CONTINUOUS DESCENT TRAJECTORY WITH OPTIMUM ARRIVAL TIME CONTROLLABILITY

Noboru TAKEICHI*, Takao HATANO*, and Yutaka FUKUDA†
***Department of Aerospace Engineering, Nagoya University**
†Air Traffic Management Department, Electronic Navigation Research Institute
takeichi@nuae.nagoya-u.ac.jp; hatano@navi.nuae.nagoya-u.ac.jp; fukuda@enri.go.jp

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Abstract

The arrival time controllability of a continuous descent operation (CDO) trajectory is discussed. The arrival time controllability is defined as a potentially achievable arrival time difference. It is uniquely determined by the aircraft speed, altitude, and the distance from runway. It is not only possible to extend the arrival time but reduce it with maintaining the minimum thrust. The CDO trajectory that has the optimum arrival time controllability is numerically analyzed, and it is demonstrated that it is possible to compose many CDO trajectories equally having the optimum arrival time controllability. Such CDO trajectory composition enables the traffic control with the flight time reduction. A set of numerical traffic simulation has proven the effectiveness of the proposed traffic control strategy. It is noteworthy that a slower trajectory for a larger arrival time controllability can achieve a faster arrival time than the one using the fastest trajectory with no arrival time controllability. It is concluded that the CDO using the proposed traffic control strategy is able to achieve a delay free air traffic with enhanced arrival time predictability.

1. Introduction

The continuous descent operation (CDO)[1] has been strongly focused because it enables the reduction of the environmental load such as noise and fuel consumption. Its trial has been demonstrated at some airports[2], and it has been recognized as one of the most potential operational concepts in several future air traffic plans[3-5]. In a CDO, an aircraft continuously descends during its arrival and approach phases[1]. Although this minimizes the noise and fuel consumption, it is considered difficult to control the separation with other traffic with maintaining the idle thrust. Therefore, it is expected difficult to achieve the CDO in a congested terminal area even through it indeed has a strong potential in such area. The tailored arrival (TA) is proposed to facilitate CDO in a congested terminal airspace[6-8]. In a TA operation each aircraft is provided with a specifically designed flight trajectory from the air traffic controller that facilitates the conflict free CDO.

There have been many strategies presented for the CDO[9-14]. Although these concepts have some difference in detail, their basic strategies could be summarized as follows: aircraft descends from the top of descent (TOD) to a merging point at a required time, and maintains an appropriate interval with a preceding aircraft by airborne separation as shown in Fig. 1. The descent from TOD to the merging point will be operated by a time-based strategic traffic control. This operation strategy is expected to enable every aircraft to reach the merging point at each one's required time maintaining almost minimum thrust without any conflict. In a previous study, however, it has been reported that the time-based separation cannot always be achieved especially due to unexpected wind[8]. To cope with such undesirable situations, the authors have presented the "arrival time controllability" concept to evaluate how large arrival time difference could potentially be made at the top of descent[15]. The arrival time controllability is uniquely determined for a CDO trajectory, and it means how large arrival time error could be compensated during the continuous descent. For example, an aircraft on a CDO trajectory with a sufficient arrival time controllability can adjust the time to reach a merging point, but an aircraft on a CDO trajectory with NO arrival time controllability can no longer continue the CDO when subjected to some disturbance.

In this study, the arrival time controllability is analyzed using a practical flight condition, and its effectiveness is demonstrated through a descent air traffic control simulation. It is possible to determine the flight trajectory with the optimum arrival time controllability from the TOD. It is expected that many aircraft become able to arrive the airport on time by scheduling their flight time along this flight trajectory. It is also expected possible to find a flight trajectory that has a certain level of the arrival time controllability throughout the continuous descent. Such a flight trajectory is expected to enable aircraft to keep the scheduled time of arrival even against disturbances such as unexpected wind, etc. In the traffic control simulation, it is aimed to present a traffic control strategy that utilizes the CDO trajectory with the optimum arrival time controllability to achieve a delay free descent traffic.

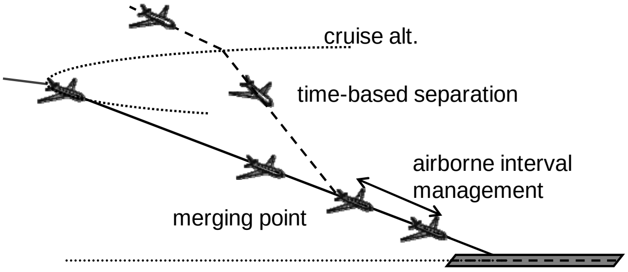

Fig. 1 Basic CDO Concept

2. Arrival Time Controllability Analysis

2.1. Arrival Time Analysis

The arrival time is defined as the time required for an aircraft to reach the final boundary condition defined at the altitude of 3000ft from its TOD. It is obtained through numerical analyses using the aircraft equations of motion considering the flight constraints such as the mach limit, flight speed limits, flap configurations, etc. Because the arrival time basically depends on the descent ratio, only the aircraft vertical motion is considered in this paper. It is also assumed that the aircraft maintains the idle thrust during descent. The numerical analyses are carried out using the B777-300 parameters[16]. The aircraft equations of motion are as follows:

$$m\frac{dv}{dt} = -\frac{1}{2}\rho v^2 S C_D - mg\sin\gamma + T_{des} \qquad (1)$$

$$mv\frac{d\gamma}{dt} = \frac{1}{2}\rho v^2 S C_L - mg\cos\gamma \qquad (2)$$

$$\frac{dh}{dt} = v\sin\gamma \qquad (3)$$

$$\frac{dx}{dt} = v\cos\gamma \qquad (4)$$

where C_D and C_L are the drag and lift coefficients. C_D is given using the parasite and induced drag coefficients, C_{D0} and C_{Di}, as the following equation:

$$C_D = C_{D0} + C_{Di} C_L^2 \qquad (5)$$

The idle thrust T_{des} is given as follows:

$$T_{des} = C_{Tdes} \cdot T_{max,climb} \qquad (6)$$

$$T_{max,climb} = C_{Tc,1}\left(1 - \frac{h}{C_{Tc,2}} + C_{Tc,3}\cdot h^2\right)\left(1 - C_{Tc,5}\left(\Delta T_{ISA}\right)_{eff}\right) \qquad (7)$$

$$\left(\Delta T_{ISA}\right)_{eff} = \Delta T_{ISA} - C_{Tc,4} \qquad (8)$$

The coefficients are provided as follows:

$$C_{Tdes} = 4.1065\times 10^{-2},\ C_{Tc,1} = 4.3706\times 10^{5}$$
$$C_{Tc,2} = 5.1125\times 10^{4},\ C_{Tc,3} = 5.7969\times 10^{-11} \qquad (9)$$
$$C_{Tc,4} = 9.4595,\ C_{Tc,5} = 4.5323\times 10^{-3}$$

The flap configuration is defined by the C_{D0} and C_{D2} values. These values are determined according to the aircraft altitude and the calibrated air speed (CAS). The CAS is calculated as:

$$v_{CAS} = \sqrt{\frac{2}{\mu}\frac{P_0}{\rho_0}\left\{\left(1 + \frac{P}{P_0}\left[\left(1 + \frac{\mu}{2}\frac{\rho}{P}v^2\right)^{\frac{1}{\mu}} - 1\right]\right)^{\mu} - 1\right\}} \qquad (10)$$

$$\mu = \frac{\kappa - 1}{\kappa} = \frac{1}{3.5} \qquad (11)$$

where P_0 and ρ_0 are the ground air pressure and density. The speed limits are also defined as:

$$v_{CAS} > v_{\min,LD} \qquad (12)$$

$$v_{CAS} < v_{\max} \quad (h \geq 10000[ft]) \qquad (13)$$

$$v_{CAS} < 250[kt] \quad (h < 10000[ft]) \qquad (14)$$

The speed limits, flap configurations, and drag coefficients are summarized in Tables 1 and 2.

In addition to the speed limit, the flight path angle limit[17] and the mach number limit are also introduced as follows:

$$-4.7[\deg] < \gamma < 0[\deg] \qquad (15)$$

$$Mach < 0.85 \qquad (16)$$

The wing area S and mass m of B777-300 are given as:

$$S = 428[m^2] \qquad (17)$$

$$m = 237600[kg] \qquad (18)$$

The flight trajectories are analyzed numerically so that they satisfy both the following initial and final boundary conditions. The initial condition is given at the TOD as:

$$\begin{aligned} h_{ini} &= 39000[ft] = 11887.2[m], \\ v_{ini} &= 250[m/s] \end{aligned} \qquad (19)$$

, and the final boundary condition is given as:

$$\begin{aligned} h_{fin} &= 304.8[m] = 1000[ft], \\ v_{fin} &= 80[m/s], \quad x_{fin} = 0[m] \end{aligned} \qquad (20)$$

Disturbances such as wind, navigation error, etc. are not considered for the clarity of this study. The analyses are carried out using MATLAB Optimization Toolbox[18].

Table 1Aircraft Configurations[16]

Cruise	$h \geq h_{\max,AP}$ or $h < h_{\max,AP}$ and $v_{CAS} \geq v_{\min,CR} + 10kt_{CAS}$
Approach	$h_{\max,AP} > h \geq h_{\max,LD}$ and $v_{CAS} < v_{\min,CR} + 10kt_{CAS}$ or $h < h_{\max,LD}$ and $v_{CAS} \geq v_{\min,AP} + 10kt_{CAS}$
Landing	$h < h_{\max,LD}$ and $v_{CAS} < v_{\min,AP} + 10kt_{CAS}$

(note: $h_{\max,AP} = 8000\,ft$,and $h_{\max,LD} = 3000\,ft$)

Table 2 Aircraft Parameters[16]

m [kg]	2.38×10^{5}	C_{D0} (Cruise)	1.69×10^{-2}
S [m^2]	4.28×10^{2}	C_{Di} (Cruise)	4.89×10^{-2}
$v_{\max}$ [kt$_{CAS}$]	3.30×10^{2}	C_{D0} (Approach)	2.25×10^{-2}
$v_{\min,CR}$ [kt$_{CAS}$]	2.08×10^{2}	C_{Di} (Approach)	4.96×10^{-2}
$v_{\min,AP}$ [kt$_{CAS}$]	1.57×10^{2}	C_{D0} (Landing)	8.69×10^{-2}
$v_{\min,LD}$ [kt$_{CAS}$]	1.44×10^{2}	C_{Di} (Landing)	4.68×10^{-2}

2.2. Concept of Arrival Time Controllability

The arrival time controllability is defined as the potentially achievable time difference between the minimum and maximum time to reach the final boundary condition. It is possible to compose a lot of flight trajectories to satisfy the final boundary condition from an arbitrary point on a CDO trajectory. Among these flight trajectories, it is further possible to find ones that have the maximum and minimum flight time. The time difference between a flight time of a CDO trajectory and the maximum or minimum time can be regarded as the extensible or reducible time. These time differences are the definition of the arrival time controllability. In addition, a flight trajectory that has the mean flight time of the maximum and minimum ones is regarded as the flight trajectory with the optimum arrival time controllability because an aircraft at TOD on this flight trajectory can potentially both extend and reduce the flight time by the largest time difference. A large arrival time controllability is expected to enhance the CDO feasibility. For example, if an aircraft is on a CDO trajectory with insufficient arrival time controllability, the aircraft can no longer continue CDO with an idle thrust or satisfy the required arrival time when it is subjected to some unexpected wind. In contrast, if an aircraft is flying on the CDO trajectory with the optimum arrival time controllability, this aircraft is able to choose another CDO trajectory that satisfies the required arrival time.

2.3. Arrival Time Controllability at TOD

The optimum arrival time controllability at the TOD is obtained through the numerical analyses on the flight trajectories with the maximum and minimum arrival time. They are presented in Fig. 2, where the solid and dashed lines show the flight trajectories with the maximum and the minimum flight time, respectively. Both trajectories are determined by the mach number limit, the flight path angle limit, and the speed limits. In the following of this paper, these flight trajectories are called as the maximum time trajectory and the minimum time trajectory. The optimum arrival time controllability ΔT_{opt} is determined from the time difference between these flight trajectories including the cruise time difference as follows:

$$\Delta T_{opt} = T_{\max} - \left(T_{\min} + \frac{\Delta TOD}{v_{ini}} \right) \qquad (21)$$

where $T_{\max}$ and $T_{\min}$ are the maximum and minimum flight time, and ΔTOD is the distance between the TOD of the maximum and minimum time trajectories. From the analyses, the optimum controllability is obtained as follows:

$$\begin{aligned} \Delta T_{opt} &= 1606.3 - (1160.8 + 28.3) \\ &= 417.2\,[\mathrm{sec}] \end{aligned} \qquad (22)$$

The CDO trajectory that has ΔT_{opt} should have the following flight time:

$$\begin{aligned} T_{opt} &= T_{\max} - \frac{\Delta T_{opt}}{2} = T_{\min} + \frac{\Delta T_{opt}}{2} \\ &= 1397.7[\mathrm{sec}] \end{aligned} \qquad (23)$$

This result should be understood that an aircraft on a CDO trajectory with this flight time T_{opt} can both reduce or extend the arrival time up to ΔT_{opt}, and that it can reduce the flight time during descent trajectory to catch up with its original schedule when the aircraft has a delay smaller than ΔT_{opt}. It is possible to compose a lot of flight trajectories with T_{opt}. Some example trajectories are shown in Fig. 3. In addition, the example trajectories for 100sec and 50sec reduction, and 100sec and 50sec extension trajectories are shown in Fig. 4. In this way, it is also possible to compose a lot of flight trajectories to achieve a specific flight time difference. Therefore, it is considered further possible to compose a flight trajectory that maintains a certain arrival time controllability even during descent.

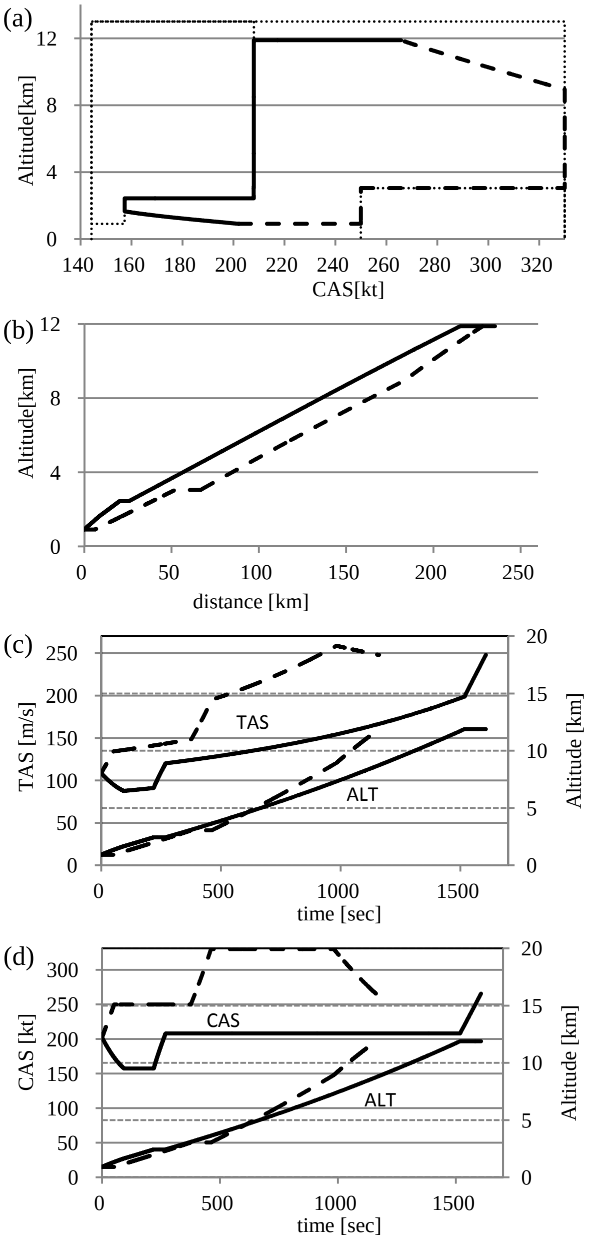

Fig. 2 Maximum and minimum arrival time trajectories (a: CAS-Altitude, b: distance-altitude, c: TAS and altitude time histories, d: CAS and altitude time histories)

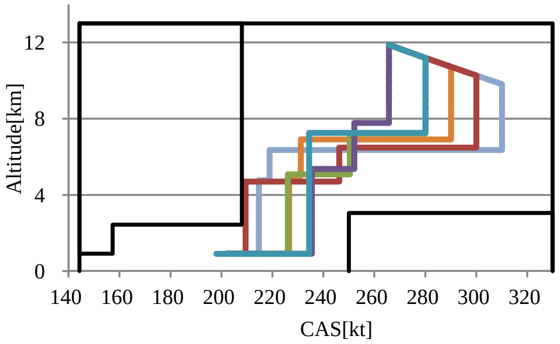

Fig. 3 Example CDO trajectories with optimum arrival time controllability (CAS-altitude)

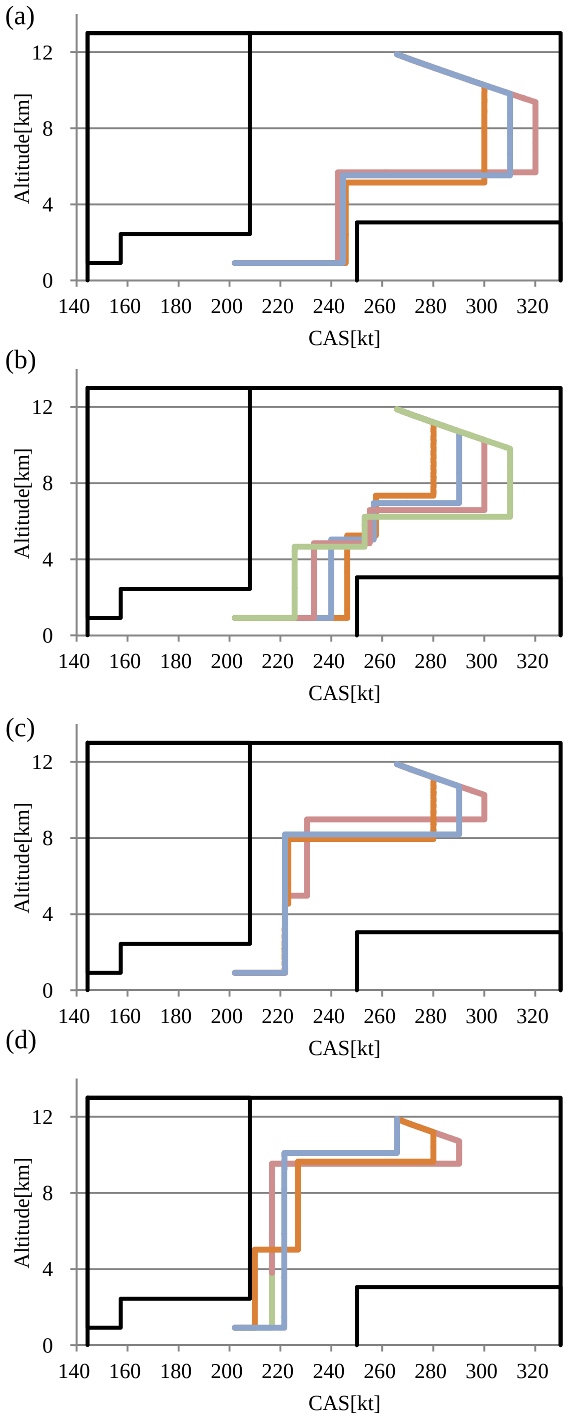

Fig. 4 CDO trajectories for arrival time control (a: 100sec reduction, b: 50sec reduction, c: 50sec extension, d: 100sec extension)

2.4. Arrival Time Controllability during Descent

Aircraft are able to select a suitable CDO trajectory to satisfy the required time arrival at the TOD. However, it is also subjected to some disturbances during descent, and some deviation from the required time of arrival will be inevitable. For a more punctual arrival, therefore, it is desirable that an aircraft can control its arrival time during descent with maintaining the idle thrust. To investigate its feasibility, numerical analyses are carried out to find flight trajectories that simultaneously satisfy the boundary conditions and achieve the flight time control. In this case, the initial boundary condition additionally includes the position *x* constraints. In this paper, the CDO trajectories from the altitude of 20000[ft] and 8000[ft] are analyzed. To analyze the optimum arrival time controllability from these altitudes, the flight trajectories that transfer to the maximum or minimum time trajectories with additional minimum numbers of legs are numerically sought for.

The maximum and minimum flight time from a specific altitude depends on the position and speed. Through the optimization on the flight time, the maximum and minimum time flight trajectories from 8000[ft] and 20000[ft] are obtained as Figs. 5 and 6. The solid lines and dashed lines denotes the maximum and minimum time trajectories, respectively. The optimum arrival time controllability are analyzed as follows:

$$\Delta T_{opt}^{8000} = 7.6[\mathrm{sec}], \quad T_{opt}^{8000} = 260.7[\mathrm{sec}] \quad (24)$$

$$\Delta T_{opt}^{20000} = 204.4[\mathrm{sec}], \quad T_{opt}^{20000} = 842.0[\mathrm{sec}] \quad (25)$$

It has been revealed that it is still possible to reduce or extend the flight time more than 200sec with the idle thrust from the altitude of 20000[ft]. It has also been shown that the flight trajectory from the altitude of 8000[ft] can achieve only a small controllability compared to those from TOD and 20000[ft] altitude. The optimum CDO trajectory that has the optimum arrival time controllability throughout the descent trajectory is obtained by connecting these trajectories as shown in Fig. 7.

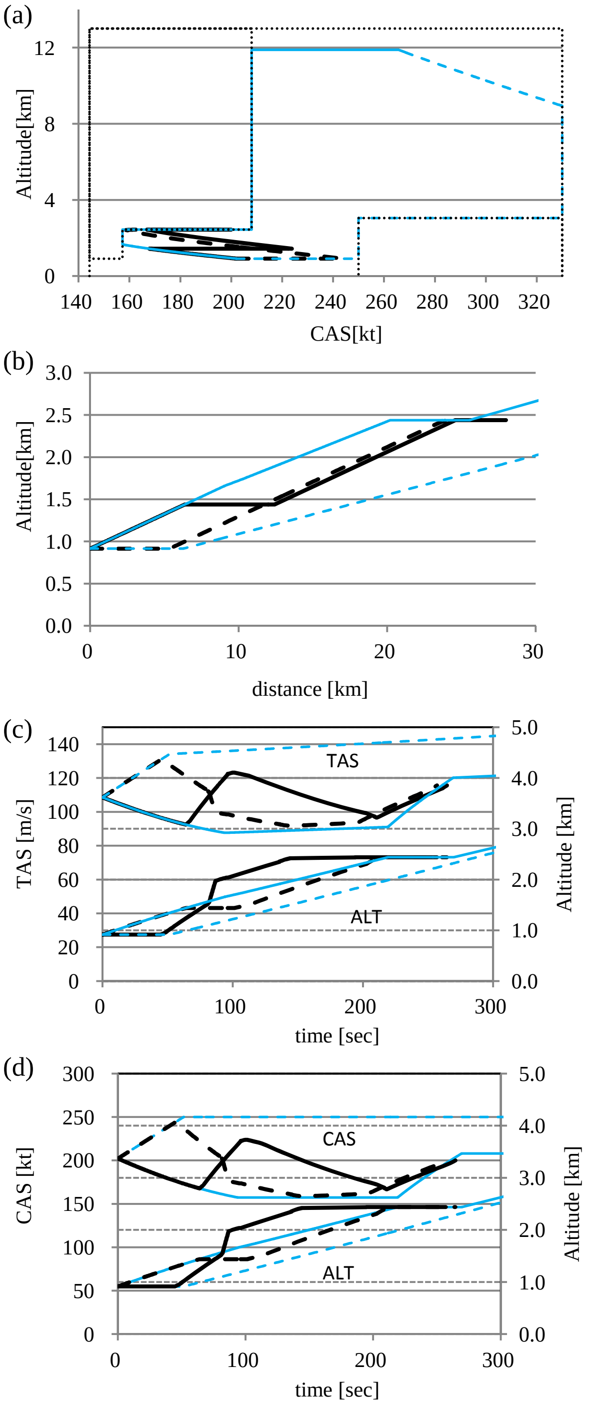

Fig. 5 Maximum and minimum arrival time trajectories from 8000 [ft] (a: CAS-Altitude, b: distance-altitude, c: TAS and altitude time histories, d: CAS and altitude time histories, blue lines: maximum and minimum arrival time trajectories from TOD)

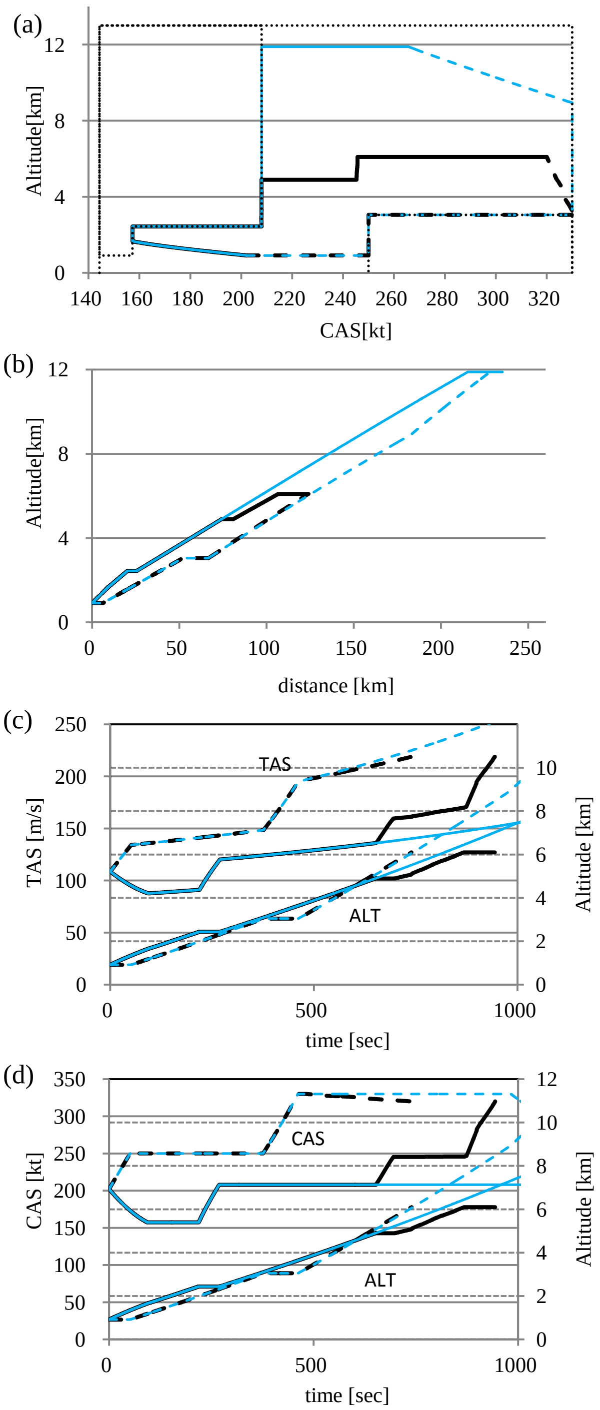

Fig. 6 Maximum and minimum arrival time trajectories from 20000 [ft] (a: CAS-Altitude, b: distance-altitude, c: TAS and altitude time histories, d: CAS and altitude time histories, blue lines: maximum and minimum arrival time trajectories from TOD)

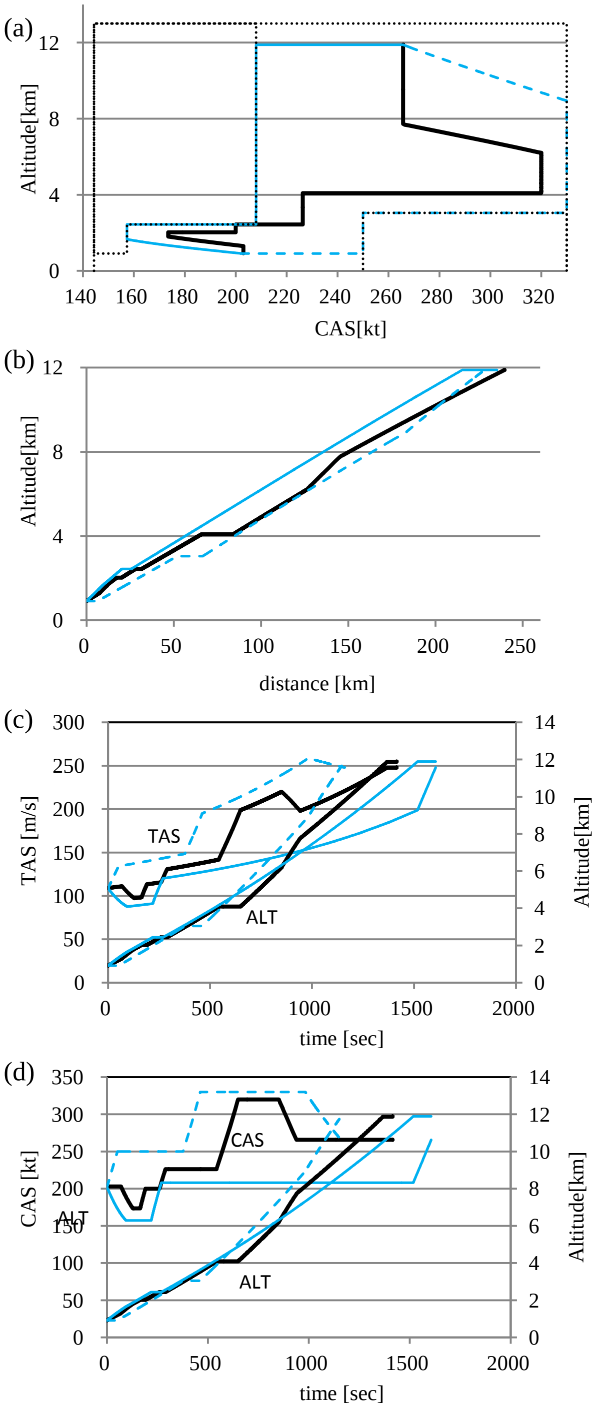

Fig. 7 CDO trajectory with optimum arrival time controllability at TOD, 20000[ft], and8000 [ft] (a: CAS-Altitude, b: distance-altitude, c: TAS and altitude time histories, d: CAS and altitude time histories, blue lines: maximum and minimum arrival time trajectories from TOD)

3. Effectiveness of Arrival Time Controllability in Traffic Control

It has been clarified through the CDO trajectory analyses that it is possible to reduce or extend the flight time not only at the TOD but at an arbitrary point during descent with maintaining the idle thrust. The effectiveness of this flight time control is investigated through the traffic control simulations.

In the traffic control simulation, it is assumed that all aircraft are scheduled to arrive the airport with a constant interval. Some disturbances are also considered on both cruise and descent trajectories that have aircraft deviate from the scheduled trajectory. Because it is possible to reduce the flight time on the CDO trajectory with maintaining the idle thrust, a traffic control strategy that takes advantage of the flight time reduction is also possible. Therefore, the following two algorithms are investigated: A) all aircraft are scheduled to fly on the minimum time trajectory, and aircraft intervals are achieved by delaying the following ones within the maximum extensible time range, and B) all aircraft are scheduled to fly on the optimum arrival time controllability trajectory, and aircraft intervals are achieved by leading all aircraft to follow their schedule within the arrival time controllability. These algorithms are illustrated in Fig. 8. In the latter strategy, the flight time control is made for achieving aircraft interval prior to following the schedule when an insufficient interval is anticipated. In both strategies, the arrival time estimation and the flight trajectory determination to achieve the required flight time control are carried out at the following two cases of opportunities; 1) at the TOD only, and 2) at both the TOD and the altitude of 20000[ft]. In addition, the half arrival time controllability case is also considered because it is expected unpractical to have aircraft fly along the flight envelope limits in actual operations. The combinations of the above traffic control strategies and conditions are summarized in Table 3, and they are called by symbols, e.g. A-1, B-2(half) etc., in the following. The aircraft are scheduled to arrive at the airport every 90[sec] over 15hours for 1 year, and they are subjected to random disturbances on both cruise and descent routes, which result in random delay. It is assumed that the disturbances result in 30[sec] average delay with 30[sec] standard deviation following the normal distribution on the cruise route and 0[sec] average with 30[sec] standard deviation on the descent route, where 75% delay occurs from the TOD to the altitude of 20000[ft].

The traffic control simulation results are summarized in Table 4. Through comparison between A-1 and B-1 cases and A-2 and B-2 cases, it is clarified that the schedule based control using the flight time reduction has the effectiveness to achieve the delay free traffic. An example one-day delay history is shown in Fig. 9. Although the delay deviations are almost the same in these 2 cases, their average has a significant difference. The example histories of the estimated delay at the TOD in A-1 case for 5 days are summarized in Fig. 10. As this figure shows, the estimated arrival time varies day by day. Therefore, it is considered that the arrival time control algorithm including the flight time reduction also achieves a better predictability of the arrival time in addition to the delay free traffic. From the B-1 and B-2 results, it is also derived that the arrival time control during descent improves the arrival time control precision, which is expected to improve the CDO feasibility. In the cases of the half arrival time controllability, it was impossible to lead the all aircraft to have sufficient interval due to insufficient controllability. As Eq. (23) implies, to achieve the arrival time controllability, all aircraft need to be scheduled to fly intentionally more slowly than possible on the fastest time trajectory. In the A-2(half) and B-2(half) cases, aircraft are scheduled to fly 100[sec] more slowly than the fastest trajectory in order to achieve the arrival time controllability of 200[sec]. However, in the numerical simulation, the arrival time delay in the A-2(half) case becomes about 160[sec] longer than that in the B-2(half) case. This means that the air traffic controlled by the algorithm B-2(half) achieves 160-100=60[sec] faster arrival than that controlled by the algorithm A-2(half). This implies the possibility that a traffic intentionally scheduled slow achieves the faster arrival.

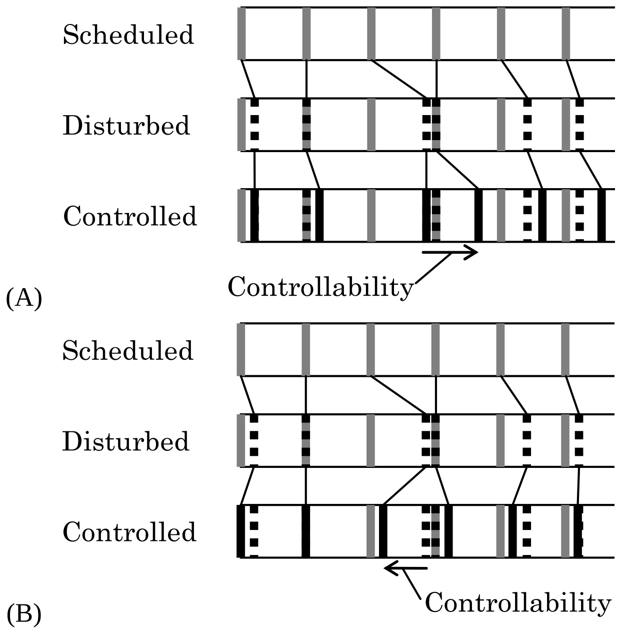

Fig. 8 Traffic control concept (A: extend only algorithm, B: extend & reduce algorithm)

Table 3 Traffic control algorithms, condition, and controllability

	Algorithm	Altitude	Controllability [sec]
A-1	Extend Only	TOD Only	0~+400 (TOD)
B-1	Extend & Reduce	TOD Only	-200~+200 (TOD)
A-2	Extend Only	TOD & 20000[ft]	0~+400 (TOD) 0~+200 (20000ft)
B-2	Extend & Reduce	TOD & 20000[ft]	-200~+200 (TOD) -100~+100 (20000ft)
A-2 (half)	Extend Only	TOD & 20000[ft]	0~+200 (TOD) 0~+100 (20000ft)
B-2 (half)	Extend & Reduce	TOD & 20000[ft]	-100~+100(TOD) -50~+50 (20000ft)

Table 4 Traffic control simulation result

	Average Delay [sec]	Standard Dev.[sec]	Insufficient Interval
A-1	113.1	34.4	0.0%
B-1	0.0	30.1	0.0%
A-2	170.8	26.4	0.0%
B-2	0.0	7.5	0.0%
A-2(half)	160.5	23.1	1.6%
B-2(half)	0.2	8.6	2.7%

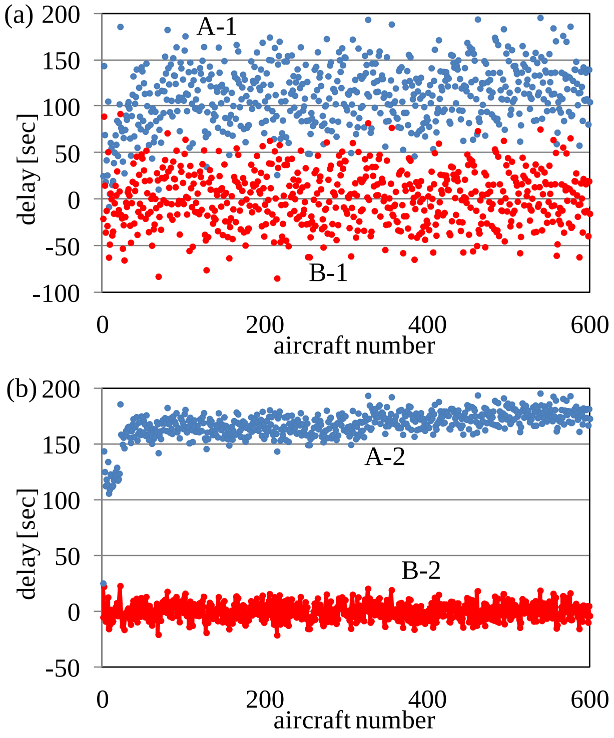

Fig. 9 Example 1 day delay history (a: A-1 and B-1, b: A-2 and B2)

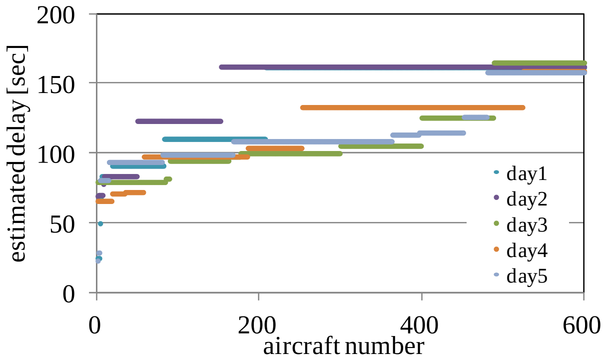

Fig. 10 Estimated arrival time delay at TOD in A-1 algorithm

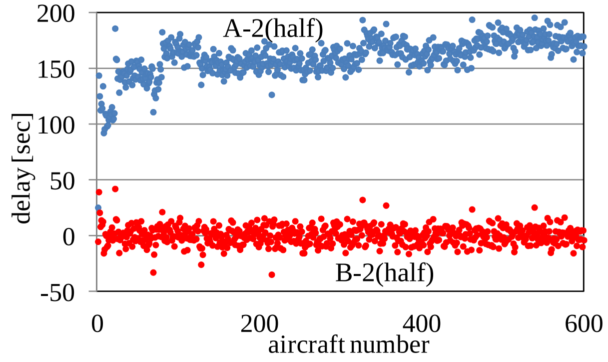

Fig. 11 Example 1 day delay history of A-2(half) and B2(half)

4. Conclusion

In this paper, it has been clarified possible to control the arrival time with maintaining the idle thrust in the CDO. It is also possible to optimize the CDO trajectory in terms of the arrival time controllability. The effectiveness of the optimized CDO trajectories are demonstrated through the CDO traffic control simulations. It has been shown that the arrival time control presented in this study enables the delay free air traffic, and that it improve the predictability of the arrival time. It is also clarified that it is further possible to compose CDO trajectories that enable the aircraft to control their arrival time without any additional fuel consumption even during the descent trajectory. Such CDO trajectory composition enhances the traffic controllability and punctuality. It is also shown that the traffic control algorithm presented in this study, that requires aircraft to fly intentionally slowly for the traffic controllability, can achieve the faster arrival. It is concluded that the CDO trajectory composition and the descent traffic control algorithm presented in this study will achieve the delay free and punctual air traffic.

There are a lot of future works for the practical use of the presented concept. The traffic controllability presented in this study is based on an assumption that aircraft are able to fly following the limit of the flight envelope. Indeed it is possible theoretically, but it is expected unpractical in actual operations. In addition, a practical scheme to derive a CDO trajectory that achieves the required flight time for the traffic control is indispensable. A more detailed investigation and some interpretation must be made for the traffic simulation, especially on the reverse phenomenon; "the slower traffic achieves the faster arrival". These investigations are expected to clarify the condition that leads the presented traffic control algorithm to bring a lot of advantage. It is also considered possible to apply the traffic control concept to general traffic such as the high-way road traffic.

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