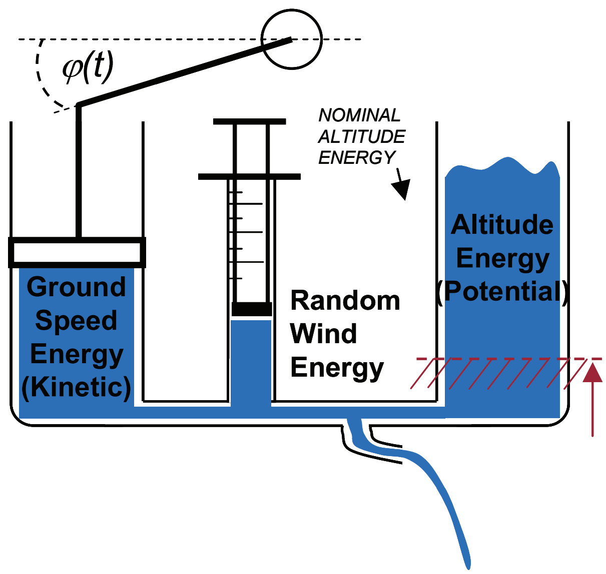

Figure 2. Proposed Mechanical Energy Balance

In the following, an outline of the derivation of the proposed guidance law is given together with a high-level description and discussion of the concept. The mathematical analysis was based on the governing equations of motion of the aircraft's center of gravity with the following assumptions:

- Symmetric flight on a vertical plane
- Idle thrust parallel to drag
- Small angles
- Negligible temporal rate of change of aerodynamic flight path angle γTAS
- Loss of momentum due to fuel burn is small compared with other forces

Then, the equations were linearized for an unknown wind perturbation about nominal descent conditions and an arbitrary vertical guidance law. The first order (linear) effects of the wind on the ground acceleration of the center of gravity were imposed to be zero and from that, a first order condition for maximum predictability was obtained, provided that the descent starts at a known ground position and ground speed.

According to this idea, the mathematical derivation proved that ground speed predictability of CDAs increases when the idle descent is executed with constant aerodynamic flight path angle (γ_{TAS} = const). It should be noted that this condition results in different geometric vertical profiles for different wind conditions in agreement with the energy balance discussions above. Furthermore, for a given aircraft, and given nominal (expected) wind and atmospheric conditions, there is one constant flight path angle descent that ensures best predictability. The specifics of this optimal descent can be determined through theoretical analysis, but details are omitted herein for brevity. These optimal flight conditions will be referred to in the following as conditions for maximum predictability.

Constant aerodynamic flight path angle CDAs flown in conditions for maximum predictability will be referred to in the following as CDAs for maximum predictability CDA-MP.

Simulation Results

A series of simulations was run to validate the analysis and estimate the predictability of this procedure in nominal and off-nominal conditions. The utilized aircraft performance model and the wind model are briefly described in this section. In further subsections, those models are used to make a quantitative assessment of the proposed concept.

Aircraft Performance Model

A three degree of freedom point-mass aircraft model was used for the simulations. The thrust, drag and fuel consumption models were based on Boeing performance data and were validated with Boeing performance software. The main physical assumptions of the model are identical to those used for the theoretical analysis.

Wind Model

In this paper, the wind is assumed to be constant with time and to vary linearly with altitude with a nominal (known) component plus a non-nominal (unknown) component which is the source of the unpredictability. The unknown component can be further subdivided into a component constant with altitude plus a component that accounts for the uncertainty in the wind variation with altitude (velocity gradient β) as shown in Figure 3.

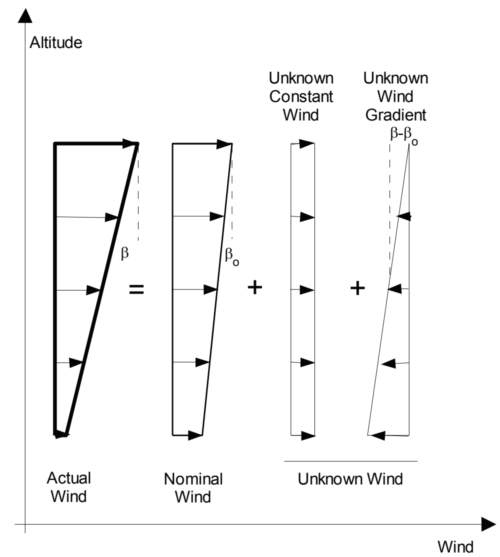

Figure 3. Wind Model

Uncertainty to Constant Wind with Altitude

The simulation results on the effect of the unknown constant wind offset with altitude were used to validate the theoretical analysis.

A first set of simulations was run for a steady atmosphere (no wind) starting at 10,000 ft and ending at 2,000 ft. The initial weight of the airplane was kept equal to W_o = 110,000 lbs for the B737-300 and simulations were repeated for four guidance law cases: CDA-RN, CDA-RT, CDA-RF and CDA-MP. In each case, the total flight time $t_{Nominal}$ was collected.

Constant wind with altitude (15 knots) was added to perform a second set of simulations for identical starting altitude, starting weight and identical values of the guidance law parameter as if the presence of the wind was unknown to the pilot or the FMC. In the case of CDA-MP, the same starting ground speed was also utilized to comply with the concept. Each simulation was stopped when the airplanes had flown the same ground track distance as in the equivalent nominal wind (non-wind) case. The total flight time $t_{Wind\text{-}Error}$ was collected from the simulations in each case.

The total flight time difference $\Delta t = t_{Nominal} - t_{Wind\text{-}Error}$ has been used as a measure of the sensitivity of the ground speed to unknown winds and thus, a measure of the predictability for each CDA type. Nevertheless, it should be noted that the CDA-MP guidance law/concept enhances ground speed and time predictability at every point along the trajectory.

The results of the simulations summarized in Figure 4 show that the CDA-MP guidance law and concept exhibit a significant improvement in predictability with respect to any of the descents based on constant inertial angle.

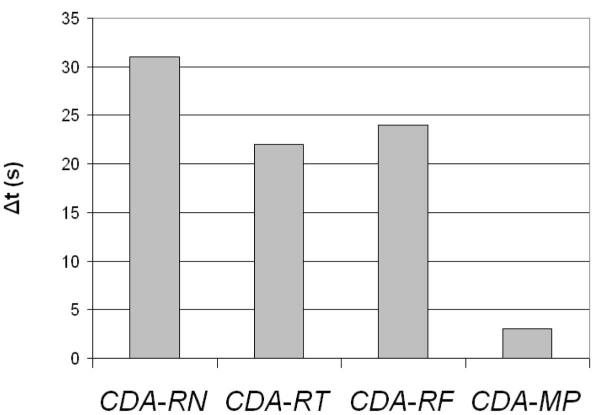

Figure 4. Predictability for Different CDA Descents

Uncertainty to Wind Gradient

The wind gradient with altitude is also expected to influence the value of γ_{TAS} for maximum predictability. This section is aimed at quantifying the importance of the wind gradient on the predictability in order to determine whether or not the nominal wind gradient (β) can be ignored in the operation and also, to estimate the influence of possible unknown wind gradients ($\beta - \beta_o$).

To determine the influence of β, two new sets of simulations were performed. The first set of descents was performed between 10,000 ft and 2,000 ft, with starting nominal weight equal to W_o, and conditions for maximum predictability. This set includes runs for a range of winds, all of them constant with altitude. The second set was run for identical initial conditions and γ_{TAS} values but with winds that are linearly decreasing from the values of the first set at 10,000 ft to zero at 2,000 ft, thus resulting in different values of β. These simulations were stopped when the airplane had flown the same ground track distances as in the equivalent runs of the first set. The differences in flight time between equivalent runs of the two sets (Δt) were plotted versus the value of β as shown in Figure 5. It can be seen that the effect of β is relatively unimportant for a typical wind gradient, extracted from measurements in the demonstrations at KSDF [1]. However, the values of γ_{TAS} could be tabulated as a function of the nominal wind gradient to achieve additional accuracy.

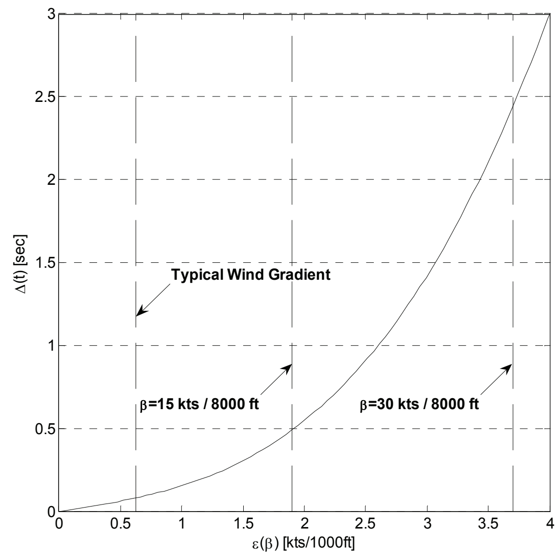

Figure 5. Sensitivity of Flight Time to Wind Gradient

Sensitivity to Uncertainties in Execution

The former sections focus on unknown winds as uncertainties that are generated in the environment and thus are external to the airplane. In addition to these, there are sources of uncertainty which are internal to the airplane that contribute to the overall detriment of the predictability. In the case of an idle descent at constant aerodynamic flight path angle (γ_{TAS} = const), predictability can be affected from inaccuracies in the airplane control system and from the inaccuracy with which the airplane weight is known. Simulations with the B737-300 model were run to investigate the influence of those two sources of uncertainty at a preliminary level.

The first set of simulations was aimed at assessing the sensitivity of the predictability to inaccuracies in the γ_{TAS} control system. A series of idle descents was simulated in steady atmosphere where γ_{TAS} was kept constant in each descent and the initial flight conditions and initial weight were identical to those of the nominal runs. The values of γ_{TAS} for the simulations were selected around the value of γ_{TAS} for maximum predictability emulating deviations in γ_{TAS} as if they were inaccuracies in the control system. It should be noted that in a real descent, γ_{TAS} would oscillate around a given value rather than remaining steady, so these results are expected to overestimate the uncertainties. However, they are still useful to predict the order of magnitude of these effects and bound the actual uncertainties associated with them.

Let $t(MP)$ be the time to cover the ground track distance flown between the top of descent (TOD) and 2,000 ft of altitude in the nominal case flying at the conditions of maximum predictability (nominal ground track distance). Let also $t(\gamma_{TAS})$ be the time to cover the same ground track distance for a γ_{TAS} slightly off of $\gamma_{TAS}(MP)$, but for identical starting altitude, weight and atmospheric conditions (but maybe different arriving altitude). Figure 6 shows the relationship between $\varepsilon(t) = t(MP) - t(\gamma_{TAS})$ and $\varepsilon(\gamma_{TAS}) = \gamma_{TAS}(MP) - \gamma_{TAS}$ as given by the simulations. It can be seen that this relationship is almost linear and that a sustained error of, for example ±0.05 degrees in γ_{TAS}, would result in inaccuracies of approximately ±4 seconds in flight time.

The former results show that in fact, predictability decays rapidly with inaccuracies in the control system. Given this, further simulations were run emulating combined uncertainties in the control of γ_{TAS} with uncertainties in the wind. In this case, the flight time to cover the nominal ground track distance is defined as $t_{wind}(\gamma_{TAS})$. Figure 7 shows $\Delta t = t(MP) - t_{wind}(\gamma_{TAS})$ as a function of $\varepsilon(\gamma_{TAS})$ for 15 knots of constant unknown wind (head or tail). As shown in the former results, the accuracy in the control of γ_{TAS} can play an essential role to achieve the greatest predictability.

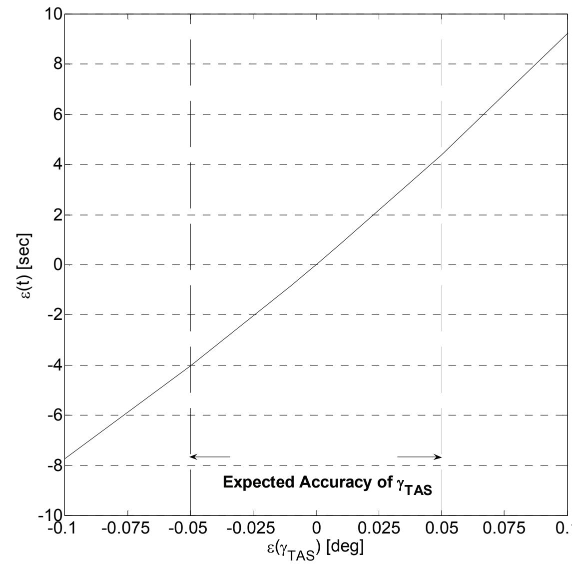

Figure 6. Sensitivity to Inaccuracies in the Control Law

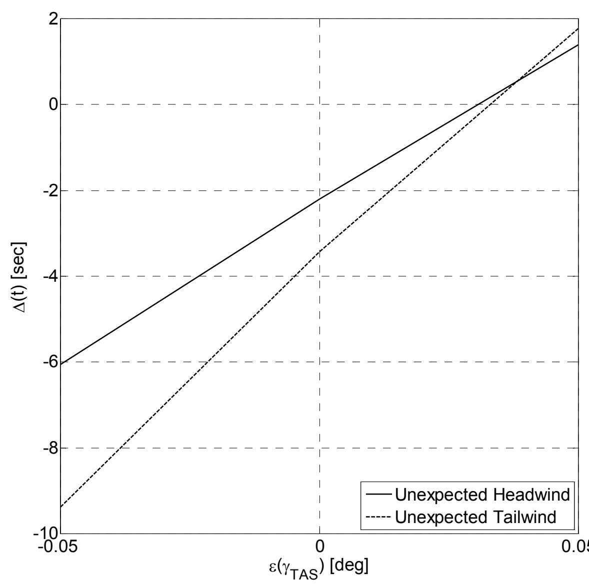

Figure 7. Sensitivity to Inaccuracies in the Control Law and Unknown Winds (15 knots) for B737-300

Provided that $\gamma_{TAS}(MP)$ depends on the aircraft weight, another important source of internal uncertainty may arise if the aircraft weight is not known accurately. Let $t(W)$ be the time to cover the nominal ground track distance for a given W slightly off of the nominal W_o, but for identical starting altitude, flight path angle γ_{TAS} and atmospheric conditions (but maybe different arriving altitude). Figure 8 shows the relationship between $\varepsilon(t) = t(MP) - t(W)$ and W as extracted from the simulations.

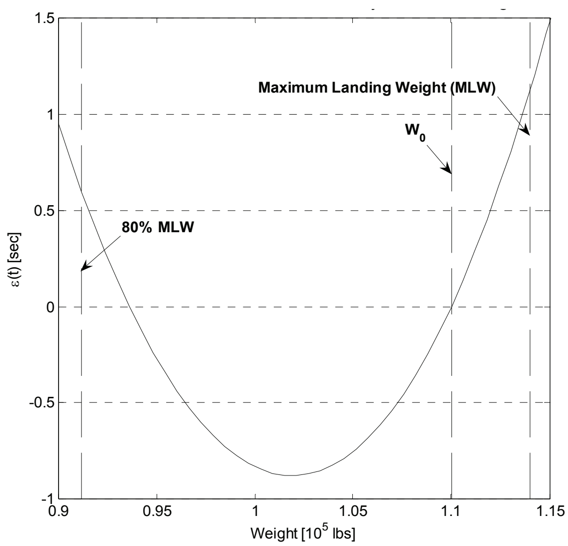

Figure 8. Sensitivity to Aircraft Weight for B737-300

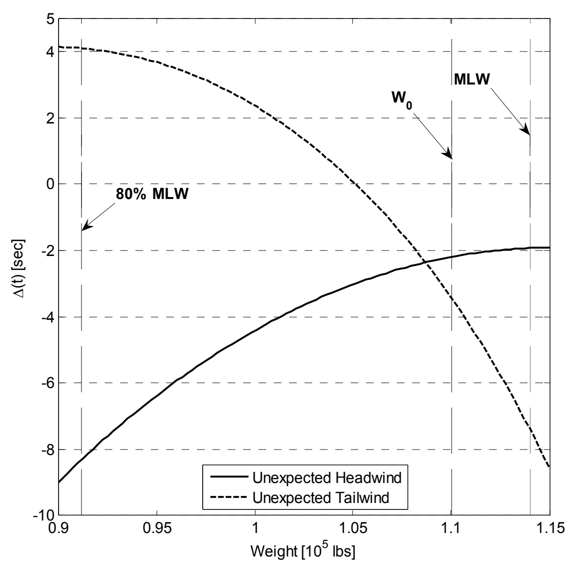

Figure 9. Sensitivity to Aircraft Weight and Unknown Winds (15 knots) for B737-300

The flight time is much less sensitive to uncertainties in the airplane weight than to inaccuracies of the control of γ_{TAS} as shown in the plots. Lastly, a set of simulations was run where uncertainties in the weight and in the wind were combined. In this case, the flight time to cover the ground track distance is defined as $t_{wind}(W)$. Figure 9 shows $\Delta t = t(MP) - t_{wind}(W)$ as a function of W for 15 knots of constant unknown wind (head or tail).

In view of these results, predictability can be improved if the values of γTAS are tabulated as a function of weight.

Noise, Time and Fuel Assessments

The experimental version of INM utilized in the SOURDINE II project was used here to estimate the single event noise impact associated with all four procedures in terms of peak values (LAmax) and Sound Exposure Levels (SEL) in dBAs. Contrarily to conventional versions of INM, this version handles a larger set of Noise Power Distance curves (noise measurements) to allow for a much more accurate estimate of the airframe noise in CDAs. For details see [3].

The values of SEL and LAmax on locations along the ground track path (equally spaced 5 NM) were averaged and given in Table 1 together with flight times and fuel consumptions for all four descents. Only relative values with respect to each optimum descent are given.

Table 1. Performance of Idle Descents

CDA Type	Time	Fuel	SEL	LA_{max}
CDA-RT	**-**	**+6%**	**+5%**	**+8%**
CDA-RF	**+7%**	**-**	**+3%**	**+5%**
CDA-RN	**+16%**	**+8%**	**-**	**-**
CDA-MP	**+10%**	**+1%**	**+2%**	**+3%**

As it can be seen in Table 1, CDA-MP has a similar performance in terms of fuel, descent time and noise impact as compared with conventional descents, which means that CDA-MP should provide improved predictability (Figure 4) while keeping all benefits derived from any other idle descent.

Conclusions

Aerodynamic flight path angle γ_{TAS} vertical guidance significantly improves ground speed predictability for idle descents if the starting ground speed is given.

In addition, predictability is further improved if the descent takes place at the optimum conditions for maximum predictability, which are a function of the aircraft model, aircraft weight, nominal wind and atmospheric conditions.

An innovative vertical guidance law was presented based on this concept. Simulations based on this concept show that it does not significantly compromise noise impact, time and fuel savings with respect to current Continuous Descent Approach practices.

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