Improved Airborne Spacing Control for Trailing Aircraft

Eri Itoh[1], Peter van der Geest[2], and Henk Blom[3]

[1]Air Traffic Management Department, Electronic Navigation Research Institute (ENRI), Tokyo, Japan
(eri@enri.go.jp)
[2, 3] Air Transport Safety Institute, National Aerospace Laboratory (NLR), Amsterdam, The Netherland
({pvdgeest, blom}@nlr-atsi.nl)

Abstract: The aim of this research is to perform a mathematical modeling and Monte Carlo simulation study of the airborne separation concept that is being described as Airborne SPacing Application using enhanced Sequencing and Merging (ASPA-S&M). The purpose of this S&M operation is to enable a more beneficial Air Traffic Management (ATM) procedure for the users and provide more consistent aircraft spacing. It also allows flight crews to manage the separation between aircraft when merging behind and following another aircraft, according to longitudinal spacing instructions that have been issued to the crew by Air Traffic Controllers (ATCo). In order to conduct the S&M operation well, the crew receives active support from a dedicated Airborne Separation Assistance System (ASAS). In this paper, a novel controller design of ASAS space keeping is developed to increase its robustness. For the evaluation of the designed controller, the ASAS components and their interactions that play a role in the aircraft behavior is captured in an integrated model using a Stochastically and Dynamically Colored Petri Net (SDCPN). Taking advantage of the SDCPN model, the effectiveness of the ASAS space keeping controller is evaluated through numerical simulations.

Keywords: Airborne Separation Assistance System (ASAS), Airborne SPacing Application using enhanced Sequencing and Merging (ASPA-S&M), Continuous Descent Arrivals (CDA), Time-Based Spacing (TBS), Stochastically and Dynamically Colored Petri Net (SDCPN), Air Traffic Management (ATM), Controller design, Complex system

1. INTRODUCTION

Airborne Separation Assistance System (ASAS) is an integrated air to air, and air to ground system which enables flight crews to maintain airborne separation by visualizing surrounding air traffic information in a cockpit display. It allows shifting Air Traffic Controller (ATCo)'s tasks to the crew during flight. One idea of recent interest in ASAS applications is Airborne SPacing Application using enhanced Sequencing and Merging (ASPA-S&M) [1]. This application asks the crew to achieve and maintain a given time-spacing to the target aircraft at a chosen waypoint. The S&M is expected to support energy saving arrivals, commonly referred as Continuous Descent Arrivals (CDA).

The motivation for our study is the need to properly understand the nominal and non-nominal behavior of many aircraft when the S&M is applied. In particular the questions are how safety and capacity depend on the setting of spacing criteria and in combination with specific S&M design aspects, and to identify any potential emergent behavior that should be taken into account in the operation design. The state of the art in scientific research is that non-nominal emergent behavior of advanced designs can be identified through conducting large scale Monte Carlo simulations with a well specified multi-agent based mathematical model of the operation [2]. In line with this, a preceding study [3] has designed an initial model of the novel operation. This research furthers the mathematical modeling and Monte Carlo simulation study for the S&M operation.

The ASAS control loop consists of Guidance, Navigation, Control (GNC), and a Global Navigation Satellite System. The guidance system contains the dynamics of aircraft, Flight Management System (FMS), autopilot, and control systems when the spacing control loop is assumed to work without any intervention of the crew and neither of ATCo. The positioning system consists of a GPS receiver and sensors with probability distributions of position/velocity error. The communication system represents an ADS-B transmitter/receiver. The GNSS system has probability distributions of the time interval while GPS is working, degraded, corrupted, and down. ASAS is represented by the combination of spacing and surveillance. A time-based spacing algorithm is applied to ASAS automatic spacing. One of the core elements which determine the performance is the design of the ASAS space keeping controller. A conventional control law for ASAS spacing controller is introduced in Ref. [4] and this has successfully been applied [5]. However this conventional design does not include robustness against random deviations, for example, deviations of initial aircraft speed and altitude. The aim of the current paper is to increase the robustness of the ASAS spacing controller, and to show the effectiveness of this novel design through numerical simulations that takes into account the complexity in the ASAS control loop.

The paper is organized as follows. In section 2, the conventional ASAS space keeping controller law is introduced. In section 3, the novel ASAS space keeping controller is developed to increase its robustness. In section 4, ASAS components and their interactions in automatic guidance are modeled using a Petri net formalism. In section 5, the performance of the improved ASAS space keeping controller is evaluated by numerical simulations. Stochastic atmospheric conditions (wind and turbulence), and initial airspeed variation are considered in these simulations. Future works are indicated in section 6.

2. CONVENTIONAL ASAS SPACING CONTROL DESIGN

2.1 ASAS time-based spacing criteria

Reference [4] proposes two different concepts for ASAS time-based spacing criteria; one is "*Constant Time Predictor (CTP) Concept*", the other is "*Constant Time Delay (CTD) Concept*" . They define the distance and time errors between a target aircraft and a trailing aircraft by using transferred ADS-B surveillance information as follows.

CTP concept

In the CTP concept, the trailing aircraft predicts its position in the future and tries to match this with the current position of the lead aircraft. The calculation of this predicted position $y_{errorCTP}$ is based on its current TAS of the trailing (own) aircraft multiplied by the time based separation criteria $t_{errorCTP}$ as follows.

$$\begin{aligned} y_{errorCTP} &= V_{own_{TAS}} \cdot t_{errorCTP} \\ &= y_{lead} - y_{own} - separation_{time} \cdot V_{own_{TAS}} \end{aligned} \quad (1)$$

Here

$V_{own_{TAS}}$: True Air Speed (TAS) of an own aircraft

$t_{errorCTP}$: Predicted time-error in CTP concept

y_{lead} : Position of a lead (target) aircraft

y_{own} : Position of an own (trailing) aircraft

$separation_{time}$: Given time separation between a target and trailing aircraft

The predicted time-error in CTP concept $t_{errorCTP}$ is expressed based on Eq. (1).

$$t_{errorCTP} = \frac{y_{lead} - y_{own}}{V_{own_{TAS}}} - separation_{time} \quad (2)$$

CTD concept

The CTD concept distinguishes from the CTP concept by the fact that the trailing aircraft tries to match its current position with the past position (the separation time before) of the lead aircraft, while taking into account the desired time based separation. The distance error in the CTD concept $y_{errorCTD}$ is given as follows.

$$\begin{aligned} y_{errorCTD} &= V_{lead_{TAS}} \cdot t_{errorCTD} \\ &= y_{lead} - y_{own} - separation_{time} \cdot V_{lead_{TAS}} \quad (3) \end{aligned}$$

Here

$V_{lead_{TAS}}$: TAS of a lead (target) aircraft

$t_{errorCTD}$: Predicted time-error in CTD concept

The predicted time-error in CTD concept $t_{errorCTD}$ is expressed based on Eq. (3).

$$t_{errorCTD} = \frac{y_{lead} - y_{own}}{V_{lead_{TAS}}} - separation_{time} \quad (4)$$

The property that the both time-based criteria can be written as distance-based criteria is shown in Eqs. (1) and (2). The distance error defined in Eqs. (1) and (2) is used in the station-keeping controller described in the next section.

2.2 Station-keeping controller

In Ref. [4], the station keeping controller has been designed to provide a Calibrated Air Speed (CAS) command $V_{cmd_{CAS}}$ to the basic aircraft controller. Considering the stability in aircraft control, the station keeping controller is of the form in Laplace domain:

$$V_{cmd_{CAS}} = K_P \cdot y_{error} \cdot (s^2 + 2\zeta_{man}\,\omega_{man} \cdot s + \omega_{man}^2) \cdot \frac{(K_I + s)}{s} \quad (5)$$

Here

K_P : Loop closure gain

y_{error} : Distance error

ζ_{man} : Maneuver damping

ω_{man} : Maneuver bandwidth

K_I : Integral gain

If CTP concept is applied, $y_{error} = y_{errorCTP}$. If CTD is applied, $y_{error} = y_{errorCTD}$.

The second derivative of the distance error in Eq. (5) could be calculated from the difference in horizontal acceleration between both aircraft. Since ADS-B link currently does not consider to transmit the acceleration, the derivative term has been approximated by using a filter on the TAS error.

$$\begin{aligned} &V_{cmd_{CAS}} \\ &= K_P \cdot \left[y_{error} \cdot \omega_{man}^2 + \left\{ \frac{s + 2\zeta_{man}\,\omega_{man}}{\tau \cdot s + 1} \left(V_{lead_{TAS}} - V_{own_{TAS}} \right) \right\} \right] \cdot \frac{(K_I + s)}{s} \quad (6) \end{aligned}$$

Here

τ : Time constant

2.3 Need for design improvements

The above ASAS space keeping controller consists of the ASAS time-based criteria and station-keeping controller has been developed in the project AMAAI (Aircraft Models for the Analysis of ADS-B based In-trail following) for model-based deviation of ADS-B system performance requirements to support ASAS [4], [5]. The aim of the project was to analyze the relationship and interaction between surveillance capabilities and the performance of the in-trail station keeping ASAS application. On the other hand, this research aims to analyze safety/capacity of airspace when the ASAS space keeping controller is applied to stochastic behaviors of multiple aircraft. Since the aims to use the controller are different, design improvements are necessary to fit our simulation study.

While implementing the conventional controller in our stochastic simulation, what we found was a lack of robustness in the controller against the input values; position error y_{error} and airspeed error $V_{lead_{TAS}} - V_{own_{TAS}}$ (see Eq. (6)). Since the station-keeping controller uses the lead compensation, it makes the tracking performance accurate. However, this characteristic causes the following three problems in our stochastic simulation:

- **Dramatic increase in airspeed command**
  When the difference of airspeed and/or position gets bigger, it causes dramatic increase in acceleration of airspeed command ($V_{cmd_{CAS}}$ in Eqs. (5) and (6)). When the initial airspeed and/or position errors between the target and trailing aircraft have deviations, there are possibilities that the conventional controller generate the dramatic change in the airspeed command. This dramatic change causes unrealistic aircraft behavior, for example, unrealistically big vertical/horizontal acceleration and the change of the angle of attack, and/or instability in automatic control of aircraft.
- **Oscillation in airspeed command**
  Since an ADS-B receiver gets the surveillance information every 1.0 second, especially the airspeed change of the target aircraft causes oscillation in airspeed command. It causes unrealistic aircraft behavior, for example, the oscillation of the angle of attack.
- **Performance deterioration in wind**
  Since both time-based criteria and station-keeping controller use TAS, the tracking performance is deteriorated in wind effects.

The ASAS spacing controller which is developed in the next section aims to solve each of these problems.

3. NOVEL ASAS SPACING CONTROL DESIGN

Here we develop the novel ASAS spacing controller, which consists of the ASAS time-based spacing criteria and station keeping controller. The improvements are given to the conversion of TAS into Ground Speed (GS), and to constraints of maximum and/or minimum limitation of position error, GS error, derivative of GS error, ratio of GS error and position error, TAS command, and derivative of TAS command as follows.

Since the update time interval of ADS-B surveillance

Table 1 Parameter settings in the ASAS spacing controller

Parameter	Value
K_P	12.0
ζ_{man}	1.3
ω_{man}	0.05
K_I	0.1
τ	0.2
ε_y	1,000 (m)
ε_v	15.0 (m/s)
$\varepsilon_{\dot{v}}$	5.0 ($\mathrm{m/s^2}$)
ε_{vyr}	0.015
$\varepsilon_{\dot{v}_{cmd}}$	6.0 (knot/s)

(1second) is longer than the update of information in flight control system, this research employed the CTP concept which utilize airspeed of an own aircraft to predict the separation distance (Eq. (1)). Under an assumption that ground speed of the lead aircraft is transmitted via ADS-B, Eqs. (3) , (4), and (6) are changed to Eqs. (7), (8), and (9) respectively.

$$\begin{aligned} y_{error\,GS} &= V_{own\,GS} \cdot t_{error\,GS} \\ &= y_{lead} - y_{own} - separation_{time} \cdot V_{own\,GS} \end{aligned} \tag{7}$$

$$t_{error\,GS} = \frac{y_{lead} - y_{own}}{V_{own\,GS}} - separation_{time} \tag{8}$$

$$\begin{aligned} &V_{cmd\,CAS} \\ &= K_P \cdot \left[y_{error\,GS} \cdot \omega_{man}^2 + \left\{ \frac{s + 2\zeta_{man}\,\omega_{man}}{\tau \cdot s + 1} \left(V_{lead\,GS} - V_{own\,GS} \right) \right\} \right] \cdot \frac{(K_I + s)}{s} \end{aligned} \tag{9}$$

In order to increase the robustness of the station keeping controller, the following constraints are given.

$$\left| y_{error\,GS} \right| \le \varepsilon_y \tag{10}$$

$$\left| V_{lead_{GS}} - V_{own_{GS}} \right| \le \varepsilon_v \tag{11}$$

$$\left| d\left(V_{lead_{GS}} - V_{own_{GS}} \right) / dt \right| \le \varepsilon_{\dot{v}} \tag{12}$$

$$\left| \left(V_{lead_{GS}} - V_{own_{GS}} \right) / y_{error\,GS} \right| \ge \varepsilon_{vyr} \tag{13}$$

$$V_{min\,TAS} \le V_{cmd\,TAS} \le V_{max\,TAS} \tag{14}$$

$$\left| dV_{cmd\,TAS} / dt \right| \le \varepsilon_{\dot{v}_{cmd}} \tag{15}$$

Here
ε_y : Upper limit of y_{error}
ε_v : Upper limit of GS difference
$\varepsilon_{\dot{v}}$: Upper limit of the derivative of GS difference
ε_{vyr} : Lower limit of the ratio of GS difference and y_{error}
$V_{min\,TAS}$: Minimum value of TAS
$V_{cmd\,TAS}$: TAS command given to autopilot
$V_{max\,TAS}$: Maximum value of TAS
$\varepsilon_{\dot{v}_{cmd}}$: Upper limit of the derivative of $V_{cmd\,TAS}$

Table 1 shows the parameter settings. The values of K_P, ζ_{man}, ω_{man}, K_I, τ are from Ref. [4] considering aircraft dynamics. The values of $V_{min\,TAS}$ and $V_{max\,TAS}$ are given from algorithm, which depend on altitude, in Ref. [6]. The values of ε_y, ε_v, $\varepsilon_{\dot{v}}$, ε_{vyr}, and $\varepsilon_{\dot{v}_{cmd}}$ are adopted to solve the problems mentioned in section 2.3 by this research.

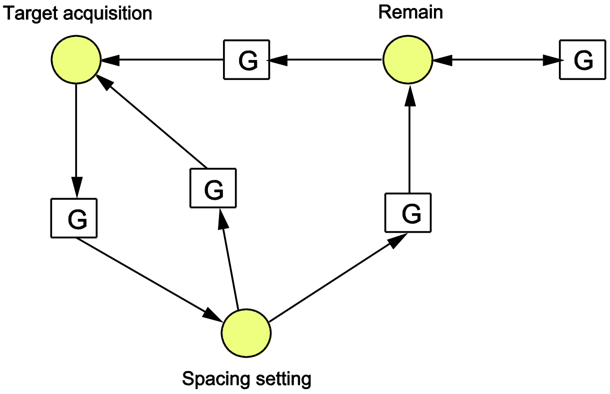

Fig. 1 ASAS spacing model

4. PETRI NET BASED SIMULATION MODEL OF ASAS SPACING

For the evaluation of the novel ASAS spacing controller, the many systems that play a role in the aircraft behavior have to be captured in an integrated model. In order to handle the complexity of this modeling challenge well, we make use of a suitable Petri net formalism, Stochastically and Dynamically Colored Petri Net (SDCPN) [7],[8].

The SDCPN is a Petri net extension which allows to represent a complex system including stochastic behaviors and dynamic processes. A Petri net is a graph of circles (named places), rectangles (named transitions) and arrows (named arcs). The places represent possible discrete modes or conditions, the transitions represent possible actions. The arcs exist between places and transition or vice versa. A condition is current if a token (represented by a dot) is residing in the corresponding place. One of the powerful advantages of Petri nets includes their graphical representation to model a complex system in all of its components and their interactions. In an SDCPN model, each token may have differential equations named color functions which represent dynamic process in the applied system.

Our preliminary ASAS model for evaluation of the ASAS spacing controller consists of the following components:

- **Aircraft evolution**
  It shows the evolution of aircraft which executes ASAS spacing.
- **FMS (Flight Management System) flight plan**
  It describes the nominal flight plan of aircraft.
- **Aircraft guidance behavior**
  It includes dynamics of aircraft including FMS, autopilot, and control systems. Initial values of aircraft speed and altitude are given by probability distributions.
- **ASAS spacing**
  Dynamics of ASAS space keeping controller, which automatically guides aircraft to keep certain time separation between a target aircraft, is given by ASAS time-based spacing criteria [4].
- **ASAS surveillance**
  It describes ADS-B information of all other aircraft in ADS-B range which the own aircraft updates every 1 second.
- **Wind model**
  It describes wind dynamics on 3 axis (x, y, z on the earth axis) as a combination of mean wind and disturbance which depends on altitude and air speed.

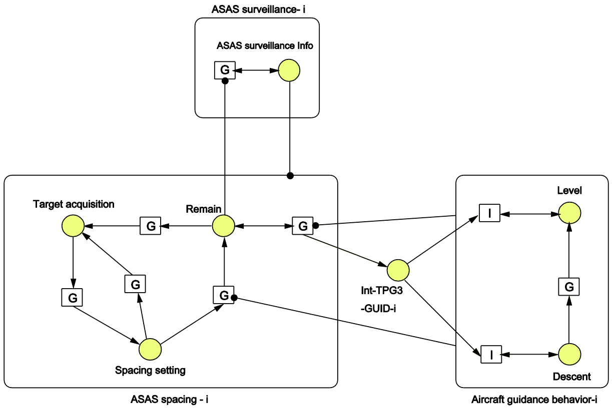

Fig. 2 ASAS spacing interactions

Figure 1 shows the SDCPN model which represents our ASAS spacing model. ASAS spacing model consists of three places; Target acquisition, Spacing setting, and Remain. When the token stays at Target acquisition, a target aircraft is selected. Spacing setting gives desired spacing time. At Remain, the ASAS space keeping controller works to keep the desired spacing time. If the selected target aircraft is not included in ADS-B range, then a token move to Target acquisition. If the target aircraft is included, a token move to Spacing setting, and Remain.

Figure 2 shows interactions of the ASAS spacing model. Three incoming arcs from ASAS surveillance and Aircraft guidance behavior model, and an outgoing arc and an outgoing interaction Petri net to ASAS surveillance and Aircraft guidance behavior. These interactions show information flows between these models. The following information is given to ASAS spacing model from ASAS surveillance and Aircraft guidance behavior model:

Incoming from ASAS surveillance

Q : Call signs of all aircraft in ADS-B range
q_{target} : Call sign of a target aircraft
$\hat{x}_1^{lead}$: x axis position of a lead (target) aircraft, positive value is given to the east direction.
$\hat{x}_2^{lead}$: y axis position of a lead (target) aircraft, positive value is given to the north direction.
V_{GS}^{lead} : Ground speed of a lead (target) aircraft

Incoming from Aircraft guidance behavior

$\hat{x}_1^{own}$: x axis position of an own (trailing) aircraft, positive value is given to the east direction.
$\hat{x}_2^{own}$: y axis position of an own (trailing) aircraft, positive value is given to the north direction.
V_{GS}^{own} : Ground speed of an own (trailing) aircraft

By using the above incoming information, an airspeed command which achieves the desired time spacing between a target aircraft and an own aircraft is calculated. The airspeed command is input to autopilot in the Aircraft guidance behavior model. The autopilot model generates thrust and pitch angle command to guide the own aircraft. The autopilot is designed based on the Total Energy Control System (TECS) [4] , [8]. We use a six degrees-of-freedom axis aircraft model in the SDCPN model.

5. SIMULATION RESULTS

5.1 Comparison with the conventional controller

Firstly, we show the effectiveness of the novel ASAS

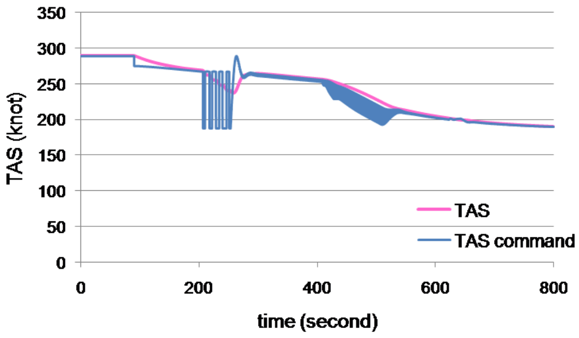

Fig. 3 Performance of the conventional controller
- TAS and TAS command

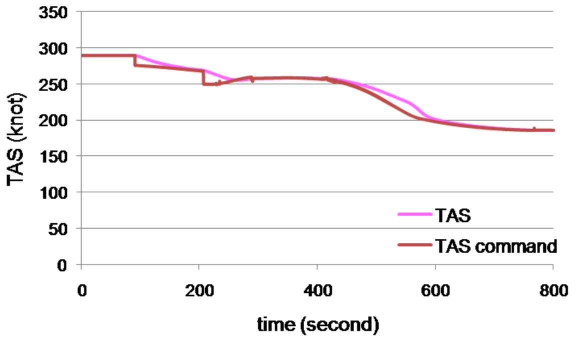

Fig. 4 Performance of the novel controller
- TAS and TAS command

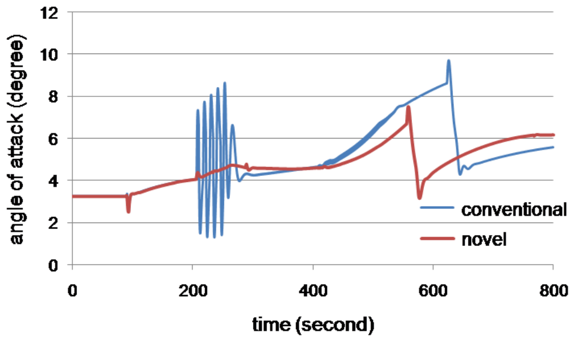

Fig. 5 Comparison of the angle of attack

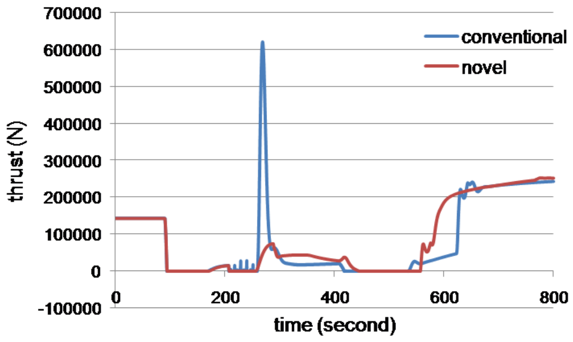

Fig. 6 Comparison of thrust

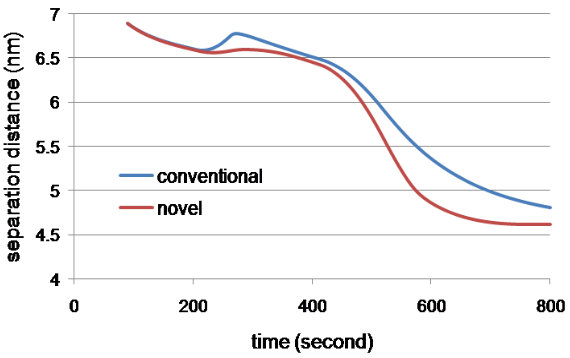

Fig. 7 Comparison of distance separation

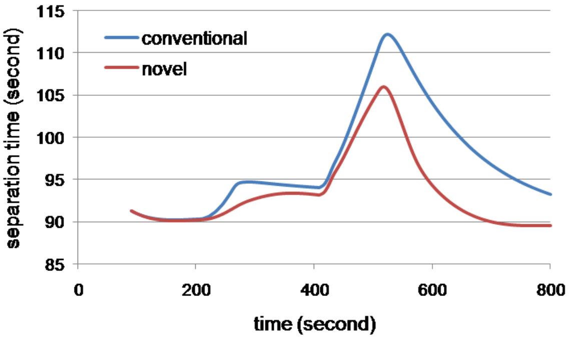

Fig. 8 Comparison of time separation

spacing controller comparing the performance with the conventional controller using the SDCPN specified models. In the simulation, a first aircraft enters Initial Approach Fix (IAF) at 10,000 ft by 240 CAS knot, then continuously descent to the Final Approach Fix (FAF) by keeping a 2.5 degree flight path. After reaching the FAF at 2,000 ft, the aircraft reduces airspeed to 180 CAS knot and increases the flap angle to 25 degrees proportionally for 100 seconds. The distance between IAF and FAF is 45.0 NM. The second aircraft (a trailing aircraft) enters IAF at 10,000 ft by 250 CAS knot and trails the first aircraft (a target aircraft) while keeping 90 seconds separation. The ASAS spacing controller works to trail the target aircraft under zero-wind condition. The B747-400 dynamics are given to the two aircraft by AMAAI tool box. We use a computing time step of 0.1 second.

Figure 3 shows the TAS control performance of the conventional controller (CTP concept). Oscillation is observed in TAS command around 200 - 250 seconds. This tendency is observed when the ratio of airspeed error and position error, $\left|\left(V_{lead_{TAS,GS}} - V_{own_{TAS,GS}}\right)/y_{error}\right|$, takes smaller values than around 0.015. When the ratio gets small, it means that the position error still exists since the airspeed of the own aircraft reach close to that of the target aircraft. Since the station keeping controller uses two inputs in the lead compensation (Eq. (6)), this unbalance in the two inputs which the initial variation in airspeed causes generates dramatic change of the airspeed command. This triggered the oscillation in airspeed command. The second oscillation was observed after around 400 seconds. It is because the ADS-B information is transmitted every one second. When the target aircraft changes the airspeed, the deviation between the updated and previous target airspeed sometimes triggers the oscillation one second cycle. Figure 4 shows the performance of TAS control that the novel controller achieves. Comparing with Fig. 3, the

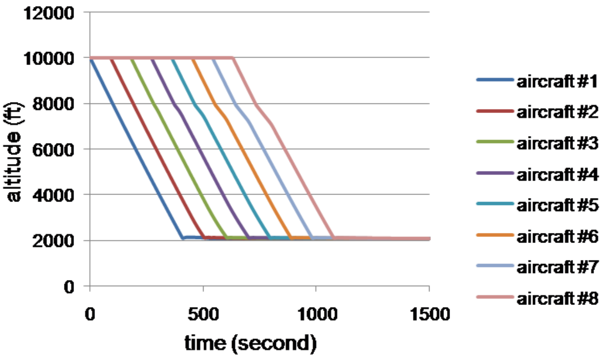

Fig. 9 ASAS spacing - altitude (no wind)

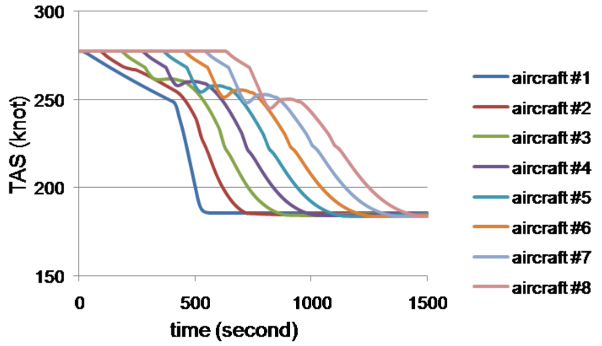

Fig. 10 ASAS spacing - TAS (no wind)

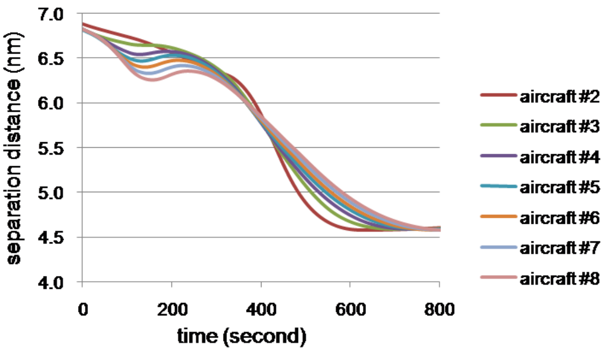

Fig. 11 ASAS spacing - separation distance (no wind)

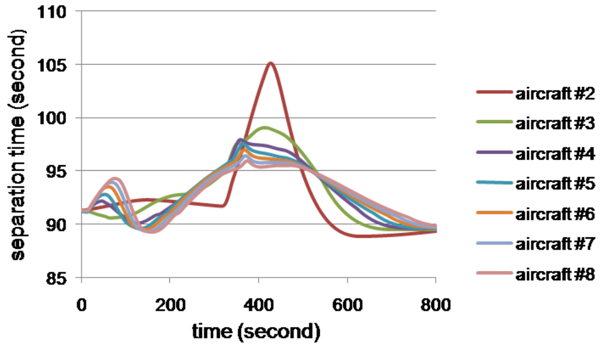

Fig. 12 ASAS spacing - separation time (no wind)

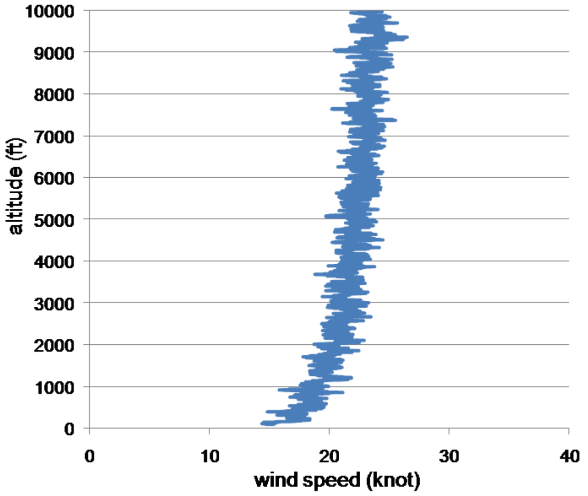

Fig. 13 Wind model

robustness in the novel controller is increased to control airspeed within reasonable bounds. Figure 5 and 6 show the comparison of the angle of attack and thrust. The conventional controller triggered oscillation in the angle of attack and thrust change, however the performance of the novel controller is improved. Figure 7 and 8 show the comparison of distance and time separation. The novel controller works to keep 90 seconds separation.

5.2 Applied to multiple trailing aircraft

Secondly, the effectiveness of the ASAS spacing controller design applied to multiple aircraft trailing is evaluated using the SDCPN specified models. A first aircraft enters the IAF at 10,000 ft by 240 CAS knot, then continuously descent to the FAF by keeping a 2.5 degree flight path. After reaching the FAF at 2,000 ft, the aircraft reduces airspeed to 180 CAS knot and increases the flap angle to 25 degrees proportionally for 100 seconds. The distance between IAF and FAF is 45.0 NM. The other aircraft trails a previous aircraft (a target aircraft) and enter IAF at 10,000 ft by 240 CAS knot 90 seconds after the target aircraft. All aircraft is assumed as B747-400. The B747-400 dynamics are given by AMAAI tool box. For the comparison of multiple trailing aircraft, the same values are given to the initial setting of CAS and altitude. We use a computing time step of 0.1 second.

Figures 9 - 12 show simulation results; altitude, TAS, separation distance, and predicted separation time (given by Eq. (8)) when the ASAS spacing is applied to in-trail following for eight aircraft (a first aircraft flies following the given scenario, then the others trail the previous aircraft.) under zero-wind condition. All aircraft conduct CDA until reaching to altitude 2,000 ft (Fig. 9). The ASAS spacing is given while controlling air speed within reasonable bounds as shown in Fig. 10. It can be shown that the ASAS spacing controller performs well to keep 90 seconds separation in Fig. 12. One of the interesting points is that the predicted error of separation time is getting smaller as increase in number of trailing aircraft (see Fig. 12).

Next, stochastic wind behavior is taken into account. Figure 13 shows the wind model applied to the simulation. The wind speed which depends on the altitude is described as sum of mean wind and turbulence based on CS-AWO [10] and Dryden model [11]. In this simulation headwind is represented by the wind model.

The performance of the novel ASAS spacing controller is

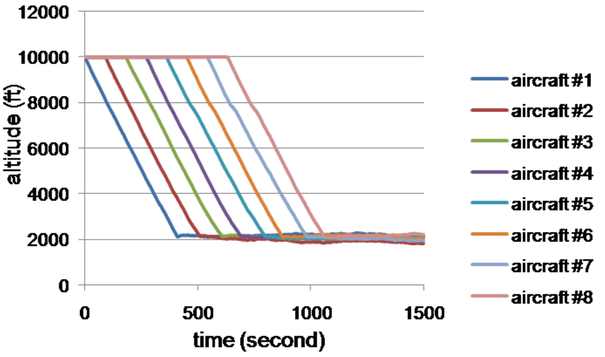

Fig. 14 ASAS spacing - altitude (wind)

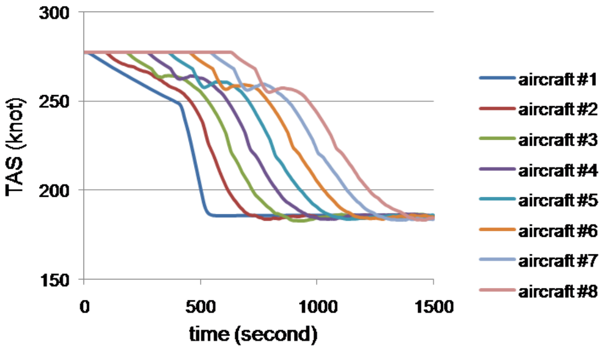

Fig. 15 ASAS spacing - TAS (wind)

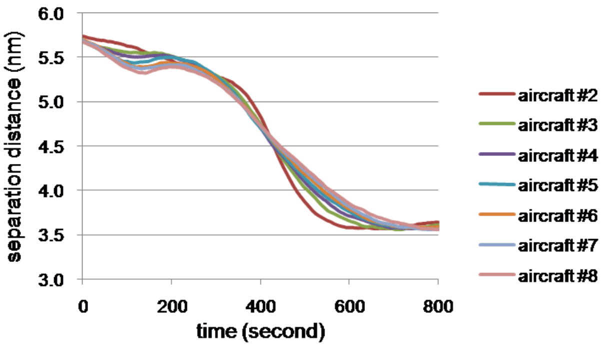

Fig. 16 ASAS spacing - separation distance (wind)

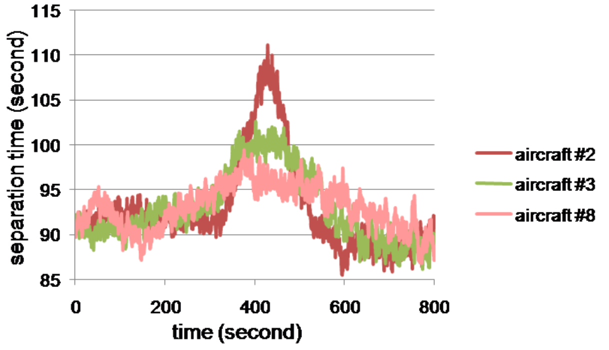

Fig. 17 ASAS spacing - separation time (wind)

confirmed in the headwind. Simulation results of altitude, TAS, separation distance, predicted separation time, are given in Figs. 14 - 17. Since the predicted separation time is affected by wind disturbance as shown in Fig. 17, both altitude and TAS are controlled within reasonable bounds (see Fig. 14 and 15). The horizontal separation distance is kept longer than 3.0 NM, which is the horizontal separation distance defined in Japanese minimum separation infringement (MSI) as shown in Fig. 16.

6. CONCLUDING REMARKS

This paper developed a novel control law for airborne based trailing of arriving aircraft. The conventional ASAS spacing controller had not been designed to cope with variations in initial conditions (i.e. airspeed, altitude, or separation errors at the time of engagement of the controller). This research has added this capability to the controller. It was shown that the novel ASAS spacing controller achieved desired spacing in CDA operation within reasonable bounds in speed control. Multiple aircraft trailing and stochastic wind speed which depends on aircraft altitude were considered in the simulation. The simulation results showed that the novel ASAS spacing controller was designed well. One of the interesting results was that the separation performance was not deteriorated due to the increase in the number of trailing aircraft under the simulated condition.

Based on this preliminary study in ASAS automatic guidance, this research is going to develop the SDCPN models and Monte Carlo simulation study for safety/performance analysis including rare events, for example, hardware failures and human performance. The current study only takes into account speed control. Hence vectoring approaches will also be studied in our follow-up research on airborne based S&M.

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